BEFORE THE
FEDERAL COMMUNICATIONS COMMISSION
WASHINGTON, DC 20554

In the Matter of	)	
	)	
Requests by Progeny LMS, LLC,	)	
FCR, Inc., Helen Wong-Armijo, and	)	WT Docket No. 12-202
PCS Partners, L.P. For Waiver and	)	
Extension of Time to Construct	)	
900 MHz Multilateration Location	)	
and Monitoring Service Licenses	)	

Reply Comments

Telesaurus Holdings GB LLC ("THL"), Skybridge Spectrum Foundation ("SSF"), Environmentel LLC, Intelligent Transportation & Monitoring Wireless LLC, Verde Systems LLC, V2G LLC, and Warren Havens (together, "Commenters") hereby file their reply comments in the above-captioned proceeding.

Commenters are submitting here their views on the importance of M-LMS to support the nation's required ITS. For this purpose, Commenters reply to comments submitted by the below entities and regarding the subject extension requests. Commenters believe it is more important to emphasize to the FCC the fundamental value of M-LMS and the great potential of currently available standards based LTE technology and equipment for integrated ITS radio communications and multilateration that will also support standards based N-RTK high accuracy location. Commenters believe it is also important to demonstrate the economic and other value of advanced ITS possible by proper use of M-LMS, which is shown by the UC Berkeley paper identified below. Commenters also refer to numerous past filings they have submitted in WT Docket No. 06-49 demonstrating the above-noted matters. Commenters believe that by review of the documents noted above and referenced herein that Commission staff will have an appropriate position upon which it can decide upon the subject extension requests, as well as consider the comments from the below-noted commenting parties.

The IEEE Local and Metropolitan Area Networks Standards Committee ("IEEE 802" or the "LMSC") opposes the subject extension requests and notes that it has interest since IEEE 802.11 Working Group and IEEE 802.15 Working Group are working on or have completed amendments to standards for equipment working in the 902-928 MHz band. In support, it asserts that GPS and "indoor location services" using cellular and Wi-Fi equipment have effectively obviated the need for M-LMS services, and that it does not see how any M-LMS proprietary technology will be able to compete with already existing technologies. As such, it "encourages" the FCC to deny the requests.

Itron, Inc. ("Itron"), the Wireless Internet Service Providers Association ("WISP A"), and Landis+Gyr Company ("L+G") (collectively, "the Part 15 Parties") argue that extensions should be granted if "justified, or cancelled" if not justified, and that for all of the subject M-LMS licensees, if their licenses are not cancelled, then they must "successfully demonstrates through cooperative testing with Part 15 interests" that their systems will not cause "unacceptable levels of interference to Part 15 devices."

As THL and SSF have stated several times in various M-LMS proceedings before the FCC, including in their and their affiliated entities' filings in WT Docket No. 06-49, the Progeny waiver docket, WT No. 11-49, and before that in RM-10403, and elsewhere before the FCC, (together, the "Past Showings"), M-LMS spectrum should be maintained for Intelligent Transportation Systems (ITS).[1] That is entirely clear in FCC rule making that created the M-LMS radio service. There is a clear need in the United States for ITS, and as shown by Commenters in their Past Showings, GPS, nor indoor cellular or Wi-Fi networks, entirely fulfill those ITS needs as suggested by IEEE 802. Regarding the nation's needs for ITS, see for example the paper by the Institute of Transportation Studies at the University of California

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[1] Commenters will not reiterate again here all of their filings contained in the Past Showings since they are already before the FCC.

Berkeley filed by THL and SSF and other of Commenters in WT Docket No. 06-49.[2]

In addition, comments that GPS obviates M-LMS were raised when the M-LMS service was initially created and were rejected by the Commission. It is clear that GPS has no communication capability. M-LMS, however, is by its design and name for "location and monitoring". The "location" may include GPS, but also involves terrestrial radiolocation, which can enhance GPS. The "monitoring" involves the communication function that under rule Section 90.353 involves a variety of data communication (and limited voice communication) that is integrated with the "location" function.

The IEEE 802 comments miss the point of ITS and the core nature of M-LMS. It is not simply a location service. In addition, ITS is not widely understood or substantially deployed in the nation at this time. However, it is a major development taking place in this country and worldwide, that unquestionably requires exactly the type of wide area, high capacity, location and monitoring wireless service that the Commission wisely established in the mid-1990s. It is a fact that M-LMS has been slow to develop for reasons apparent in WT Docket No. 06-49 and prior thereto, in RM-10403. However, the fact is that, at this time, there is an especially clear and compelling need for M-LMS systems and services for the exact purposes the Commission stated in the primary rulemaking Order establishing M-LMS and the current rules. That Order made clear that M-LMS was for support of future advanced ITS systems and applications that had not yet been fully defined or in substantial deployment, including by state and local government agencies, whose roles are required for the core traffic safety and efficiency functions of advanced ITS. Parties in M-LMS licensing and rulemaking proceedings, including this subject proceeding, do not show a fundamental understanding of either ITS, or in location and communications technologies appropriate for M-LMS, or the Commission's rulemaking Orders

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[2] Also, see Exhibit 3 hereto that contains the final report. The final report can also be viewed at: http://www.its.berkeley.edu/publications/UCB/2011/RR/UCB-ITS-RR-2011-1.pdf

in which ITS was described in specific terms, identifying various components of advanced ITS being planned for the nation.

Regarding the IEEE 802 comments on proprietary technology, those are comments on the subject extension requests, which do not describe standard-based technology for their M-LMS. However, Commenters response on that topic is that there is standards-based technology available, as explained and shown herein, and whereas the M-LMS licensees captioned above have not shown any due diligence to understand use of standards-based technologies for their M-LMS, the Commission should consider the value of viable, standards-based technology in its decision on the extension requests. Exhibit 1 hereto contains a paper by Dr. Nishith Tripathi regarding use of LTE on M-LMS,[3] and Exhibit 2 contains a paper by Konstantinos Trichias regarding LTE for ITS.

Thus, any decision on the subject extension requests should reflect the matters presented above regarding the critical ITS purposes of M-LMS, including as indicated above the location and integrated communication requirements, which no other radio service has been established to provide.

By this filing, the Commenters do not waive any past argument or position they have submitted to the FCC with regard to topics of this filing.

Dated: August 31, 2012

Respectfully submitted,

/s/ [Filed electronically.]

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Warren C. Havens, Individually and
as President of the other Commenter
entities:
Telesaurus Holdings GB LLC

[3] "Tripathi Paper," by Dr. Nishith Tripathi, "LTE Deployments in the LMS Band for ITS Radio Communications and Location", July 18 2012, version 1.0. This was commissioned by THL and SSF and their associates. This paper includes numerous references that support the various premises and conclusions in the paper.

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EXHIBIT 1

LTE Deployments in the LMS band

for ITS Radio Communications and Location

Nishith D. Tripathi, Ph. D.

Version 1.0

July 18, 2012

Intelligent Transportation Systems (ITS) can support different classes of applications such as co-operative road safety, co-operative traffic efficiency, and co-operative local services and global Internet services. Standard bodies and research organizations are actively pursuing technologies such as the IEEE 802.11p and Long Term Evolution (LTE) for the ITS. This paper provides a comprehensive view of the LTE and its suitability for the ITS. The unique features of LTE that make LTE attractive for the ITS applications are discussed. The deployment of LTE in the Location and Monitoring Service (LMS) band is described. The paper concludes that LTE can provide an efficient and cost-effective nationwide wireless system to support the ITS applications as well as other applications such as the wireless services on trains, smart electric grid and location based services.

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1. Introduction and Organization of the Paper

SkyTel has commissioned this paper for use before the FCC and other federal agencies and other public uses. The author of this report has previously submitted comments to the FCC on the Progeny test report regarding the Location and Monitoring Service (LMS).

About the Author

Dr. Nishith Tripathi is a principal consultant at Award Solutions, a provider of technical consulting and specialized technical training for wireless communications. Dr. Tripathi's students include senior personnel from companies throughout the wireless industry as well as other wireless engineering instructors. Dr. Tripathi specializes in a variety of technologies, including IS-95, CDMA2000, 1xEV-DO, GSM, GPRS, EDGE, UMTS, HSDPA, HSUPA, HSPA+, WiMAX, and LTE. He received his doctorate in Electrical and Computer Engineering from Virginia Tech, and he has held several strategic positions in the wireless arena. As a Senior Engineer for Nortel Networks, Dr. Tripathi gained direct hands-on experience analyzing and optimizing the performance of CDMA networks, in such areas as capacity, handoff and power control algorithms, supplemental channel management algorithms, and switch antenna diversity. As a Senior Systems Engineer and Product Manager for Huawei Technologies, he worked on the infrastructure design and optimization of CDMA2000, 1xEV-DO, and UMTS radio networks. Dr. Tripathi is the co-author of *Radio Resource Management* (2001) and *Cellular Communications: A Comprehensive and Practical Guide* (forthcoming) with Professor Reed. Dr. Tripathi has also contributed chapters to the following books: “Net Neutrality: Contributions to the Debate” (Edited by Jorge Perez Martinez, 2011) and “Neuro-Fuzzy and Fuzzy-Neural Applications in Telecommunications” (Edited by Peter Stavroulakis, Springer, April 2004). Dr. Tripathi's complete vita is attached.

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LTE is a fourth-generation (4G) cellular technology. LTE can provide an efficient and cost-effective nationwide wireless system to support a variety of scenarios such as intelligent transportation systems (ITS), smart electric grid, environment protection, and accurate location determination. Smart globe 4G (SG4G) refers to a smart LTE-based wireless infrastructure that serves a variety of purposes depending on the needs in a given geographic area and/or needs of wireless devices. The need for a nationwide wireless infrastructure is being recognized in different countries around the globe. This paper primarily considers LTE deployments in the LMS band (i.e., 902-928 MHz) to support the ITS.

The rest of the paper is organized as follows. Section 2 provides a glimpse of how LTE and its evolution known as LTE-Advanced have emerged. Section 3 discusses why the LTE deployment in the LMS band is a good solution for the ITS and what LTE features can ensure harmonious coexistence with the Part 15 devices and systems. The ways in which LTE can directly and indirectly support the determination of the vehicle location are summarized in Section 4. The potential of LTE for the ITS applications is discussed in Section 5. The LTE deployments at the 700 MHz band and the 900 MHz band are considered in Section 6. Section 7 focuses on the areas where the benefits of LTE can be enhanced through customization for the trains and the vehicles compared to LTE deployments in traditional cellular networks. Finally, the current research trends in the area of application of the LTE and the IEEE 802.11p to the ITS are reviewed in Section 8.

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2. Introduction to LTE and LTE-Advanced

Cellular technologies have evolved from the analog first-generation (1G) technologies to high-performance fourth-generation (4G) technologies in just about three decades. Figure 1 illustrates the evolutionary path of cellular technologies.

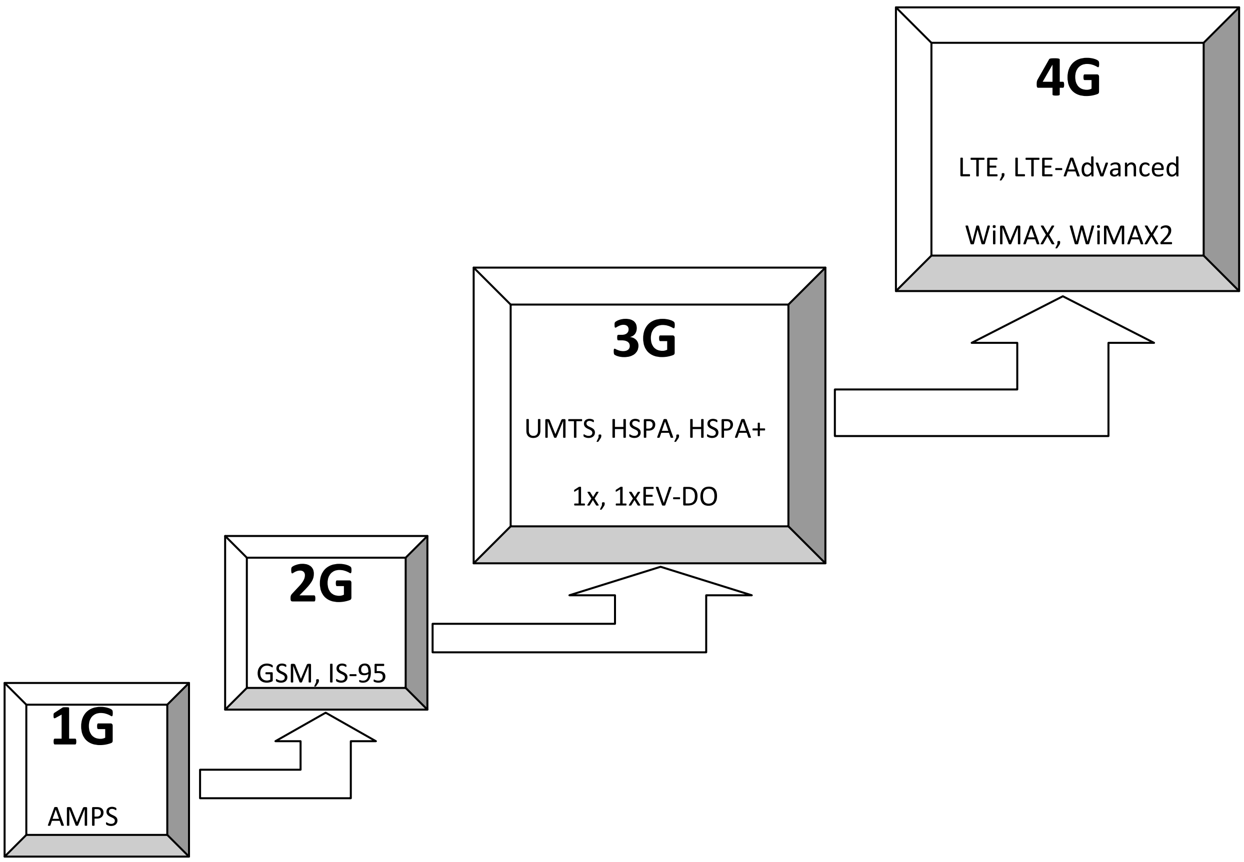

Figure 1. Evolution of Cellular Technologies

Advanced Mobile Phone System (AMPS) was a 1G cellular system in the U.S. and was replaced by digital cellular systems such as Global System for Mobile Communications (GSM) and Interim Standard- 95 (IS-95). 2G GSM systems evolved to third-generation (3G) Universal Mobile Telecommunication System (UMTS) and 2G IS-95 evolved to 3G 1x. 3G UMTS Release 99 experienced upgrades such as High Speed Packet Access (HSPA) and enhanced HSPA called HSPA+. Evolution of 1x is 1xEvolution Data Optimized (1xEV-DO). AT&T and T-Mobile have essentially nationwide 3G coverage with a typical market using UMTS for voice services and HSPA+ for data services (e.g., web browsing and email). Verizon Wireless and Sprint have essentially nationwide 3G coverage with a typical market using 1x for voice services and 1xEV-DO for data services. An organization called third-generation partnership project (3GPP) defined specifications for UMTS, HSPA, and HSPA+, while an organization called third-generation partnership project 2 (3GPP2) defined specifications for 1x and 1xEV-DO.

3GPP defined UMTS in Release 99, HSPA in Release 5 and 6, and HSPA+ in Release 7. LTE was introduced by 3GPP in Release 8. While technologies such as UMTS, HSPA+, and 1x utilize a multiple access technique called Code Division Multiple Access (CDMA), LTE utilizes a different technique called Orthogonal Frequency Division Multiple Access (OFDMA). OFDMA is more attractive than CDMA for high-speed data. Enhancements to the basic LTE are specified in LTE-Advanced, which has been introduced in Release 10. While Release 8 LTE supports the highest data rates of 300 Mbps in the downlink and 75 Mbps in the uplink, LTE-Advanced can support 3 Gbps in the downlink and 1.5 Gbps in the uplink. Worldwide Interoperability for Microwave Access (WiMAX) is a competing 4G technology, and, WiMAX2 is an evolution of WiMAX. WiMAX uses the standard called 802.16e-2005 that is defined by an organization called Institute of Electrical and Electronics Engineers (IEEE).

U.S. cellular service providers such as AT&T, Verizon Wireless, Metro PCS, and U.S. Cellular have already launched LTE networks. Sprint plans to launch LTE in mid-2012 and T-Mobile plans to launch in 2013 [T-Mobile_LTE_Launch]. While the 3G cellular market had two main competing technologies, UMTS and 1x/1xEV-DO, the 4G cellular market would essentially be dominated by LTE. For example, while AT&T is using 3G UMTS, Verizon Wireless and Sprint are using 3G 1x and 1xEV-DO. However, AT&T, Verizon, and Sprint have chosen LTE. Even some of the operators that have already deployed WiMAX are now planning to deploy LTE. For example, Clearwire is currently offering WiMAX, it has announced plans to deploy LTE in the first half of 2013 [Clearwire_LTE].

LTE is expected to become a truly global cellular technology. LTE is gaining momentum around the globe[1] (see [3GAmericas_LTE_Deployments] for the LTE deployment statistics). In addition to 8 commercial LTE networks in the U.S., there are 3 LTE networks in Canada and 6 LTE networks in 4 countries in Latin America (specifically, Brazil, Colombia, Puerto Rico and Uruguay). Overall, there are 74 commercial LTE networks in 40 countries with more than 110 commercial networks expected by the end of 2012. Furthermore, more than 334 operators have announced their commitments to LTE. LTE is being deployed at this time and features of LTE-Advanced would be deployed in 2014 and later.

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[1] The LTE deployment statistics mentioned here are from [3GAmericas_LTE_Deployments].

Table 1 summarizes main features and characteristics of Release 8 LTE [3GPP_LTE_Overview].

Table 1. LTE Features and Characteristics

Area	Features or Characteristics	Comments
Multiple Access Technique	OFDMA in the downlink SC-FDMA in the uplink 15 kHz subcarrier spacing	Achieves high spectral efficiency
Multiple Antenna Techniques	Transmit and receive diversity Spatial multiplexing (SU-MIMO) Beamforming SDMA (MU-MIMO)	Example benefits of increased reliability and high throughput
Duplexing	FDD, TDD, and H-FDD	A UE can support more than one duplexing technique
Frame Structure	10 ms frame and 1 ms subframe	Enables fast adaptation to changing radio channel conditions and reduces latency
Radio Channel Bandwidth	1.4, 3, 5, 10, 15, and 20 MHz	Flexibility of deployments and future upgrades
Frequency bands	Various FDD and TDD bands	Flexibility of deployments and improved roaming
Network Architecture	Distributed and scalable eNodeBs in the radio network MME, S-GW, P-GW, and HSS in the EPC	Scalability
Services and Quality of Service (QoS)	IMS for operator-controlled services PCC to facilitate end-to-end QoS	Rapid and cost-effective deployment of services
UE Categories	Five	Flexibility
Interworking with Other Technologies	2G and 3G cellular technologies WiFi	Facilitates seamless mobility and load balancing
Performance	Peak data rates of 300 Mbps in the downlink and 75 Mbps in the uplink Radio network latency of 10 ms Idle to connected transition delay of 100 ms	Enhanced performance compared to previous cellular technologies

A multiple access technique allows multiple users to access and use the system at the same time. For the multiple access technique, LTE uses OFDMA in the downlink and single carrier- frequency division multiple access (SC-FDMA) in the uplink. Compared to OFDMA, SC-FDMA has more complex transmitter and receiver but improves the uplink throughput near the cell-edge by reducing the peak-to-average power ratio of the transmitted signal. OFDMA and SC-FDMA involve allocation of narrow bandwidth radio channels called subcarriers to the user equipments (UEs) or mobile devices for downlink and uplink data transmissions. A given channel bandwidth is divided into multiple subcarriers. For example, there are 600 subcarriers in the 10 MHz channel bandwidth with 15 kHz subcarrier spacing. The use of

OFDMA and SC-FDMA on the air interface contributes to high spectral efficiency. Different classes of multiple antenna techniques are supported. Transmit and receive diversity improve the reliability and are especially useful near the cell-edge. Spatial multiplexing technique called single use- multiple input and multiple output (SU-MIMO) significantly increases throughput for a given user by reusing the same subcarriers to transmit different information from different antennas. Up to (4x4) SU-MIMO in the downlink is supported with 4 transmit antennas at the eNodeB and 4 receive antennas at the UE. Beamforming focuses energy in a given direction to increase signal to interference ratio (SIR) and hence throughput. Space Division Multiple Access (SDMA), also known as multi user- multiple input multiple output (MU-MIMO), reuses the same subcarriers for different UEs in the cell and differentiates these UEs in space via beamforming. SDMA increases user throughput and cell throughput.

A duplexing method allows the UE to simultaneously transmit and receive signals. Three duplexing methods are supported- frequency division duplex (FDD), time division duplex (TDD), and half-FDD (H-FDD). FDD uses one part of the frequency spectrum for transmission and a different part of the frequency spectrum for reception. TDD uses the same frequency spectrum for transmission at one instant and for reception at another instant. H-FDD supports transmission on one part of the spectrum and reception on another part of the spectrum but does not support transmission and reception exactly at the same instant; some periods are for transmission, and other periods are for reception. A UE can support more than one duplexing technique. The UE uses a specific duplexing technique during a given time period based on the capability of the base station (called evolved Node B or eNodeB in LTE) it is communicating with.

The radio frame is 10 ms long and is divided into ten subframes. The frame is used to convey information about the network (e.g., identity of the service operator). The subframe is used for resource allocation and data transmission. The short time period of the subframe enables fast adaptation to the changing radio channel conditions and reduces latency.

An operator has a wide range of radio channel bandwidths to choose from while deploying LTE. The supported channel bandwidths are 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz. Furthermore, an operator can change the channel bandwidth in future. For example, an operator can initially use 5 MHz bandwidth and change it to 10 MHz in future without adversely affecting any UEs.

LTE supports numerous frequency bands for FDD and TDD, providing flexibility of deployments and facilitating roaming across the operators using different frequency bands. More details of frequency bands are discussed later in this section.

The network architecture is distributed, which makes it easy to scale up the network as the subscriber base grows. The overall network called the Evolved Packet System (EPS) and consists of the radio network called Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and the core network called the Evolved Packet Core (EPC). The E-UTRAN consists of the eNodeBs. The absence of a radio network controller (RNC) in the E-UTRAN reduces the overall latency by reducing the backhaul delay and the processing delay. The EPC interfaces with the E-UTRAN as well as non-LTE technologies such as UMTS and 1xEVZ-DO. The EPC includes the nodes such as Mobility Management Entity (MME), Home

Subscriber Server (HSS), Serving Gateway (S-GW), and the Packet Data Network Gateway (P-GW). The MME has a signaling connection with the UE, which is used to carry out functions such as authentication and activation of security mechanisms such as encryption. The HSS stores the information about the subscribers such as the subscriber profile. The P-GW allocates an IP address to the UE. The S-GW forwards the downlink and the uplink packets of a UE between the P-GW and the correct eNodeB. The eNodeB allocates radio resources to the UEs so that the IP packets can be transmitted over the air interface. When the user is browsing the Internet, the IP packets from a web server arrive at the P-GW and pass through P-GW, S-GW, and eNodeB and finally reach the UE. All the interfaces among the EPS nodes are standardized and the operator can buy different network elements from different vendors. Furthermore, each network node can be independently provisioned.

LTE supports a variety of IP-based applications using IP Multimedia Subsystem (IMS). Nine different levels of Quality of Service (QoS) are supported. A QoS architecture called Policy and Charging Control (PCC) is defined to facilitate implementation of end-to-end QoS between the UE and P-GW. The use of IMS enables rapid and cost-effective deployment of services such as Voice over LTE (VoLTE) and Short Message Service (SMS).

Five UE categories are defined to characterize different capabilities. For example, the currently available UE Category 3 has two receive antennas and can support 100 Mbps in the downlink and 50 Mbps in the uplink.

LTE supports interworking with 2G and 3G cellular technologies and Wireless Fidelity (WiFi). Such interworking facilitates seamless mobility across the technologies and can also help balance load across different technologies via handover.

LTE offers superior performance compared to previous cellular technologies. LTE supports peak data rates of 300 Mbps in the downlink and 75 Mbps in the uplink when full potential of Release 8 is realized. The radio network latency of 10 ms; the IP packets between the eNodeB and the UE can experience delay as little as 10 ms. The transition from the idle mode to the connected mode can occur in just 100 ms, allowing many UEs to stay in the idle mode and conserving precious radio resources. The connected mode allows data transfer, while the idle mode helps conserve UE’s battery power.

Let’s take a quick look at LTE-Advanced, which is evolution of LTE. While Release 8 introduces LTE, LTE-Advanced is introduced in Release 10. LTE-Advanced is fully backward compatible with LTE. LTE and LTE-Advanced can share the same spectrum. A legacy LTE can work with both LTE infrastructure and LTE-Advanced infrastructure. Additionally, an LTE-Advanced UE can work with both LTE infrastructure and LTE-Advanced infrastructure. Table 2 summarizes main features of LTE-Advanced. Some of the LTE-Advanced features would be available in Release 11 and later releases.

Table 2. Features of LTE-Advanced

Feature	Feature Specifics	Comments
Carrier Aggregation	Use of multiple LTE carrier frequencies for data transmission between the eNodeB and a given UE.	Flexible combining of different frequency bands for higher throughput
Enhancements to Multiple Antenna Techniques	(8x8) SU-MIMO in the downlink (4x4) SU-MIMO in the uplink	High throughput
Relays	Layer 3 self-backhauling relay (advanced repeater)	Increased coverage at a lower cost
Coordinated Multipoint (CoMP) Transmission and Reception	Different flavors of soft handover with possible transmission from multiple cells and reception at multiple cells	Increased reliability and increased throughput near cell-edge

The main features of LTE-Advanced are carrier aggregation, enhanced antenna techniques, relays, and Coordinated Multipoint (CoMP) transmission and reception. Carrier aggregation allows combining of multiple carrier frequencies for data transmission between the eNodeB and a given UE with each carrier backward compatible to a Release 8 carrier frequency. Up to five carrier frequencies can be combined with each carrier having the largest bandwidth of up o 20 MHz. In the frequency domain, the carrier frequencies could be contiguous or non-contiguous (e.g., from different frequency bands). Carrier aggregation enables the operator to exploit fragmented spectrum (e.g., some spectrum at 700 MHz and some spectrum at the AWS spectrum). Carrier aggregation increases user throughput and cell throughput.

While Release 8 supports up to (4x4) SU-MIMO in the downlink, LTE-Advanced supports up to (8x8) SU-MIMO in the downlink in Release 10. Release 8 allows the UE to transmit from a single antenna. Release 10 support (4x4) SU-MIMO in the uplink. Beamforming is also enhanced in Release 10 to achieve better performance.

LTE-Advanced also enhances the network architecture by introducing relays. A relay can be considered as an enhanced form of a repeater. The repeater is a low-cost solution to increase coverage without using regular full-fledged base stations. When the goal is to increase coverage at a lower cost without adding capacity, relays are useful. LTE has defined so-called Layer 3 self-backhauling relay that increases coverage and uses LTE-based wireless backhaul between the donor eNodeB and the relay node. Direct connectivity between the relay node and the EPC does not exist; the relay node communicates with the UEs and the donor eNodeB only. The communication between the UEs and the relay node and between the donor eNodeB and the relay node can be achieved using the same or different spectrum.

Coordinated Multipoint (CoMP) transmission comes in different flavors. For example, multiple cells can transmit the same packet to the UE and the UE combines the signals from these cells for reliable reception. In another flavor of CoMP transmission, multiple cells are ready to transmit to the UE but only one cell transmits the packet. The specific cell that actually transmits the packet to the UE can be dynamically and quickly changed. The CoMP reception in the uplink involves multiple cells listening to the UE signal and one of the eNodeBs processes the packets received in different cells. The main benefits of CoMP transmission and reception are increased reliability and increased throughput near cell-edge.

Let's take a closer look at the frequency bands. Table 3 gives examples of the frequency bands supported by LTE. See [3GPP_36.101] for an exhaustive list of LTE frequency bands.

Table 3. Example LTE Frequency Bands

LTE Operating Band	Duplexing	Uplink Frequency Range (MHz)	Downlink Frequency Range (MHz)	Comments
2	FDD	1850-1910	1930-1990	PCS Band; Sprint's initial LTE deployments
8	FDD	880-915	925-960	LTE band closest to the LMS band
12	FDD	699-716	729-746	Enables lower 700 MHz A Block operators to offer LTE in the U.S.
13	FDD	777-787	746-756	Verizon Wireless LTE deployments in the U.S.
14	FDD	788-798	758-768	Covers part of the Public Safety spectrum in the U.S.
17	FDD	704-716	734-746	AT&T LTE deployments in the U.S.
26	FDD	814-849	859-894	Sprint's future LTE deployments (by 2014)
40	TDD	2300-2400	2300-2400	For TD-LTE deployments in China and India
41	TDD	2496-2690	2496-2690	For Clearwire's TD-LTE deployments in the U.S.

The current 700 MHz LTE deployments in the U.S. use FDD Bands 12, 13, and 17. Verizon deployments use Band 13, while AT&T deployments use Band 17. U.S. Cellular deployments use Band 12. Band 14 covers part of the spectrum reserved for Public Safety. The Public Safety spectrum ranges from 758 MHz to 775 MHz in the downlink and from 788 MHz to 805 MHz in the uplink. Band 40 facilitates TD-LTE deployments in China and India, while Band 41 will be used by Clearwire for TD-LTE deployment in the U.S. While Sprint's initial LTE-FDD deployments will use 1900 MHz PCS band (Band 2), the FCC's recent approval of the use of 800 MHz spectrum for LTE would enable Sprint to use the 800 MHz spectrum (Band 26) for LTE-FDD as well [Sprint_LTE_FDD_1900MHz_1] [Sprint_LTE_FDD_1900MHz_2] [Sprint_LTE_FDD_800MHz].

The FDD band 8 covers the frequency ranges widely used for GSM deployments around the globe. GSM is the most widely deployed cellular technology today. However, the number of GSM-only UEs is declining and 2G GSM spectrum is increasingly used by more efficient technologies such as UMTS. As the GSM frequency spectrum is refarmed for LTE, Band 8 eNodeBs and UEs would become widely available. Furthermore, a typical chipset usually supports both FDD and TDD. The LMS TDD band (ranging from 902 MHz to 928 MHz) overlaps with LTE FDD Band 8. Hence, it should be relatively easy and inexpensive to convert an LTE FDD Band 8 to support the LMS band. The mix of TDD and FDD spectrum would be quite common for LTE subscribers of Sprint and Clearwire in the U.S in 2013 and beyond [Qualcomm_FDD_TDD_ClearwireBand41] [Sprint_FDD_TDD].

Even in the absence of any Band 8 support today, one LTE vendor has already confirmed that the LTE eNodeB and the UE using LMS TDD and WiFi can be developed within about 18 months or so. There are two main processing blocks in a transceiver, a baseband processor and a Radio Frequency (RF) processor. The baseband processor implements LTE-specific functions at the baseband such as implementation of OFDMA and SC-FDMA. The RF processor involves functions such as filtering for a given frequency band. The main design changes in converting a Band 8 FDD equipment into an LMS band TDD equipment would involve proper RF filtering and removal of the duplexer. Such design changes are relatively simple and would not be expensive.

Since suitable software that facilitates the transitions between the FDD mode and the TDD mode would have been available in 2013 due to the expected TDD-FDD mix in case of Sprint and Clearwire subscribers, such software would largely be reusable in case the LMS equipment for LTE also supports the 700 MHz Public Safety FDD band 14. An LTE UE already supports multiple frequency bands such as 700 MHz band for LTE and 850 MHz cellular band and 1900 MHz PCS bands, the support for the LMS band and 700 MHz Public Safety is certainly well within the general capabilities of the UE designs today.

The LMS band LTE equipment would benefit from the huge economies-of-scale benefits of LTE. LTE is being deployed for wide area coverage like a traditional cellular system. Hence, LTE would be quite suitable for both for wide area coverage and corridor coverage for SG4G. In cellular networks, corridor coverage type scenario is encountered for highway coverage in rural areas. The eNodeB transmit power is not defined in the standard and any suitable high power amplifier (HPA) can be used at the eNodeB. A 40 W HPA at the eNodeB for a transmit antenna is quite common in commercial LTE deployments. Currently, Power Class 3 is defined for LTE UEs with the maximum transmit power of 200 mW or 23 dBm. It is possible to re-design UEs to meet any higher power needs of LMS if desired.

We will see in Section 6 that Japan is in the process of making some spectrum available at both 700 MHz and 900 MHz bands; some networks have already been launched at the new 900 MHz band in Japan.

3. Suitability of LMS LTE for ITS and SG4G

The LMS band ranges from 902 MHz to 928 MHz. The FCC allows the LMS band to be shared between the LMS users and Part 15 devices and systems [FCC_LMS] [Havens_CommentsOnProgeny] [Tripathi_CommentsOnProgeny]. Hence, any system planned for the LMS band such as the LMS LTE system should consider the coexistence with Part 15 devices and systems.

The review of the spectrum survey by the Shared Spectrum Corporation, funded by NSF, reveals that the Part 15 usage is somewhat significant in specific metro areas [SharedSpetcrum_SpectrumReports]. If the Part 15 interference is properly accounted for in an LMS LTE system design (more specifically, in the LTE link budget), the LMS LTE can efficiently and cost-effectively meet the needs of ITS and SG4G. In rural areas, the Part 15 usage and hence the interference between the LMS LTE and the Part 15 devices and systems would be substantially less. Additionally, Part 15 usage would be relatively little along transport corridors, since a vast majority of Part 15 devices and systems use in low power and short range devices in and around homes and enterprise facilities. Part 15 devices and systems are not intended for wide area or corridor coverage. The user traffic patterns are different on the highways and homes and offices. For example, if there are more people on the road, there will be fewer people at homes and in offices. Hence, when LMS LTE users are using the LMS band, many of the Part 15 users would probably not be using the LMS band at that time. Hence, there would be some degree of spatial and temporal separation of the spectrum use by LTE for long-range ITS and by Part 15 devices and systems for short-range communications.

An additional LMS-sister band is also available for short-range ITS. The FCC established rules for Dedicated Short Range Communications (DSRC) Service for the ITS in the 5.9 GHz band [FCC_Part90_SubpartM]. This band ranges from 5.850 GHz to 5.925 GHz. The availability of this additional non-LMS band for the ITS use will further reduce contention between the use of 902-928 MHz by LMS LTE for ITS, and the use of 902-928 MHz by Part 15 devices and systems, because a portion of the traditional ITS traffic will now be on the 5.9 GHz band.

Let's discuss the LTE characteristics that would reduce interference between the LMS LTE and Part 15 devices and systems. As mentioned in Section 2, the LTE power levels are relatively low. For example, the maximum UE transmit power is 23 dBm or 200 mW for a Power Class 3. The typical eNodeB uses a 40 W (i.e., 46 dBm) HPA.

The FCC has specified the 30 W ERP per transmitter for the LMS band, and, this power level could be used for a narrowband channel with 25 kHz bandwidth (see Paragraph 79 in [FCC_Power]): "Narrowband communication links .... e.g., 25 kHz ... channels .... enhance ... viability and flexibility of ... multilateration systems .... maximum power ... 30 watts ERP."

LTE is a wideband system and the applicable power limit per 5 MHz transmitter would be (30 W * 5 MHz/25 kHz= 6000 W). Two hundred (i.e., 5 MHz/25 kHz) narrowband transmitters with each transmitter using a 25 kHz narrowband radio channel and 30 W ERP would generate the RF energy equivalent to a single wideband transmitter using a 5 MHz wideband radio channel and 6000 W ERP.

Hence, a 5 MHz LTE transmitter using 6000 W ERP would be operating within the FCC's current power limit rules. Furthermore, since LTE in the LMS band will be used for communications, LTE transmitters would be classified as "other transmitters" for the purpose of meeting spectral emission mask requirements defined by Emission Mask K in [FCC_Emission]. More specifically, the LTE transmitter would not be required to have attenuation within its own passband (i.e., from 904 MHz to 909.75 MHz) and would need to meet this attenuation requirement outside the passband: 55 + 10 * log(P) dB, where (P) is the highest emission (watts) of the transmitter inside the licensee's sub-band. An LMS LTE operator would have the flexibility of using up to 6000 W ERP and may actually use much less than 6000 W ERP based on a given deployment scenario. Typical cellular LTE deployments may use about 60 dBm EIRP (e.g., 46 dBm HPA power plus 14 dB antenna gain= 60 dBm), equivalent to 57.85 dBm ERP[2] or 610 W ERP. Furthermore, the LTE eNodeB transmits power on the traffic channel only when necessary for packet transmission; only the subcarriers that are part of the allocated PRBs are transmitted. The non-traffic subcarriers that are periodically transmitted by the eNodeB lead to very little transmit power (e.g., about 10% from a given antenna or transmitter).

LTE also has a closed-loop power control mechanism for the uplink, where the transmit power of the UE is controlled to a minimum level (i.e., below the maximum power level of 23 dBm) that can provide the desired data rate and that can minimize interference. Furthermore, since the LMS LTE will focus energy on transportation corridors only using highly directional antennas, the LTE users will experience high signal to interference ratio (SIR) and hence better performance. Similarly, Part 15 devices will also experience significantly less interference because they will essentially be outside the LMS LTE coverage area.

LTE has numerous mechanisms that can minimize the interference between the LTE users and the part 15 users. The eNodeB scheduler can allocate resources to the UEs such that interference is minimized. For example, the LTE UEs report the observed channel conditions to the eNodeB every few milliseconds. These UEs can be configured by the eNodeB to report such channel conditions for different parts of the channel bandwidth. Hence, if some part of the spectrum is occupied by Part 15 users during a given period, the eNodeB can choose other parts of the LTE spectrum for LTE UEs, avoiding interference between the LTE users and part 15 users. The eNodeB uses the downlink power efficiently as well, reducing the average interference. The overhead channels in the downlink do not cause much interference, because they consume only about 10%-12% of the total eNodeB transmit power. Furthermore, the eNodeB transmits the traffic channels only when required for data transmissions. The hybrid automatic repeat request (HARQ) process of LTE ensures that the redundancy of transmission is resorted to only when necessary, thereby reducing the overall interference. The eNodeB chooses the most appropriate combination of modulation scheme and amount of coding UE (and this could potentially change every millisecond in LTE!) for the given channel conditions experienced by the UE, further utilizing the resources optimally and thereby reducing the amount of overall interference. The dynamic use of a variety of antenna techniques such as transmit diversity, SU-MIMO, beamforming, and MU-MIMO also utilizes the radio resources efficiently and has similar impact on interference like the selection of the suitable modulation scheme and amount of coding.

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[2] EIRP (dBm) =ERP (dBm) +2.15. ERP (W)= 0.001 * $10^{(0.1\text{*ERP (dBm)})}$.

After LMS LTE is deployed, Part 15 vendors themselves may find it very useful to integrate the LMS LTE in some of their products, because LTE has huge capacity and is capable of supporting numerous machine-to-machine (M2M) communications simultaneously. The 3GPP is working on optimizing LTE for M2M communications [ETSI_LTE_M2M]. Example M2M applications include telemetry (e.g., utility meters), telematics (e.g., traffic and weather information for vehicles), fleet management (e.g., cargo tracking), and security and surveillance (e.g., public surveillance and movement monitoring). LTE supports a large number of connected mode UEs (e.g., more than 250 in a cell or sector[3]) and much higher number of idle UEs due to a highly-efficient air interface and fast idle-to-connected transition time (less than 100 ms).

A preliminary analysis carried out for SkyTel indicates that the LTE deployment in the LMS band for a train corridor (e.g., North East Corridor) is feasible and its expected coverage is comparable to the use of LTE in the traditional cellular networks. The analysis used -105 dBm noise from the Part 15 users for the LTE uplink link budget calculations. The measured Part 15 interference in metro areas ranged from -105 dBm to -80 dBm in Shared Spectrum reports. Since the Part 15 devices and systems are less likely to be close to railway tracks, a noise value close to the minimum level is appropriate. Other link parameters include the eNodeB receiver noise figure of 4 dB, the eNodeB receive antenna gain of 21 dB, and the resource allocation for 2 Physical Resource Blocks to achieve the average cell-edge data rate of about 60 kbps, 40% uplink (and 60% downlink) for the TD-LTE configuration, signal to noise ratio (SNR) of 2.4 dB for the reliable detection of the packets for a UE at the cell-edge (corresponding to QPSK modulation and 1/3 coding), interference margin of 1 dB, shadow fading margin of 5.4 dB for 75% cell-edge reliability. The uplink link budget was found to be 139 dB. Assuming the center carrier frequency of 907 MHz for a 5 MHz TD-LTE system, **the cell radius is 3.6 miles for a suburban environment and 12.1 miles for an open space (rural) environment** based on the widely used Hata propagation path loss model. When the cell radius is 3.6 miles, two eNodeBs are spaced apart by (2*3.6 = 7.2 miles). Since the cell radius greater than 3 km is projected to be very valuable, the LMS LTE is thus quite promising and even has a good margin to work with.

A preliminary analysis carried out for SkyTel indicates that even a narrow band version of LTE using just 1.4 MHz wide channel in the 217-235 MHz range could be quite useful. In particular, since the propagation path loss is much less at lower frequencies than at higher frequencies, a large cell size is feasible for LTE. The deployment could be quite inexpensive in the 217-235 MHz range. This frequency range could be used to supplement the regular LMS LTE coverage or to add extra capacity. Even carrier aggregation could be exploited across the LMS band and this 200 MHz band.

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[3] A UE in the connected mode has a dedicated radio connection with the eNodeB in a cell. This radio connection includes a Radio Resource Control (RRC) signaling connection and (usually) one or more data radio bearers (DRBs) for data transmission. A UE in the idle mode does not have a dedicated radio connection but is monitoring the E-UTRAN periodically so that it can transition to the connected mode whenever there is a need for data transmission.

4. LTE and Location Services

Release 9 of UMTS defines location services (LCS), where a variety of location based services (LBS) such as Emergency 911 or E911 calls and value-added services (e.g., directions to a restaurant and a list of restaurant in the vicinity of the mobile device) can be offered to the LTE subscribers. The main benefits of the LTE LCS are as follows.

- ✓ LTE LCS is a fully-standardized solution that gives the service operators flexibility while choosing the vendors for various network elements and mobile devices.
- ✓ LTE LCS enables economies-of-scale due to the expected massive cellular adoption of LTE.
- ✓ LTE LCS facilitates interoperability testing due to the standardized nature of the solution.
- ✓ The LTE service provider can offer LBS as part of its existing IMS (IP Multimedia System) network, which enables rapid introduction of new services cost-effectively.
- ✓ The LBS can be assigned a suitable class of Quality of Service (QoS) as the LBS are operator-aware and operator-controlled services. LTE supports nine different QoS classes, and, a given application is assigned an appropriate QoS class.

LTE has its own fully-standardized location solutions including a control plane or signaling solution and a user plane solution (i.e., Secure User Plane or SUPL). LTE supports a variety of positioning techniques including a multilateration technique[4]. While LTE currently does not have millimeter-level accuracy through its standardized techniques, it enhances the accuracy achievable by a pure Global Positioning System (GPS)-based approach.

A brief overview of LCS in LTE can be found in [Tripathi_LCS_Overview]. See [MSF_LCS_LTE] and [Ericsson_Positioning_LTE] for details of the LTE LCS architecture and LTE positioning methods. Estimation of location accuracy of various LTE positioning methods can be found in [Ranta_Positioning_LTE]; the overall E911-mandated accuracy targets can be met by combining multiple positioning methods.

Let's summarize the main UE positioning techniques supported by LTE. These techniques include Enhanced Cell Identity (E-CID), Assisted- Global Navigation Satellite System (A-GNSS), and Observed Time Difference of Arrival (OTDOA) [3GPP_36.305].

- ❖ **E-CID**. Since the UE in the connected mode has a dedicated a radio connection with the E-UTRAN, the E-UTRAN knows about the cell where the UE is located. The eNodeB can then use measurements of the round trip time (RTT) to determine the distance between the eNodeB and the cell. The angle-of-arrival (AoA) can finally be used to find the UE location, because the distance and the angle together are adequate to locate the UE.

[4] It is up to the cellular service provider the specific nature of the LCS solution and the specific technique(s) chosen for positioning. Furthermore, different LTE mobile devices would have different LCS capabilities. Existence of a Global Positioning System (GPS) receiver in the mobile device is becoming common today (including LTE).

- **A-GNSS**. A-GNSS is a generic term where satellite signals are used by the UE to make measurements. In the U.S., Assisted- Global Positioning System (A-GPS) can be expected be popular. The UE's search for satellites is facilitated by conveying the information about the satellites to the UE.

- **OTDOA.** This is a traditional multilateration technique where the E-UTRAN signals are processed by the UE to provide a report to the E-SMLC. Each E-UTRAN cell transmits cell-specific reference signals. In addition, special positioning reference signals (PRS) have been defined in Release 9 to support the UE positioning. The UE can now make measurements of the reference signals and provide a measurement report to the E-SMLC. The E-SMLC determines the actual location of the UE based on the UE measurements (and potentially the eNodeB measurements as well).

In summary, LTE supports a variety of UE positioning techniques in a standardized fashion. Multiple techniques can be combined for a more refined location estimate.

LTE can use unicast transmissions or broadcast transmissions depending upon the type of information. The UE-specific information is transmitted using regular unicast transmissions. For example, unicast transmissions are relevant to services such as web browsing and email. In contrast, if some information is applicable to multiple UEs in the cell, broadcast transmissions would be preferred instead of unicast transmissions. For example, to provide traffic or weather updates applicable to a given geographic area, broadcast transmissions would be much more efficient than unicast transmissions. Unicast transmissions would involve sending the identical information using dedicated resources for different users. In contrast, a broadcast transmission of such information would involve single transmission of a given IP packet carrying the weather and traffic updates. The precious radio resources (and network resources such as backhaul) would be used much more efficiently by the broadcast transmissions.

LTE supports broadcast transmissions for multimedia applications using Multimedia Broadcast Multicast Services (MBMS). While the basic MBMS was introduced in Release 8, evolved MBMS (eMBMS) was defined in Release 9. Recall from Section 2 that 1 ms subframes are used for data transmissions. The basic MBMS requires all resources of a cell to be dedicated to MBMS. However, eMBMS allows some subframes to be used for broadcast data transmissions, while the remaining subframes can be used for regular unicast data transmissions. Furthermore, the number of subframes to be used for eMBMS can be dynamically determined based on the needs at a given time. Hence, eMBMS is attractive to the service providers from the perspective of efficiency. Qualcomm and Ericsson demonstrated such eMBMS capability at Mobile World Congress in Spain in early 2012 [Ericsson_eMBMS] [Qualcomm-eMBMS].

Examples of the ITS data that can be transmitted using eMBMS include weather, road conditions, changes in metro-transit and inter-city public transport schedules, location-based advertising and availability information (e.g., gas and alternative-fuel stations, hotels, food services, medical facilities, road-side attractions, and special events). In addition to efficiently transmitting such ITS data, eMBMS can also be exploited to transmit Network Real-Time Kinematic (NRTK)[5] positioning data to achieve millimeter-level (e.g., 10 to 15 mm) location accuracy[6]. As reported in [NRTK_Ireland], mobile infrastructures of 2G and 3G cellular technologies (and broadcast radio) are being used to support the NRTK positioning systems in Ireland. LTE can thus easily be utilized to facilitate implementation of the NRTK method.

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[5] In the basic RTK positioning method [NRTK_Langley], a receiver at a reference site makes measurements that are transmitted to one or more rover receivers (e.g., mobile devices). The rover receivers combine their own measurements with the measurements received from the reference sites and accurately determine their coordinates. However, atmospheric and satellite-position errors decorrelate with increasing distance between reference sites and rover receivers. Hence, the location accuracy decreases with distance, limiting the effective distance between reference sites and rover receivers. The Network RTK method overcomes such distance limitation of the basic RTK method. In the NRTK method, data from a number of reference sites are used to determine the measurement errors across the network and corrections are provided to the rover receivers. The accuracy of the location estimate at the rover receiver is thus enhanced [NRTK_Langley].

[6] Some researchers are working on methods such as the use of mesh net for vehicle-to-vehicle communications to achieve sub-meter accuracy with high reliability [MeshNet]. The 5.9 GHz band identified for the DSRC as mentioned in Section 3 can be used for such vehicle-to-vehicle communications.

5. Potential of LTE for ITS and SG4G

LTE possesses certain features that make it especially suitable for ITS and SG4G. These features include interference solutions, flat and distributed network architecture, very efficient air interface, huge economies-of-scale, large ecosystem, varying levels of Quality of Service, extensive security, and well-defined evolution path. Let's take a closer look at these LTE features next.

Since LTE for the ITS will be deployed using the LMS band that is shared with the Part 15 devices and systems, mechanisms that can minimize interference would be quite beneficial. As mentioned in Section 3, the relatively low power levels of the UE and the eNodeB, closed loop power control for the uplink to minimize the UE's transmit power, low power consumed by the overhead channels, and transmission of the traffic channels only when needed reduce the transmit power and hence the interference generated by LTE. The techniques such as HARQ, adaptive modulation and coding, and dynamic selection of an antenna technique minimize the redundancy of transmissions, leading to effective utilization of radio resources and minimization of interference. Fast feedback from the UE on the prevailing radio channel conditions (on the order of few milliseconds) in different parts of the LTE channel and the fast and dynamic resource allocation by the eNodeB scheduler can help avoid the spectrum portions with high LTE and Part 15 interference.

The 3G cellular network architecture is centralized and often ATM-based, which makes it relatively complex to scale up the network. In contrast, LTE has flat and distributed network architecture. Both the E-UTRAN and the EPC are IP-based and scalable as noted in Section 2.

LTE's air interface is very efficient. The advances in electronics have made it possible to implement OFDMA for the mobile system. The narrowband nature of LTE subcarriers facilitates design and optimization of multiple antenna techniques. Spectral efficiency, quantified by bits/sec/Hz, is quite high for LTE[7], reducing the cost per bit and supporting more users simultaneously.

LTE is expected to be a dominant 4G cellular technology as older, less efficient cellular technologies are replaced by LTE and/or new spectrum (e.g., 700 MHz) becomes available. Even the operators that have already deployed the competing 4G technology, WiMAX, (e.g., Clearwire) are moving toward LTE. The deployment of LTE in the LMS band would thus benefit from LTE's huge economies-of-scale due to the dominance of LTE.

Since LTE would dominate the global deployments, it would enjoy a large ecosystem, making it easy to find multiple vendors offering UEs, eNodeBs, nodes of the EPC, IMS, and PCC, and applications (e.g., Voice over LTE or VoLTE, SMS, and interactive gaming).

LTE defines nine classes of Quality of Service in the form of QoS Class Indicators (QCIs). Each QCI corresponds to a specific set of parameters (e.g., existence or absence of data rate guarantee, delay, and priority). Different classes of subscribers (e.g., platinum, gold, and silver) and applications with different QoS needs (e.g. voice vs. email) can be supported using different QCIs.

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[7] The peak spectral efficiency for Release 8 LTE is 300 Mbps/20 MHz= 15 bits/sec/Hz for the downlink.

LTE support multiple security mechanisms such as mutual authentication, anonymity, ciphering and integrity protection. Mutual authentication enables the UE to authenticate the network and the enables the network to authenticate the UE. Anonymity minimizes the use of original identities such as International Mobile Subscriber Identity (IMSI) by relying upon temporary identities such as Globally Unique Temporary Identity (GUTI) when possible. Ciphering can be used to encrypt the signaling messages and user traffic. Integrity protection adds a message authenticate code to the signaling message at the sender to allow the receiver to verify that the message has not been altered between the sender and the receiver. Ciphering and integrity protection can be independently activated for the link between the UE and the eNodeB and for the link between the UE and the MME.

LTE has a well-defined evolution path. LTE-Advanced is the next stage of evolution, which is introduced in Release 10. Release 10 has already been finalized by the 3GPP. The work on Release 11 is currently ongoing in the 3GPP. Some features of LTE-Advanced such as carrier aggregation are specified in Release 10, while others such as CoMP transmission and reception are designated for future releases (e.g., Release 11 and beyond). See Section 2 for a brief overview of LTE-Advanced features. Widespread commercial deployments of LTE-Advanced are expected to occur in 2013 [LTE-Advanced_Deployments].

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6. LTE at 700 MHz and 900 MHz

Current LTE deployments in the U.S. are primarily at 700 MHz. As mentioned in Section 2, Verizon Wireless deployments are using FDD Band 13 in the upper 700 MHz band. AT&T is using FDD Band 17 in the lower 700 MHz band.

To meet the needs of the ITS and the SG4G efficiently and cost-effectively, LTE can be deployed in the U.S. in the 900 MHz LMS band using the TDD version of LTE, more formally known as Time Division- LTE (TD-LTE). Since current LTE chipsets for the UEs can easily support at least 3 different frequency bands with up to two frequency bands below 1 GHz, the Public Safety FDD Band 14 in the upper 700 MHz band can also be supported. Even Release 8 LTE UEs can support both FDD and TDD and can support multiple frequency bands. The UE will use a suitable duplexing mode and a suitable frequency band based on the E-UTRAN cell that it finds. The UE software that governs the selection of a duplexing mode and frequency band would most likely be available in 2013 as mentioned in Section 2. Recall from Section 2 that Sprint and Clearwire UEs would be able to switch between the duplexing modes and the frequency bands because the Sprint LTE deployments would be using FDD and the Clearwire will be using TDD band 41. The current LTE chipsets already support both FDD and TDD. The 3GPP tried to minimize the differences between the FDD operation and the TDD operation to minimize the market segmentation.

A Public Safety user with a UE that supports the LMS band and the 700 MHz Public Safety band can access the LTE services in more geographic areas. As mentioned in Section 5, users and applications of users can be allocated different QoS including priority and targets for data rates and latency.

Other countries such as Japan may have LTE deployments in 700 MHz and 900 MHz bands as well. Japan is making new spectrum available at both 700 MHz and 900 MHz [Japan_700_900]. In particular, ITS may be allocated spectrum within 715 to 725 MHz frequency range. In a February 2012 press release from the Japanese Ministry of Internal Affairs and Communications, it was mentioned that it would be possible in Japan for wireless systems to utilize (i) some 700 MHz frequencies becoming available due to the digitization of terrestrial television broadcasting and (ii) some 900 MHz frequencies becoming available due to the reorganization of frequencies used by 2G wireless systems as of July 2011 [Japan_700MHz_Feb2012]. Softbank's deployment of HSPA+ in the 900 MHz band was approved by the Japanese Ministry of Internal Affairs and Communications in February 2012 [Softbank_900MHz_HSPA+]. Softbank plans to install 16,000 base stations in 2012 and 41,000 base stations by 2016 to achieve 99.9% population coverage. Furthermore, Softbank would be operating both FDD and TDD variants of LTE and has already launched a TD-LTE network with 2000 eNodeBs. Softbank's LTE-FDD system will use 900 MHz band [Softbank_TD-LTE_May2012] [Softbank_FDD_TDD_LTE]. Softbank's TD-LTE system is using 20 MHz wide channel at the 2.5 GHz spectrum [Softbank_TD-LTE_Band] [Softbank_TD-LTE_Bandwidth].

LTE at the 700 MHz band is identified in [Wireless_Harmonization] as the wireless network for global harmonization to serve the needs of mission-critical wireless systems such as public safety, utilities, railways, and transport. North America and Asia are also mentioned in [Wireless_Harmonization] as the continents preparing for the 700 MHz deployment of LTE for public safety communications.

Deployment of LTE at lower bands such as 700 MHz and 900 MHz can provide benefits in the coverage-driven deployments in a rural environment. The propagation path loss is smaller at lower frequencies (e.g., 700 MHz to 900 MHz) and larger at higher frequencies (e.g., above 1.8 GHz). Significant savings in CapEx are possible in such cases [LTE_LowBandDeployments]. Operators such as Telstra in Australia are exploring the deployments of LTE at the 900 MHz band, making it easier to re-design eNodeBs and UEs to suit the LMS band [Telstra_900MHz_1] [Telstra_900MHz_1].

The 3GPP recently completed a study item on the deployment of UMTS and LTE at 900 MHz [3GPP_LTE_900MHz]. This 3GPP report explored the standardization work needed to facilitate deployment of LTE at 900 MHz in Japan and Korea. The 3GPP notes that Japan is initially targeting 900 MHz to 905 MHz for the uplink and 945 MHz to 950 MHz for the downlink and would eventually allocate 900 MHz to 915 MHz for the uplink and 945 MHz to 960 MHz for the downlink by 2015. The 3GPP also observes that Korea is targeting the 905 MHz to 915 MHz for the uplink and 950 MHz to 960 MHz for the downlink. The report states that Band 8 is adequate to support LTE FDD deployments at 900 MHz and no additional band needs to be defined. The report concludes that it is possible to utilize Band 8 in Japan for 900 MHz FDD with some operational features such as constraints on the resource allocations and over-provisioning of the uplink control channels to meet emission requirements. The emerging 900 MHz ecosystem for LTE FDD in Japan and Korea would directly benefit the 900 MHz TD-LTE deployment in the LMS band due to the inherently designed commonalities of FDD and TDD versions of LTE.

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7. LTE and LTE-Advanced for Vehicles and Trains

While generic UEs and eNodeBs would work for the LMS band, some of the ITS applications such as the Internet access for train passengers and the access to IMS applications along the highways could benefit from a higher degree of customization. Example areas of such customization include increased power levels of the UE and the use of more physical antennas.

A typical Power Class 3 UE has the maximum transmit power of 200 mW or 23 dBm. Depending upon the type of the device, it is possible to increase the maximum transmit power by using a power amplifier with higher power rating. Such UE can be used in train compartments as a MiFi[8] to serve train passengers using WiFi laptops and smart phones. A higher maximum transmit power can be exploited to increase the cell size or improve cell-edge throughput performance for a given cell size.

Release 8 LTE supports up to four antennas at the eNodeB and the UE, and LTE-Advanced supports up to eight antennas. While a typical handset has limited space to be able to house more than two LTE antennas, the UEs customized for trains and vehicular applications could be made larger and hence could house more than two antennas, perhaps four or even eight. The coverage along the railway tracks and highways would typically involve two cells (or sectors) per eNodeB instead of three cells (or sectors) per eNodeB in a typical cellular scenario. Hence, it will be relatively easier to use more antennas per cell at the eNodeB. The feasibility of more antennas at both the UE and the eNodeB in the trains and in the vehicular environment means that higher peak and average throughput can be achieved via SU-MIMO and beamforming. Furthermore, more battery power is available on the trains and in the vehicles compared to traditional cellular handsets to enable use of more complex and intensive antenna techniques (especially for the uplink transmissions) while ensuring a long battery life.

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[8] MiFi acts like a regular LTE UE while communicating with the eNodeB and appears like a WiFi router to WiFi-enabled laptops and mobile devices.

8. LTE for ITS: Overview of Research Efforts

Current research trends indicate the LTE is being actively considered for the ITS applications [ETSI_LTE_ITS] [ResearchAndMarkets_LTE_ITS] [Fowler_LTE_ITS]. Some research studies have evaluated the suitability of LTE for the ITS applications. For example, the uplink operations of LTE are simulated for an ITS network under various network conditions and network parameter settings in [Trichias_LTE_ITS]. The simulation results indicate that LTE can meet the latency and capacity requirements of the ITS and can even outperform an alternative solution based on the IEEE 802.11p standard in some cases. SkyTel may sponsor research at a U.S. university and a European university to further evaluate the suitability of LTE for a variety of ITS applications.

The IEEE 802.11p standard can provide vehicle-to-vehicle (V2V) and Infrastructure-to-Vehicle (I2V) communications and is suitable for DSRC. The standard is intended for applications such as collision avoidance, heavy traffic avoidance, and commercial applications. The 802.11p standard benefits from the existing family of 802.11 WLAN standards. Since IEEE 802.11p utilizes the DSRC and a 5.9 GHz, its performance is degraded in non-line-of-sight situations such as an urban environment. In contrast, LTE is designed to deal with such NLOS issues easily. The main benefit of the IEEE 802.11p-based ad-hoc network compared to LTE is reduced latency due to direct communications among the vehicles. LTE utilizes the infrastructure network for communication between the two vehicles, incurring a longer delay. The benefits of LTE are found to be large capacity and a long communications range. Furthermore, LTE can provide additional services such as transmission of data for location estimates with millimeter-level accuracy and commercial and non-commercial services.

Let's briefly discuss certain ITS aspects, some of which are incorporated by the simulator in [Trichias_LTE_ITS]. An ITS vehicle transmits two types of messages, (i) a very short message called Cooperative Awareness Message (CAM) containing information such as the position of the vehicle and the current velocity, and (ii) Event Triggered messages that provide warnings to the rest of the vehicles on the network about an unexpected situation. The CAMs are transmitted at a regular interval (e.g., 10 Hz) and they are instrumental in obtaining a highly accurate environment picture for movement prediction. The CAMs represent a vast majority of the messages being transmitted in an ITS network. The Event Triggered messages are rather triggered by specific events on the road, and while they occur infrequently, they are much more important than the CAMs because they help maintain the safety of the vehicles and drivers. Three main classes of ITS applications identified in [Trichias_LTE_ITS] are Co-operative (Active) road safety, co-operative traffic efficiency, and co-operative local services and global Internet services. The first class of applications aims to improve road safety and may involve CAMs with 20 Hz frequency and stringent latency requirements in the range of 50 to 100 ms. Example applications of this class include collision avoidance, pre-crash sensing and emergency electronic brake lights. The second class of ITS applications, co-operative traffic efficiency aims to improve traffic fluidity. The frequency of CAMs may be in the range of 1 to 5 Hz and the latency targets are in the range of 100 to 500 ms. Example applications of this class include traffic light optimal speed advisory, and recommended itinerary. Finally, the third class of ITS applications, co-operative local services and global Internet services, aim to provide advertisements and on-demand information to the vehicles on a commercial or non-commercial basis. Example applications for this class include map updates, media downloading, and locations and driving directions for restaurants, hotels, and gas stations in the vicinity of the vehicle. The latency targets for this class are usually above 500 ms.

Let's summarize the main features of the LTE simulator used in [Trichias_LTE_ITS]. The simulator models a highway with 3 lanes and variable number of vehicles per lane. The CAM is referred to as the beacon. It generates CAMs with a given beacon frequency (e.g., 10 Hz) to mimic ITS traffic load and uses a typical beacon size of 100 Bytes. An LTE system with 10 MHz bandwidth at 900 MHz is assumed with the eNodeB antenna height of 30 m. The path loss and Signal to Interference and Noise Ratio (SINR) of each vehicle is calculated according to the distance of the vehicle from the eNB with the path loss calculated using the Okumura-Hata model for rural areas. This SINR is used to calculate the supportable data rate. Three different scheduling schemes are implemented for resource allocation: (i) Dynamic scheduling that treats the ITS traffic and the non-ITS background in the same way and allocates resources dynamically every 1 ms subframe, (ii) Dynamic scheduling that allocates resources dynamically every 1 ms subframe but gives a higher priority to the ITS traffic, and (iii) Semi-persistent scheduling for the ITS traffic to reduce control signaling overhead and to increase capacity and dynamic scheduling for the background traffic.

The simulation variables include the number of vehicles, average velocity of vehicles, beacon size, beacon frequency, background call size and arrival rate and cell range. The examples of performance metrics quantified in the simulator are end-to-end beacon delay, percentage of beacons that meet the ITS criteria, the total load on the network (i.e., the percentage of radio resources being used), control signaling load, and background traffic throughput.

The simulation results indicate that the beacon delay is around 18 ms up to 95% of the traffic load. About 700 ITS users with 10 Hz beacon frequency can be supported by LTE while meeting the beacon delay requirements of ITS and supporting the background traffic. The paper concludes that the combination of 802.11p and LTE may be the best solution for the ITS. More specifically, the 802.11p is found to be more suitable for the cooperative road safety class because of its extremely low beacon latencies. LTE is found to be more suitable for the cooperative traffic efficiency class and the Cooperative local services and internet class because of its large capacity, range, and reasonably low latencies.

While [Trichias_LTS_ITS] provides a good preliminary view of the potential LTE applications for ITS, the simulator can be enhanced for a more comprehensive and realistic performance evaluation. For example, multiple eNodeBs along a highway can be modeled instead of a single cell to incorporate more realistic effects of out-of-cell interference and handover. Both CAMs and event-triggered messages can e incorporated. In addition to the uplink, downlink can also be simulated. The eNodeBs with two cells and high-gain directional antennas can be modeled to focus on highways instead of modeling omni-directional eNodeBs that cover the highway and other large areas. The LMS LTE dedicated to the ITS applications would be more appropriate, eliminating the need for non-ITS background traffic. SkyTel may sponsor research to enhance the capabilities of such simulator and to carry out suitable proof-of-the-concept field testing.

Respectively submitted,

____

(N. D. Tripathi)

07/17/12

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AREAS OF EXPERTISE

LTE (E-UTRAN and EPC), LTE-Advanced, WiMAX, 1xEV-DO (Rev. 0 and Rev. A), UMTS R99, HSDPA, HSUPA, HSPA+, CDMA2000 1xRTT, IS-95, CDMA, OFDM, OFDMA, Advanced Antenna Technologies, IP-related Technologies, IMS

PUBLICATIONS

- Author of an upcoming **book** (with Jeffrey H. Reed), "Cellular Communications: A Comprehensive and Practical Guide," ***Accepted for Publication by IEEE/Wiley***, 2012. (**Book Contents**: Introduction to Cellular Communications, Elements of a Digital Communication System, Radio Propagation, IP Fundamentals, GSM, GPRS, EDGE, IS-95, CDMA2000 1xRTT, R99 UMTS/WCDMA, 1xEV-DO Rev. 0, HSDPA, 1xEV-DO Rev. A, HSUPA, HSPA+, IMS, Emerging 4G Technologies)
- Author of a **book** (with Jeffrey H. Reed and Hugh F. VanLandingham), "Radio Resource Management in Cellular Systems," Kluwer Academic Publishers, 2001.
- Contributor (With Jeffrey H. Reed) to the article, "Technical Challenges in Applying Network Neutrality Regulations to Wireless Systems," in the book titled "Net Neutrality: Contributions to the Debate," Edited by Jorge Perez Martinez, 2011.
- Author of one chapter in the book, "Neuro-Fuzzy and Fuzzy-Neural Applications in Telecommunications," Editor- Peter Stavroulakis, Springer, April 2004.

EXPERIENCE

AWARD SOLUTIONS *March '04 to Present*

Principal Consultant

- Successfully launched a new program to ensure and develop SME (Subject Matter Expert) expertise in the areas of LTE RAN and Ethernet-based Backhaul. Developed processes and plans to facilitate SME certification. Devised expertise development plans, on-line tests, and defense tests. Directed the oral defense meetings for the final stage of SME certification.
- Managed and led SMEs for following course development projects: LTE Bootcamp-Phase II (**Topics**: End-to-end Data Sessions in LTE-EPC, PCC: QoS and Charging Architecture for LTE, Voice over LTE (VoLTE) using IMS, Voice services using CSFB and

SRVCC, LTE and eHRPD Interworking, LTE and GSM/UMTS interworking, and LTE-Advanced), and LTE Radio Network Planning and Design.

- Mentored SMEs to prepare them to teach technologies such as LTE, WiMAX, OFDM, and Advanced Antennas.
- Developed courses on LTE-Advanced and TD-LTE.
- Developed two sessions, TD-LTE and Self Organizing Network (SON), as part of LTE Bootcamp- Phase II for an infrastructure vendor.
- Enhanced the LTE Radio Network Planning and Design course to reflect configurations of commercial deployments using LTE log-files and to adhere to customer-specific RF design guidelines.
- Continued to teach a variety of LTE and HSPA+ courses (e.g., VoIP, IMS, and IPv6 for LTE and HSPA+ Signaling) at new and existing clients.
- Delivered several web-based sessions of LTE Bootcamp- Phase II.

Lead SME

- Taught *first-time offerings* of courses at various clients to acquire new training business.
- Managed and guided SMEs for timely and quality-controlled completion of following course development projects: LTE/1xEV-DO Interworking, EPC Overview, HSPA+ Overview, Fundamentals of RF Engineering, IP Convergence Overview, and Advanced Antenna Techniques.
- Devised and implemented strategies to maximize the quality of project deliverables and to accelerate the completion of the deliverables.

SME- Course Development

- Developed an in-depth LTE Bootcamp Series for an infrastructure vendor (**Topics**: EPS Network Architecture, OFDMA/SC-FDMA, Radio Channels, System Acquisition & Call Setup, DL & UL Traffic Operations, Handover, and Antenna Techniques).
- Developed numerous instructor-led and web-based training courses by working in a team environment (**Examples**: Interworking of LTE with 1xEV-DO & 1xRTT, LTE Air Interface, WiMAX Essentials, WiMAX Network Planning, UMB, 1xEV-DO, HSUPA, Multiple Antenna Techniques, and IP Convergence).
- **Example Course Contents**: Network architecture, air interface features, DL & UL data transmission, call setup, handover/handoff, resource management, and interworking.
- Designed outlines for several new courses.

Senior Consultant- Training

- Taught *in-person* and *web-based* (via WebEx and LiveMeeting) courses at major chip-set manufacturers, infrastructure & device vendors, service operators, and test-tool vendors.
- Delivered an in-depth LTE bootcamp multiple times for a major LTE infrastructure vendor.

- **Area Expertise**: LTE Radio Network Planning & Design (including Certification), Interworking of LTE with (1xEV-DO, 1xRTT, UMTS, and GERAN), LTE Protocols & Signaling, LTE Air Interface, WiMAX Networks and Signaling, 1xEV-DO Optimization, 1xEV-DO Rev. 0 and Rev. A, IP Fundamentals, HSDPA/HSUPA/HSPA+, UMTS R4/R5 Core Networks, UMTS Network Planning and Design
- Strived to make the training experience full of *relevant* knowledge and to maximize the value of training to students.

VIRGINIA TECH *January'10 to Present*

Adjunct Professor

- Co-taught the cellular communications class.
- Developed and presented the lecture material.
- Designed and graded quizzes.

HUAWEI TECHNOLOGIES *October '01 to March '04*

Product Manager and Senior Systems Engineer

- Worked with engineers to resolve numerous **field trial issues** for **CDMA2000** systems.
- Defined test procedures for various features to evaluate performance of the CDMA2000 product.
- Designed advanced RL MAC and Power Control algorithms for a 1xEV-DO System.
- Designed various high-performance radio resource management (RRM) algorithms for the **CDMA2000** base station and base station controller. Major designed features include adaptive forward link and reverse link call admission control algorithms, dynamic F-SCH rate and burst duration assignment algorithms, R-SCH rate assignment algorithm, F-SCH burst extension and termination mechanisms, schedulers, forward link and reverse link overload detection and control algorithms, SCH soft handoff algorithm, F-SCH power control parameter assignment mechanism, adaptive radio configuration assignment algorithm, load balancing algorithm, and cell-breathing algorithm.
- Worked on the design of an RRM simulator to evaluate the performance of call admission control, load control, and scheduling algorithms for a **CDMA2000** system.
- Designed system level and network level simulators to evaluate the capacity gain of the smart antenna-based **UMTS** systems employing multiple beams.
- Reviewed **UMTS** RRM design and proposed enhancements related to call admission control, cell breathing, load balancing, soft capacity control, potential user control, and AMR control.
- Educated engineers through presentations to facilitate development of the **1xEV-DO** product.
- Led a team of engineers to define a comprehensive **simulation tool-set** consisting of link level simulator, system level simulator, and network level simulator to evaluate performance of CDMA systems including **IS-95**, **IS-2000**, **1xEV-DO**, **1xEV-DV**, and **UMTS**.
- Managed a group of engineers, prepared project plans, and established efficient processes to meet the requirements of the **CDMA2000** BSC product line.

NORTEL NETWORKS *September '97 to September '01*

Senior Engineer

<u>Radio Resource Management, July '99 to Sept. '01</u>

- Developed a comprehensive RRM simulator that models data traffic and major features of the MAC layer and physical layer. Analyzed various aspects of the RRM for several test cases. The performance results such as capacity and throughput were used in educating the service providers on the RRM for IS-2000 systems.
- Proposed a generic call admission control algorithm and filed a patent with the U.S. Patent Office.

<u>Management of Supplemental Channels, June '00 to Sept. '01</u>

- Designed and analyzed supplemental channel management for enhanced data performance and filed a patent with the U.S. Patent Office.

<u>Data Traffic Modeling, Jan. '99 to Sept. '01</u>

- Prepared a common framework for data traffic models for analysis of systems carrying data (e.g., 1xRTT and UMTS). Types of analysis include RF capacity, end-to-end performance, and provisioning. The data models for telnet, WWW, ftp, e-mail, FAX, and WAP services are considered.

<u>Multi-Carrier Traffic Allocation, June '99 to Sept. '01</u>

- Provided MCTA capacity improvements (compared to non-MCTA systems) that proved to be identical to the ones observed during the field-testing. Developed a method to estimate the MCTA capacity using the field data. This method was used in estimating MCTA capacity gains by RF engineering teams.

<u>SmartRate and Related Vocoder Designs (e.g., SMV), June '99 to Sept. '01</u>

- Provided estimates of SmartRate capacity improvements that were found to be close to the observed capacity gains in the field tests.

<u>CDMA Based Fixed Wireless Access Systems, Sept. '97 to Dec. '98</u>

- **Capacity Estimates**. Determined the system capacity for a variety of configurations using an IS-95 based simulator. These configurations include different rates such as 9.6 kbps and 13 kbps, different deployment scenarios such as 2-tier embedded sector and border sector, and different diversity techniques such as switch antenna diversity and phase sweeping transmit diversity. These capacity estimates were used for various project bids. The simulator utilizes propagation channel models extracted from the actual field measurements.
- **Handoff and Power Control Algorithms**. Analyzed existing handoff and power control mechanisms for fixed wireless systems and proposed new approaches.

- **Bridge between the Simulator and a Deployed System**. Developed a procedure to estimate the loading level for the simulator so that the capacity estimate from the simulator is close to the achieved capacity in real systems.
- **Switch Antenna Diversity Schemes**. Proposed three algorithms to exploit mobile switch antenna diversity. These schemes provide a low-cost solution that significantly enhances RF capacity.
- **Combined Overhead Power and Handoff Management**. Proposed a method of combined management of overhead channel power and handoff to improve capacity.

Educator

- Made presentations on topics such as data modeling, fixed wireless systems, and AI tools.
- Taught "Introduction to Wireless" class at Nortel.
- Prepared tutorials on the standards such as 1xRTT, 1xEV-DO, and UMTS.

VIRGINIA TECH *January '93 to August '97*

Research/Teaching Assistant, Mobile & Portable Radio Research Group (MPRG), Electrical Engineering

- Developed adaptive intelligent handoff algorithms to preserve and enhance the capacity and the Quality of Service of cellular systems.
- Helped *develop* and *teach* a new wireless communications course **(DSP Implementation of Communication Systems**) as part of an **NSF** sponsored curriculum innovations program. Implemented different subsystems of a communication system (e.g., a digital transmitter, a carrier recovery system, a code synchronizer, and a symbol timing recovery system) using the **Texas Instruments** TMS320C30 DSP development system.
- Refined the class material for undergraduate and graduate signal processing classes.
- Investigated different aspects involved in dual-mode adaptive reconfigurable receivers as part of a project sponsored by **Texas Instruments**.

PATENTS/DRAFTS (AUTHOR/CO-AUTHOR)

- Enhanced Power Control Algorithms for CDMA-Based Fixed Wireless Systems, Patent Number 6,587,442, Filed Date: October 28, 1999.
- Method and apparatus for managing a CDMA supplemental channel, Patent Number 6,862,268, Filed Date: December 29, 2000.
- Dynamic Power Partitioning Based Radio Resource Management Algorithm, Patent Disclosure No.: 11942RR, Filed Date: August 23, 2000.
- Switch Antenna Diversity Techniques at the Terminal to Enhance Capacity of CDMA Systems, Patent Disclosure No. RR2544, Filed Date: June 19, 1998.
- Adaptive Radio Configuration Assignment for a CDMA System, October 2003.
- Multi-carrier Load Balancing for Mixed Voice and Data Services, October 2003.
- Methodology for Hierarchical and Selective Overload Control on Forward and Reverse Links in a CDMA System, October 2003.
- A New Predictive Multi-user Scheduling Scheme for CDMA Systems, November 2003.
- A New Method for Solving ACK Compression Problem by Generating TCK ACKs based on RLP ACKs on the Reverse Link, October 2003.

ACTIVITIES

Member of **IEEE**. Reviewed research papers for the *IEEE Transactions on Vehicular Technology*, *IEE Electronics Letters* and the *IEEE Control Systems Magazine*.

EDUCATION

VIRGINIA POLYTECHNIC INSTITUTE & STATE UNIVERSITY **Blacksburg, VA**

Ph.D., Wireless Communications, August 1997, Overall GPA: 3.8/4.0

Dissertation: Generic adaptive handoff algorithms using fuzzy logic and neural networks

M.S., Electrical Engineering, November 1994, Overall GPA: 3.8/4.0

GUJARAT UNIVERSITY **Ahmedabad, India**

B.S., Electrical Engineering, September 1992

EXHIBIT 2

Master of Science Thesis

Modeling and Evaluation of LTE in Intelligent Transportation Systems

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Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS)
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Chair of Design and Analysis of Communication Systems (DACS)

In collaboration with the Netherlands Organization for Applied Scientific Research (TNO)

EXAMINATION COMMITTEE
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Modeling and Evaluation of LTE in Intelligent Transportation Systems

Master of Science Thesis

For the degree of Master of Science in
Design and Analysis of Communication Systems group (DACS)
at Department of Electrical Engineering
at University of Twente

by

Konstantinos Trichias

October 6, 2011

Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS)
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UNIVERSITY OF TWENTE.

Abstract

In this thesis, we present an innovative Long Term Evolution (LTE) Uplink model, for operations in the vehicular environment, and we evaluate the performance of LTE in an Intelligent Transportation System (ITS), in order to examine if LTE is a viable candidate for ITS communications, and if so, to steer further scientific research in that area. Because of the fact that the vast majority of research on a communications protocol for ITS applications, has been strictly focused on IEEE 802.11p, some other promising options such as LTE, have not received the proper attention by the scientific community. In this thesis the suitability of LTE for ITS communications is being investigated and its capability to handle the strict ITS communication requirements is being examined. The model built in the context of this thesis, simulates the Uplink operations of LTE, in a vehicular network supporting ITS, under various network conditions and various network parameter values. The outputted results, indicate that LTE can meet the ITS requirements both in terms of latency and capacity, and in some cases even outperform the 802.11p standard. The multiple simulations under various network conditions, give us a clear image of LTE's behavior during network operation, and provide a useful guide for anticipating the standard's performance when the network's parameters change. The identification of both standards' strong and weak points, through the comparison of their performance, allows us to draw conclusions about the potential use of each standard in an ITS concept and propose the most promising areas for further research.

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First of all I would like to express my gratitude to my thesis project supervisors Dr. Ir. Geert Heijenk and Prof. Dr. Hans J.L. van den Berg from the University of Twente and Dr. Remco Litjens and Dr. Ir. Jan de Jongh from TNO, for the valuable time that they have dedicated to this project and to me personally. Their continued interest in this project, their innovative guidance and their insightful comments, made the completion of this thesis project possible. I would also like to thank my colleagues from TNO, Yakup Koc, Miroslav Zivkovic and Carolien van der Vliet for the day to day help that they offered me, and their continuous support. I would also like to thank, all of my colleagues in the PoNS department of TNO, who welcomed me and helped me, any chance they got. Finally, I would like to thank from the bottoms of my heart, my family, for their moral, emotional and material support throughout this whole period of my Master of Science studies.

Kostas Trichias

Enschede, The Netherlands
October 6, 2011

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List of Abbreviations

3GPP	3rd Generation Partnership Project
AC	Access Class
AIFS	Arbitration Inter Frame Space
AMC	Adaptive Modulation and Coding
CAM	Cooperative Awareness Message
CCH	Control Channel
CDF	Cumulative Distribution Function
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CW	Congestion Window
DCF	Distributed Coordination Function
DL	Downlink
DSRC	Dedicated Short Range Communications
EDCA	Enhanced Distributed Channel Access
eNB	evolved Base Station
EPC	Evolved Packet Core
EPS	Evolved Packet System
ESR	Estimated Sensing Range
FDD	Frequency Division Duplexing
FDR	Frame Delivery Ratio
GUI	Graphic User Interface
I2V	Infrastructure to Vehicle
IDM	Intelligent Driver Model
IMT	International Mobile Telecommunications
IP	Internet Protocol
ITS	Intelligent Transportation System
LOS	Line Of Sight
LSTI	LTE / SAE Trial Initiative
LTE	Long Term Evolution
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
NAS	Non Access Stratum
NGMN	Next Generation Mobile Networks
OBU	On Board Unit
OFDM	Orthogonal Frequency Division Modulation

OFDMA	Orthogonal Frequency Division Multiple Access
PDU	Payload Data Unit
PHY	Physical
QoS	Quality of Service
RAN	Radio Access Network
RRC	Radio Resource Control
RSU	Road Side Unit
RTT	Round Trip Time
SAE	System Architecture Evolution
SC-FDMA	Single Carrier Frequency Division Multiple Access
SCH	Service Channel
SINR	Signal to Interference and Noise Ratio
SNR	Signal to Noise Ratio
SPS	Semi Persistent Scheduling
TDD	Time Division Duplexing
TPC	Transmission Power Control
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UTRA	UMTS Terrestrial Radio Access
V2V	Vehicle to Vehicle
VANET	Vehicular Ad-hoc Network
VoIP	Voice over IP
WLAN	Wireless Local Area Network

1

Introduction

The latest developments that have taken place over the past few years in most areas of wireless communication and wireless networks, in combination with the growth and evolvement of the automotive industry, have opened the way for a totally new approach to the matters of vehicular safety, driving behaviour and on-the-road entertainment, through the integration of multiple equipment and technologies in one vehicle. Within this concept, the term *Intelligent Transportation Systems* (***ITS***) refers to adding information and communications technology to transport infrastructure and vehicles in an effort to improve traffic safety and to reduce traffic congestion and pollution. Vehicles are already sophisticated computing systems, with several computers onboard. The new element is the addition of wireless communication, computing and sensing capabilities. Vehicles collect information about themselves and the environment and exchange information with other nearby vehicles and the infrastructure. Therefore communication plays a crucial role in ITS. Pre-crash sensing or co-operative adaptive cruise control, are some examples of ITS applications.

The ***IEEE 802.11p*** standard is considered to be the future of Vehicular Ad-hoc Networks (***VANETs***) and is capable of providing vehicle-to-vehicle (***V2V***) and Infrastructure-to-Vehicle (***I2V***) communications. The standard will be used for Dedicated Short – Range Communications (***DSRC***) within the concept of ***ITS,*** and will provide safety and infotainment applications such as collision avoidance, traffic avoidance, information downloading, commercial applications and others. The standard originates from the well known “family” of 802.11 WLAN standards and inherits the salient characteristics of this family, but also, it is modified in order to cope with the specific characteristics of the vehicular environment.

The 802.11p standard is considered the main and most important candidate for communication within the context of ITS and it seems to perform well for active safety use cases thanks to its very low delays and communication range of several hundred meters. Nonetheless, there are still some problems that originate mostly from the decentralized ad-hoc nature of the protocol, that lead us to believe that the information exchange in ITS can also be handled via a different kind of network, and more specifically via a cellular network. A possible candidate for the job is the forthcoming ***Long Term Evolution (LTE)*** which is developed by 3GPP. Such a solution presents a number of attractive benefits mostly thanks to the wide availability of cellular technology and devices. The infrastructure that already exists for this system, ensures early and low cost deployment of ITS services. Moreover, since the demand for Internet connectivity is rising, cellular modules become more and more common in vehicles, which guarantees a high penetration rate for the ITS. Finally, the improved performance of this new cellular system, which offers, high data rates, low latencies, long communication ranges, accommodation for high speed users and a number of new interesting features, renders it ideal for use in ITS systems.

An important factor that should be taken under consideration when examining the use of LTE in ITS systems is that in contrast to the decentralized ad-hoc operation of the 802.11p standard, vehicle communication over cellular networks always requires network infrastructure. Therefore, the communication pattern looks different since the vehicles will transmit their messages to a central server, from where they are directly delivered to the area of relevance. This major design difference of the two protocols is the reason that they present different behavior under different circumstances and applications, and also the reason that LTE is considered a possible candidate for ITS communication, since it can offer reliable communication is cases where the 802.11p fails to do so. One of the most characteristic such cases, is the communication in inner city conditions such as busy intersections. Because the radio Line of Sight (**LOS**) will often be blocked by buildings and the Non-Line of Sight (**NLOS**) reception of packets is complicated because of the relatively high frequency of 802.11p (5,9 GHz) and the difficult fading environment, the performance of 802.11p is severely degraded in such a case. On the other hand the lower operating frequencies of LTE and the fact that the base stations are located at high positions, means that it can cope better with the NLOS issues, offering more reliable communication [4].

The goal of this thesis is to examine the technical feasibility of the use of LTE in the ITS network and to compare its performance with that of the 802.11p standard. More precisely the behavior of LTE will be examined under different circumstances that can be encountered in the vehicular network and its performance will be evaluated in relevance to the various parameters that affect it. Different scheduling schemes and features of LTE will be examined in order to find out the most suitable mode of LTE for ITS communication. Finally, a comparison with the performance of 802.11p will be made in order to evaluate the suitability of the two protocols for this type of communication, and to decide which one of them – or probably a combination of the two – is a better solution for ITS communication.

The outline of this thesis is structured as follows. In *Chapter 2*, the findings of the literature study are presented. The function of the three major systems involved in this thesis is explained in detail (ITS, LTE and 802.11p) and the relevant features of each technology are presented. In *Chapter 3*, the motivation behind the research and the research questions that we are trying to answer are presented, while in *Chapter 4*, the system model is presented. A full description of the model that was built is given, as well as the modeling choices, assumptions and simplifications that were made. Finally, the simulation scenarios under consideration are presented. In *Chapter 5*, the simulation results are presented in detail. The system behavior is analyzed based on the results and the different features of LTE are evaluated in terms of suitability for the ITS network. Moreover, the results of the simulations are compared with the results of 802.11p under the same network circumstances and the differences and similarities are analyzed. Finally, in *Chapter 6*, the conclusions about the suitability of LTE for ITS networks are drawn and further work on the subject is discussed.

2

System Definition & Standards Description

In this chapter the findings of the literature study are presented and explained. In *Section 2.1*, the exact definition of an ITS network is given and the requirements that have to be met in order to support the various applications of ITS are presented. In *Section 2.2*, the IEEE 802.11p standard is analyzed and its use in the vehicular environment is explained. Finally, in *Section 2.3*, the Long Term Evolution (LTE) standard is presented along with its most intriguing features for use in an ITS environment.

2.1 Intelligent Transportation Systems (ITS)

The *Intelligent Transportation System* (ITS) concept, came to life by the vision to provide safer, more efficient and more entertaining use of vehicles and the road infrastructure by inter – connecting all the vehicles in one network. The communication among vehicles has the potential to increase the range and coverage of location and behavior awareness of vehicles, and enable highly developed pro-active safety systems. The basic, and very simple, idea behind the ITS concept is that each vehicle on the road collects information about itself and its environment through a network of sensors, processes them by making use of its highly evolved on-board computers and exchanges them with other nearby vehicles and infrastructure. In this way, each vehicle has an adequate knowledge of the conditions of the road ahead, the traffic patterns and the environment around it as well. The same scheme can be proven extremely useful in cases of unexpected conditions on the road, by warning every vehicle in the area about an upcoming danger and thus avoiding an unpleasant incident such as a collision or dangerous - last minute - evasive maneuvers. The realization of this concept has only recently become possible through the amazing developments in many technological areas such as micro-electronics, telecommunication technologies and sensor networks [4].

2.1.1 Standardization & Current Work

The ITS is a very promising field, with a big number of possible applications. That is why various companies, institutes and organizations have been involved with it over the past years. This fact has resulted in the definition of various standards around the world, concerning vehicular communications. Although these standards share some basic characteristics, especially in the *Physical* (PHY) and *Medium Access Control* (MAC) layers, they differ substantially in the upper layers of the protocol stack, and at the end, result in different systems. Although the main efforts in the ITS field take place in Europe, the USA and Japan, there are laboratories and institutes all around the world that carry out research on this topic. The research that has been carried out so far, has resulted in many remarkable projects such as Coopers, CVIS, Safespot and DSRC(IEEE 1609.x). A big initiative is in place by EU, US and international organizations to share their knowledge on the subject and evolve and standardize the technology, in a way that is suitable for the national and international needs of transportation.

The various standardization bodies are in constant communication with the participating organizations and the standards evolution teams, through a Group of Experts, in order to harmonize the various approaches and provide feedback to the standardization process. This cycle of constant standardization inter-connection is shown below in ***Figure 2.1*** [13] [14].

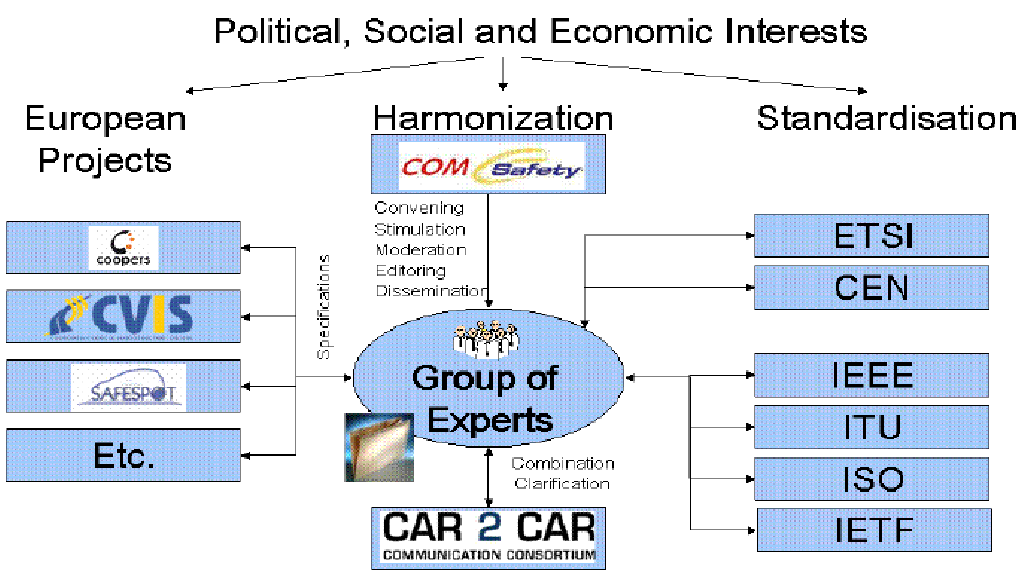


Figure 2.1: ***Interconnection of ITS projects, organizations and standardization***

2.1.2 <u>Communication Patterns</u>

There are two distinct communication patterns in ITS, depending on the network circumstances and needs. The first pattern is characterized by each vehicle transmitting a very short message which is called *Cooperative Awareness Message* (CAM) and contains regular information such as the position of the vehicle, the current velocity, the bearing, etc. These messages are transmitted at a regular interval with a high rate (10 Hz are often assumed) and enable the deduction of a highly accurate environment picture as a basis for movement prediction. This is the basic form of an ITS message and constitutes the overwhelming majority of the messages being transmitted in an ITS network. A depiction of this function in a vehicular network is shown in ***Figure 2.2a***.

The second communication pattern is characterized by the transmission of extra messages, which are called *Event Triggered* messages, which aim at warning the rest of the vehicles on the network about an unexpected situation. These messages don’t have a fixed schedule of transmission, but are rather triggered by specific events on the road, thus the name *Event Triggered* messages, and constitute a tiny portion of the total messages transmitted on the network. Even though these messages are very rare, they are much more important than the Cooperative Awareness messages, since they help maintain the safety of the vehicles and drivers. That is why, when an *Event Triggered* message is generated, it is very important that it receives priority over the CAMs in the network, so that it can reach its destination within the predefined time limits which are very stringent. As it is obvious, a delayed *Event Triggered* message, constitutes nothing but irony to the driver that has just crashed because he/she didn’t receive the message on time. The functionality of this pattern is depicted in ***Figure 2.2b*** [13].

a) b)

Figure 2.2: a) ITS periodic messages b) ITS Event Triggered message

2.1.3 ITS Classes & Applications

The number of possible ITS applications that arise from the connectivity of the vehicles is enormous and each of them has a different set of requirements. These ITS applications can be roughly divided into three main categories or classes which are constituted by applications with the same requirements, more or less. The most important of these requirements that absolutely has to be met and the most difficult one to achieve, is the delay requirement, because of the importance of on-time delivery in ITS, especially in the case of Event Triggered messages. The three main classes of ITS applications are:

- ***Co-operative (Active) road safety:*** The primary objective of applications in this class is the improvement of road safety. Moreover, it is proven that actively improving road safety may lead to secondary benefits which are referred to by the term “passive road safety”. This class is by far the most demanding since the frequency of the generated messages (if they are not event-triggered) is as high as 20 Hz and the latency requirements are very stringent around ***50 – 100 ms***. Some example applications of this class are: Collision avoidance, Pre-crash sensing, Emergency electronic brake lights etc.

- ***Co-operative traffic efficiency:*** The primary objective of applications in this traffic management class is the improvement of traffic fluidity. Once more, traffic management can offer some secondary benefits which are not directly associated with it. This class has mediocre performance requirements with the message generation frequency varying from 1 to 5 Hz and the latency within ***100-500 ms***. Some example applications of this class are: Traffic light optimal speed advisory, Traffic information and recommended itinerary etc.

- ***Co-operative local services & global Internet services:*** Applications in this class advertise and provide on-demand information to passing vehicles on either a commercial or non-commercial basis. The main components of this class are infotainment, comfort and vehicle services. The latency requirements for this class are very relaxed and are usually ***above 500 ms***. Some examples of applications in this class are: Maps update, electronic commerce, media downloading etc.

When designing or evaluating a system, it is very important to know the kind of real life applications that this system will have, since that knowledge will provide the benchmark for the evaluation of the performance. As it is obvious from the presentation of ITS applications above, there is a huge diversity in the requirements that the ITS will have to meet in order to accommodate these applications. The three different classes and their requirements are neatly presented in a compact form in ***Table 2.1*** below, which will provide a very easy to use reference when evaluating the performance of the different communication protocols. In this way, it will be fairly easy to determine which applications can be served by which communication protocol [6].

Class	Objective	Beacon Frequency	Latency Requirement	Examples (Apps)
Co-operative (Active) Road Safety	Road Safety, Collision Avoidance	10 – 20 Hz	50 – 100 ms	Collision Avoidance, Pre-crash sensing
Co-operative Traffic Efficiency	Improvement of Traffic Fluidity	1 - 5 Hz	100 – 500 ms	Traffic Information, Speed Advisory
Co-operative Local Services & Internet	Infotainment, Comfort Commercial Use	On Demand	> 500 ms	Maps Update, e-commerce, Media Downloading

Table 2.1: ITS Classes & Requirements

2.2 IEEE 802.11p

As mentioned earlier, the IEEE 802.11p standard is considered the main candidate for use in ITS networks. In order to understand what makes it so suitable for vehicular communications, we will have to take a look at the structure of the standard. The standard originates from the well known "family" of 802.11 WLAN standards, thus inheriting the main features and salient characteristics of this family. As a consequence, it is responsible for the functionality of the PHY and MAC layers of the protocol stack. The 802.11p version is specifically modified in order to cope with the specific characteristics of the vehicular environment. In order to get a full understanding of the standard we will examine its PHY and MAC layers separately and we will find out what its advantages and disadvantages are.

Before going into the technical specifications of the standard, it is very important to understand how communication is achieved when using the 802.11p. As mentioned before, the 802.11p is a wireless Ad-hoc network. This means that there is no fixed infrastructure needed in order to achieve communication between two parties. Each node in a 802.11p network is equipped with transmitting and receiving antennas and they all use the air as their shared medium for transmission. Once a transmission has been made, all the vehicles within the transmission range of the sender can receive the message. It is a very simple and straightforward way of communication, but because there is no infrastructure, and hence no central entity to coordinate the transmissions of all the nodes, it is very important to have a very good *Medium Access Control* (MAC) policy in order to avoid collisions between transmitted packets.

As most Ad-hoc networks, 802.11p makes use of a relatively simple MAC mechanism which is called *Carrier Sense Multiple Access with Collision Avoidance* or better known as ***CSMA/CA***. This mechanism is based on two simple principles, *Listen Before-Talk* and B*ack-Off if someone else is talking*. When a node wants to transmit, it first checks ("senses") the channel in order to determine whether it is already in use by another node, and if it is free then the node starts its transmission immediately (*Listen-Before-Talk*). In the case that the channel is busy, the *Back-Off* mechanism takes over. The node waits until the other node finishes its transmission and it senses that the channel is free again. Then it waits an additional, small, random amount of time which ensures that no two nodes will start transmitting at the same time. If the node doesn't get channel access after that, because another node started transmitting first, then the whole process starts over. ***CSMA/CA*** is a very simple and easy to implement scheme, but it has its drawbacks as we will see later on [15].

2.2.1 PHY Layer

The 802.11p PHY layer is based on *Orthogonal Frequency Division Modulation* (OFDM), and originates from the 802.11a PHY layer, which has been modified in a few areas in order to cope with the specificities of the vehicular environment. The most notable modification is that the 802.11p version uses half the clock/sampling rate of 802.11a, which affects several parameters. Specifically, it leads to reduced delay and bigger guard intervals, which makes the signal more robust against fading. The most notable characteristics of 802.11p PHY are listed below [12] [14]:

- **Operational Frequency:** The spectrum around 5.9 GHz has been allocated specifically for use by vehicular communications systems

- **Bandwidth:** In the USA, a total BW of 70 MHz is available for 802.11p which is divided into seven 10 MHz channels. In Europe, the European Commission has allocated 30 MHz of spectrum for safety and traffic applications and an additional 20 MHz will be allocated for commercial applications.

- **Channels:** The available BW is divided into the *Control* channel (CCH) and the *Service* channels (SCH). The CCH is used for establishment of communications and broadcasting to the vehicles, while the SCH is used for V2V and I2V communications. The different channels cannot be used simultaneously in the case of a single transceiver.

- **Symbol length:** The symbol length is doubled compared to 802.11a PHY, to provide more robustness against fading.

- **OFDM:** 64-point Inverse Fast Fourier Transform, 48 subcarriers for data, 4 pilot subcarriers, 11 guard subcarriers. Half the subcarriers compared with 802.11a.

- **Modulation schemes:** It uses the same coding schemes as 802.11a (BPSK, QPSK, 16/64 QAM)

- **Data Rate:** The available data rates are halved compared to 802.11a, namely 3-27 Mbps.

- **Range:** Optimum range is 300m but it can reach a maximum of 1000m

2.2.2 MAC Layer

The 802.11p MAC layer is equivalent to the 802.11e Enhanced Distributed Channel Access (EDCA) Quality of Service extension. That means that it is based on the traditional Carrier Sense Multiple Access (CSMA) mechanism and its most salient characteristics are listed below [16]:

- **Channel Access:** Like 802.11e, the 802.11p standard uses Congestion Windows (CW), Back-off timers and Arbitration Inter-Frame Space (AIFS) mechanisms in order to coordinate the channel access among the users.

- **Quality of Service:** Prioritization is very important in 802.11p standard, since it is essential to differentiate services for emergency safety messages (Event Triggered messages) and simple periodic or commercial use messages. That is why, the standard uses four different Access Classes (ACs) with different priorities and assigns to them different AIFS and CW values. The smaller the AIFS and the CW the higher the priority of the AC. The different ACs of 802.11p are shown below in ***Figure 2.3*** .

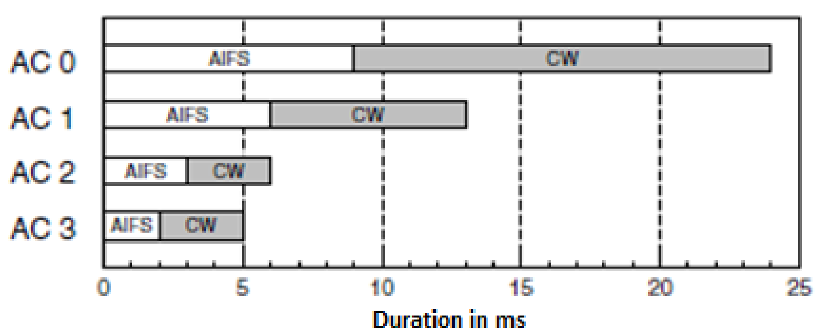


Figure 2.3: Different AIFS & CW values for different Access Classes

- **Modes of communications:** In 802.11p vehicles can communicate with one another in an Ad-hoc manner using their On-Board Units (OBU) achieving V2V communication, or they can make use of the available infrastructure by communicating with the Road Side Units (RSU) achieving I2V communication. However, from the 802.11p point of view there is no fundamental difference between the two cases.

2.2.3 Advantages & Disadvantages of 802.11p

As mentioned above, the 802.11p standard is an amendment to the well known 802.11 WLAN standard family, thus, inheriting all of its advantages like simplicity, fairness, ease of use etc. Also the fact that the 802.11 technology is very well known and used in multiple applications throughout the world ensures system compatibility with a number of other useful applications. Furthermore, it enables relatively reliable communication using cheap hardware and software. The modifications that took place in the PHY and MAC layers of 802.11p have allowed it to adapt to the needs of the vehicular environment and deal with some of the particularities and issues that arise in this environment. Nevertheless, some very important problems still remain unsolved, and impose restrictions and limitations to the performance of the standard. Most of them originate from the physical conditions of the VANET environment, such as high mobility of the nodes and the rapidly time-varying channel and result in the degradation of the systems' performance by imposing serious problems on the communication such as frequent disconnections and unacceptably high delays.

Most of the 802.11p's disadvantages are caused by its ad hoc nature, and they are well known problems that all ad hoc networks face. But in the case of 802.11p things are even more crucial because of the stringent delay requirements that it has to meet in order to accommodate the ITS applications. Some of these problems are the hidden node problem *(two nodes transmit at the same time because they cannot sense each other transmitting and their packets collide at the receiver*), the high mobility of the nodes, the fair implementation of the channel access and prioritization scheme and the optimal transmit power that each node must use in order not to interfere with adjacent transmissions. The solutions to these problems, cannot afford to degrade the performance of the standard especially when it comes to transmission delays. Furthermore, one very important problem that has been identified for the use of 802.11p in vehicular networks is that it faces severe scalability issues. That means that even though the standard performs very well under normal traffic circumstances, it doesn't have the capacity to accommodate a large number of users. As a consequence the performance of the standard drops fast with an increasing number of participating vehicles in the network and its performance is no longer acceptable for ITS applications.

As it is obvious from the characteristics that were presented above, the 802.11p standard is a very good candidate for vehicular communication, but the fact that there are a few unresolved issues with its performance means that a search for an alternative communication protocol which can either assist or replace 802.11p, would provide useful scientific data to the development of the future vehicular and ITS networks.

2.3 Long Term Evolution (LTE)

Long Term Evolution (LTE) is a cutting edge technology which includes some new extraordinary features that were never before used in wireless and mobile communications and which give LTE an advantage compared to other technologies. Apart from that, some features that were included in older releases of the current mobile telephony standard, called *Universal Mobile Telecommunications System* (UMTS), were improved and refined in order to provide LTE with the capability of performing better than any other mobile communications standard and in order for it to cover the needs of a great variety of applications. Some of these features are ideal for use in the case of ITS applications, where the rapidly changing environment and the very stringent delay requirements, pose some very difficult performance requirements on the communications scheme. With the use of some of these features the delays are minimized and the performance of LTE can be optimized in order to accommodate the special needs of the vehicular environment such as low latency, transmission of small periodic packets, reception of a transmission by multiple receivers etc. In this section, the features, functionality and capabilities of LTE will be presented so that its role in a future ITS network can be evaluated.

2.3.1 LTE Structure

For the better understanding of the standard, it is very important to have a solid image of the standards structure and architecture. At this point the reader should keep in mind that LTE is an infrastructure based network, which means that the communication always takes place through a base station and never directly between two or more users. That is after all the biggest difference of this standard from the 802.11p standard that was presented earlier. The LTE and its core network architecture which is called *Service Evolution Architecture **(SAE)*** are two complementing work items handled by 3GPP. It is often referred to as the fourth generation (**4G**) of mobile networks, however the first release of LTE (Release 8) is not expected to meet the 4G criteria that are put forth *by International Mobile Telecommunications* committee (IMT-advanced). The first release that is expected to meet these criteria is Release 10. In parallel to the standardization activities, the *Next Generation Mobile Networks **(NGMN)*** was founded to drive the 4G development from the operator side.

LTE describes the new radio access technology or Radio Access Network (***RAN***) which defines the interaction between the evolved Base Stations (***eNB***) and the terminals of the users (User Equipment ***- UE***). This is an evolution of the *UMTS Terrestrial Radio Access* (UTRA) scheme that was used in UMTS and that is why it is called Evolved – UTRA (***E-UTRA***). The radio interface is based on *Orthogonal Frequency Division Multiple Access* (***OFDMA***) in the downlink and on *Single Carrier Frequency Division Multiple Access* (***SC-FDMA***) in the uplink. LTE supports multi-antenna techniques such as *Multiple Input – Multiple Output* (MIMO) and beam-forming to increase peak and cell edge bit rates respectively.

The SAE work group defined the new core network architecture which is called *Evolved Packet Core* (***EPC***) and consists of two new network nodes for the packet switched domain, the PDN-Gateway (P-GW) and the Service Gateway (S-GW). The EPC introduces enhanced Quality of Service (QoS) handling as well as interoperability with non 3GPP access technologies. The system architecture consisting of LTE and EPC is denoted *Evolved Packet System* (EPS) and is shown below in ***Figure 2.4*** .

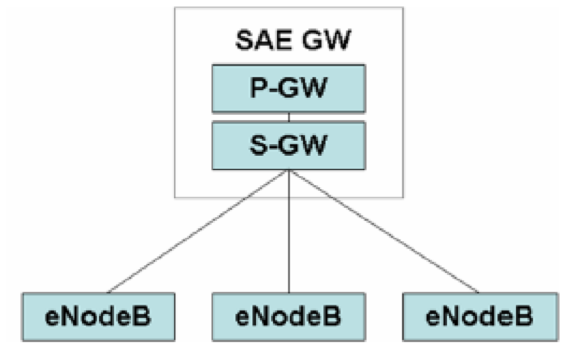


Figure 2.4: EPS architecture

In the IP based EPS, the number of nodes were reduced as well as the number of interfaces in the network architecture. The flat system architecture, consisting only of the eNBs and the Gateway (GW), contributes to the low latency of the system. Besides the significant improvement in data rates and latency that this architecture offers, it also achieves a more cost efficient network structure. Additionally the spectrum flexibility was improved, allowing LTE to operate in frequency carriers of 1.25 to 20 MHz (Bandwidth) and in frequency bands from 700 MHz to 2.6 GHz [5].

2.3.2 <u>Peak Data Rate / Spectral Efficiency</u>

As defined by 3GPP, E-UTRA should support significantly increased instantaneous peak data rates. The supported peak data rate should scale according to size of the spectrum allocation. Note that the peak data rates may depend on the numbers of transmit and receive antennas at the UE. The targets for *downlink* (DL), meaning the communication with direction from the eNB to the UE, and *uplink* (UL), meaning the communication with direction from the UE to the eNB, peak data rates, are specified in terms of a reference UE configuration comprising:

- Downlink capability – 2 receive antennas at UE
- Uplink capability –1 transmit antenna at UE

For this baseline configuration, the system should support an instantaneous downlink peak data rate of 100 Mb/s within a 20 MHz downlink spectrum allocation (5 bps/Hz) and an instantaneous uplink peak data rate of 50 Mb/s (2.5 bps/Hz). The peak data rates should then scale linearly with the size of the spectrum allocation. The *LTE/SAE Trial Initiative* (LSTI) proved that these targets are met by LTE by performing simulations and real-life testing. As can be seen in ***Figure 2.5*** below, LTE achieves these goals both in the *Frequency Division Duplexing* (FDD) mode as well as the *Time Division Duplexing* (TDD) mode [7] [9].

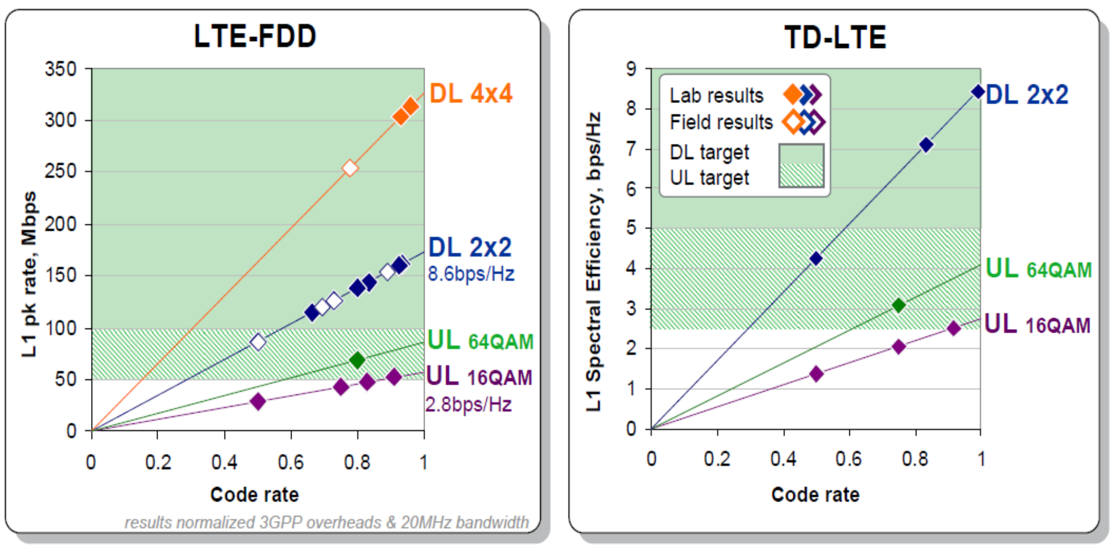


Figure 2.5: Lab & field results for LTE's peak data rates and spectral efficiency

2.3.3 <u>Latency</u>

As mentioned before, the most important requirements that LTE has to meet in order to be suitable for ITS applications are the delay requirements, since most of these applications are extremely delay sensitive and if the time requirement for a packet expires then the information in that packet is no longer useful or it can lead to a fatal accident. Such a scenario would lead to the degradation of the credibility of the system. The latency that any packet in an LTE network will encounter is divided into two major parts, the *Control Plane Latency* (C-plane latency) and the *User Plane Latency* (U-plane latency).

Control plane latency is the time required for performing the transitions between different LTE states. A UE in LTE is always in one of three states, Connected (active), Idle or Dormant (battery saving mode). 3GPP defines that the transition time from the Idle state to the Connected state should be less than *100 ms*, excluding downlink paging and *Non-Access Stratum* (NAS) signaling delay. Furthermore, it is defined that the transition time from the dormant state to the connected state should take less than *50 ms*. The LSTI performed measurements in order to verify that LTE meets these requirements. The results from these measurements are shown below in ***Figure 2.6***, and as it is obvious LTE performs even better than the worst case requirements for the Idle to Connected transition which is the most frequently used [1] [7] [9].

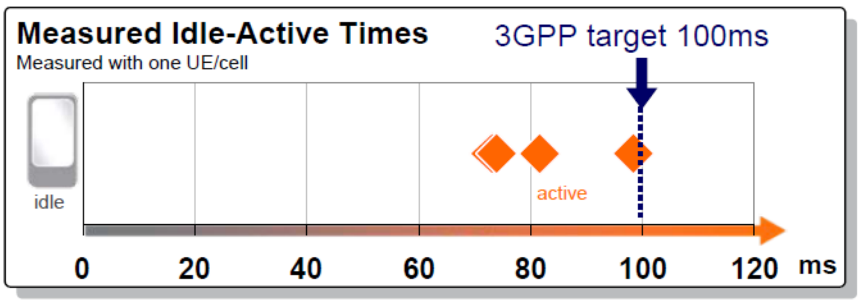


Figure 2.6: LSTI measured Idle-Active times for LTE and 1 UE/cell

The user plane latency is defined by 3GPP as the one way transit time between a packet being available at the IP layer in the UE edge node and the availability of this packet at the IP layer in the RAN edge node, in this case the eNB. Under the current specifications a U-plane latency of around *5 ms* one way is expected from the E-UTRA. Low U-plane latency is essential for delivering interactive services like gaming, VoIP and most importantly in our case live feedback from the road network.

The LSTI performed measurements to establish the ping Round Trip Time (RTT) between the UE and the eNB (2*U-plane latency) as well as the End-to-End ping delay. A schematic diagram of the network structure that was used for the measurements as well as the results, are shown in ***Figure 2.7*** below [7] [9].

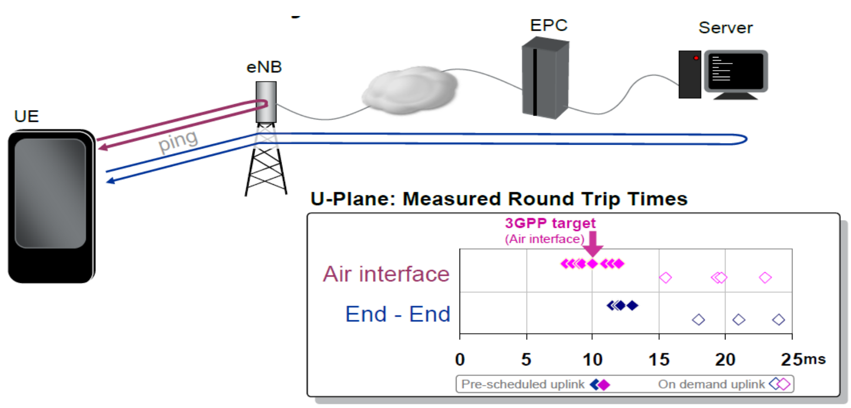


Figure 2.7: Network structure and Air interface & End-End delay measurements for LTE

As we can see in ***Figure 2.7***, some measurements have been conducted with a pre-scheduled assignment for the uplink resources. This is a special feature of LTE which might prove valuable for ITS applications and it will be discussed thoroughly in the following sections. The results from the LSTI measurements show that the 3GPP requirements for the Air interface can be met when pre-scheduled assignment is used, but when the default dynamic assignment of uplink resources is used then the delay is a little bit over the limit. On the other hand, the measurements taken for the End-to-End delay are extraordinary and they show that LTE can accommodate even for applications with very tough delay requirements. The exact value of the End-to-End delay in an LTE network as well as the components that comprise it are shown below in ***Table 2.2*** [2].

Delay component	Delay value
Transmission time uplink + downlink	2 ms
Buffering time (0.5 × transmission time)	2 × 0.5 × 1 ms = 1 ms
Retransmissions 10%	2 × 0.1 × 8 ms = 1.6 ms
Uplink scheduling request	0.5 × 5 ms = 2.5 ms
Uplink scheduling grant	4 ms
UE delay estimated	4 ms
eNodeB delay estimated	4 ms
Core network	1 ms
Total delay with pre-allocated resources	13.6 ms
Total delay with scheduling	20.1 ms

Table 2.2: End-to-End delay and latency components

2.3.4 <u>Mobility</u>

According to the requirements set forth by 3GPP, the E-UTRAN shall support mobility across the cellular network and should be optimized for low mobile speed from 0 to 15 km/h. Higher mobile speed between 15 and 120 km/h should be supported with high performance. Mobility across the cellular network shall be maintained at speeds from 120 km/h to 350 km/h (or even up to 500 km/h depending on the frequency band). Voice and other real-time services supported in the circuit switched domain in Release 6 UMTS, shall be supported by E-UTRAN via the packet switched domain with at least equal quality as supported by UTRAN (e.g. in terms of guaranteed bit rate),over the whole of the speed range [7].

The LSTI, performed extended measurements in order to verify whether the current LTE Release 8 meets the mobility requirements of 3GPP. The results for different mobile speeds are shown below in ***Figure 2.8***, in terms of throughput vs *Signal to Noise Ratio* (SNR) according to the distance of the mobile from the eNB. As we can see from the graph, LTE shows brilliant performance for low mobile speeds and little impact is obvious for mobile speeds up to 120 Km/h. Even though the performance degrades for high speeds, we can see than extremely high mobile speeds are still supported. Hence, all the original mobility requirements of 3GPP are successfully met by LTE [9].

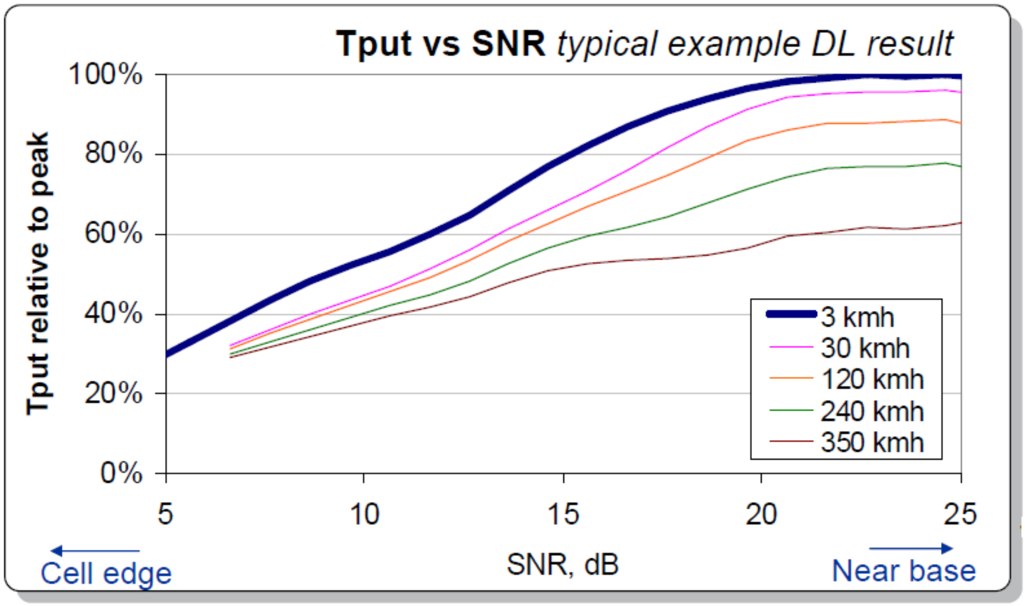


Figure 2.8: Throughput vs SNR for different mobile speeds in LTE

3

Motivation & Research Questions

In this chapter, the reasoning behind this eight months-long research project is explained. The facts that motivated this thesis and the research questions that we are trying to answer, is a prerequisite knowledge before going any deeper into the scientific content of this project. The motivation and research goals will clarify the scientific purpose of this thesis. In order to justify the fact that LTE is considered the most promising alternative communication system for use in the future ITS networks, a more thorough investigation of the technological and commercial aspects of the system is required. A number of reasons have qualified LTE as a possible candidate for use in ITS networks and they are listed below:

- **Extraordinary Performance:** The unprecedented performance that LTE promises, is essential for meeting the ITS requirements. The high Data Rates (100 Mbps DL, 50 Mbps UL) and very low latencies are needed to ensure in time delivery of the time-critical ITS packets. Moreover the large communication range of LTE might prove very useful for covering big parts of highways and road infrastructure, and the support for high mobility nodes, which LTE offers, is essential for operation in a vehicular network.

- **Readily Available:** The fact that LTE is a technology which is already very mature and commercial networks are already being deployed around the world, ensures that there will be a very high penetration rate for the LTE technology and for the ITS applications that it may support.

- **Infrastructure Based Technology:** As mentioned before, a lot of the problems that 802.11p faces in ITS scenarios are due to the fact that it is an infrastructure-less network. The Infrastructure based LTE will not face these problems and will provide an alternative, more reliable, approach for communication within ITS.

- **Existing Infrastructure:** By the time that ITS will be ready for deployment, the LTE network will already be in place, which will ensure an early and low cost deployment of ITS services, since no new hardware will have to be purchased and installed from the providers.

- **<u>LTE special features:</u>** The fact that LTE has been designed to handle efficiently VoIP traffic, especially with the use of Semi-Persistent Scheduling (see *Section 4.4.2*), is a huge advantage for the ITS, since VoIP and ITS have very similar applications that require the same treatment by the network.

The points mentioned above, are the reason that this thesis aims at evaluating the performance of LTE within the context of ITS networks. The main goals of this project are to discover the performance boundaries of LTE technology in relation to the requirements of typical ITS applications, to understand how the different parameters of the vehicular network, such as vehicle density and beaconing frequency, affect the performance of LTE and to compare the performance of LTE in ITS networks, with that of the 802.11p standard. Moreover, the effect that the introduction of LTE in ITS, has on existing cellular traffic will be examined and different possibilities for improving the performance of LTE in the ITS context will be investigated.

In order to focus the scope of this thesis project, the above goals have been refined into specific research questions, which would guide the research in the correct path. By answering these questions, the capabilities and possibilities of LTE in an ITS network would be clear and its performance could be compared and evaluated according to the 802.11p standard. These *Research Questions* are the “driving force” behind the research carried out in this thesis and they are presented below:

- Can LTE meet the requirements of all the ITS applications? If not, which ones can it support?

- Can LTE support both vehicular and normal mobile telephony users (background traffic)? What is its exact capacity?

- How does the background traffic affect the ITS traffic?

- Does differentiation and prioritization between ITS and background traffic help ITS performance?

- What are the exact advantages gained by the infrastructure of LTE compared to the infrastructure-less 802.11p?

- What is the gain that Semi-Persistent Scheduling offers? Are there any drawbacks from using this scheduling scheme?

- How do the different parameters of the network affect the performance of LTE?

- At which point the performance of LTE is no longer acceptable?

- Does the performance degrade gracefully or abruptly with increasing number of vehicles in the network?

- How does LTE performance compare to the 802.11p performance in ITS scenarios?

- Would a combination of LTE and 802.11p be functional? Which applications would be supported by which system?

The answer to these questions will provide an in-depth understanding of the performance and capabilities of LTE in an ITS network and will mark the starting point for further scientific research, regarding the involvement of LTE in Intelligent Transportation Systems.

4

LTE Modeling & Simulation Options

In order to be able to evaluate the performance of an ITS network, using LTE as the communication protocol and to answer the research questions of this thesis, a model had to be built which simulates the functionality of LTE and the circumstances of a vehicular network. This simulator is the main tool of this thesis and will provide the necessary insight about the performance of ITS using LTE. Unfortunately, due to the great complexity of LTE and vehicular networks, we had to limit the focus of our research and make some very important choices about which aspects of these systems are modeled in the simulator. In this chapter the modeling choices, assumptions and simplifications that were made are explained and justified, and a full description of the model is given. *In Section 4.1* the network layout is discussed and the main characteristics of our model are presented. In *Section 4.2* the traffic characteristics of the vehicular environment are given as well as the data traffic that LTE has to handle. In *Section 4.3* the propagation environment is described and in *Section 4.4* the radio resource management that LTE uses is discussed. Finally, in *Section 4.5* the simulation environment and the basic functionality of the simulator are presented.

4.1 System Model

The simulator used in this thesis, was created in the Borland Delphi programming language and it simulates the functionality of a LTE cellular network in a vehicular environment, making use of ITS applications. In this section, the basic modeling scenario are presented and some basic terminology about the scenario is explained. Also, the basic modeling choices made in this simulator are justified.

4.1.1 Simulated Scenario

The environment that our model simulates and its basic principles are depicted below in ***Figure 4.1***. The vehicles communicate with each other over a commercial LTE cellular network, at the same time that other mobile users are establishing data connections with the same network. The vehicular environment simulated is a rural highway with multiple lanes and a variety of traffic patterns. The LTE part of the model simulates the function of a LTE cell operating in the 900 MHz band with a bandwidth of 10 MHz. The eNodeB of the cell is situated in the middle of the simulated highway (length-wise), at a height of 30 meters and uses an omni-directional antenna. LTE serves both vehicular and background mobile telephony users at the same time and it has to meet the QoS requirements for each service, respectively, although in our scenario no QoS is taken into consideration for the background traffic. For the purposes of this model the communication load offered to the network by the vehicles, from now on will be mentioned as *ITS load* or *ITS traffic*, while the load offered by the normal telephony users will be mentioned as *background load* or b*ackground traffic*.

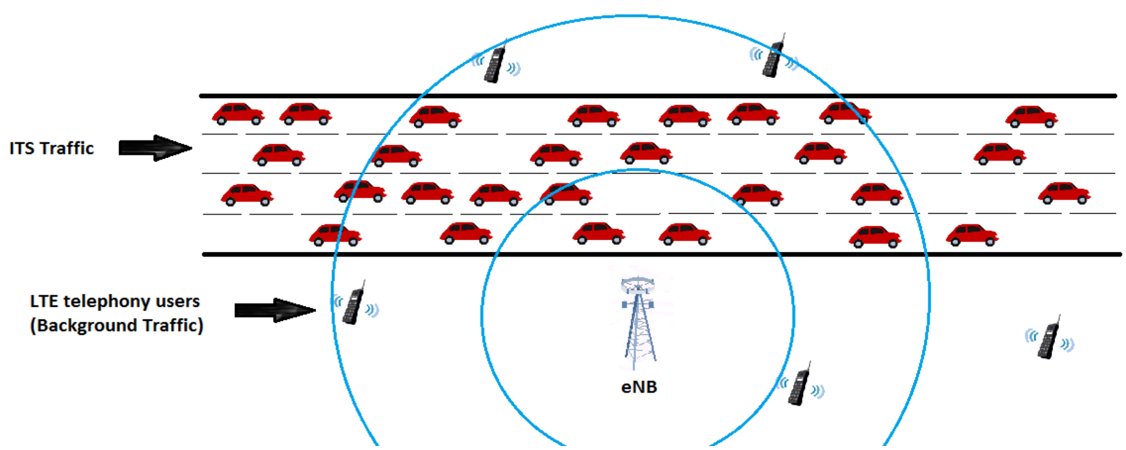


Figure 4.1: Basic modeling scenario

In this basic simulation scenario that is presented above, all the vehicles participate in an ITS and exchange periodic messages with each other through the eNB. Because these messages have predefined size and are generated in regular intervals, they are called *beacons*, and the frequency with which they are being transmitted is called *beaconing frequency*. Each beacon transmitted by each vehicle, has to reach the eNB and go through the whole LTE network before it can be delivered to the rest of the ITS users, through a broadcast transmission by the eNB. The beacon can be broadcasted also from neighboring eNBs, to increase the range and the number of recipients, but in our scenario only one cell (eNB) is taken into account. The exact path that a beacon takes through the network is:

UE → eNB → core network → gateway → ITS server → gateway → core network → eNB → broadcast→ UE

At the same time, the LTE network has to serve the background users which appear in a random fashion and offer extra load to the cell. For the purposes of this thesis, it is assumed that all the background users are establishing data connections with the LTE network, so that the offered load can be easily measured in kilobits per second (kbps).

4.1.2 <u>Focus on Uplink</u>

As mentioned before LTE is a complex technology and it entails many different aspects. Unfortunately, not all aspects of LTE could be modeled within the context of this thesis project and some choices had to be made about which of them were more essential to incorporate to the simulator and which ones could be omitted. After an extensive literature study and by taking into account all of the available facts, we chose to model and focus on the Uplink (UL) of LTE and not to include the Downlink (DL) in the simulator. That choice was made based on the fact that the UL presents the most challenges when used in a vehicular environment, as the one described in *Section 4.1.1*. On the other hand, while in a normal cellular network the DL has to serve more traffic than the UL (usual traffic patterns entail much more data downloading than uploading), in the ITS case the traffic generated by the vehicles, is almost equal for the DL and the UL (transmitted beacons), thus, it is generally believed that the DL will be able to fulfill the requirements of ITS applications. Although the delay requirements imposed by LTE are a concern for both DL and UL, due to the limitations and generally worse performance of the UL compared to the DL (*see Section 2.3*), the UL is considered to be the bottleneck of the system for the ITS usage case.

The superiority of the DL is caused by some of the advanced features that it incorporates, mainly due to the fact that the eNB plays the most important role in the DL. The transmission power of the eNB is by far superior to that of a UE and it potentially uses a more advanced MIMO scheme (2 x 2 MIMO). Additionally, there is no channel access delay for the eNB and it can make use of the broadcast channel for disseminating the information instead of transmitting the information separately to each user. These features ensure that the DL has higher data rates and lower latencies than the UL, and should encounter no difficulties in meeting the strict ITS requirements.

The UL on the other hand is mostly dependent on the *User Equipment* (UE) which naturally is a much weaker node than the eNB. Its transmission power is significantly less than that of the eNB, and because of the size restriction it makes use of a simple receive diversity scheme (1 transmit antenna, 2 receive antennas). Moreover, its dependency on the battery power, limits even further its transmission and processing capabilities. For those reasons, the UL is considered the weak point of the system and that is why this research is focusing on evaluating the UL performance. If it is proven that the UL is able to handle the ITS load and requirements, then there should be no problem for the DL to support ITS applications too.

4.2 Traffic Characteristics

The creation of this model requires the simulation of two distinct, cooperating systems, namely, the LTE network and the vehicular network (road). In this section, we will describe in detail the traffic characteristics of both these systems. As far as the vehicular network is concerned, the creation of the road and the movement prediction of the vehicles in it, will be discussed, while for the case of the LTE network, the data traffic generated by both ITS and background users will be explained in detail.

4.2.1 Intelligent Driver Model (IDM)

For the creation of the road network and the simulation of the movement of the vehicles, the *Intelligent Driver Model* (***IDM***) developed by Treiber, Hennecke and Helbing was used [18] [19]. In traffic flow modeling, the IDM is a time-continuous car-following model for the simulation of freeway and urban traffic. It was developed in the year 2000 to improve upon results provided with other "intelligent" driver models, which presented less realistic properties.

The IDM is a "car-following model", i.e., the traffic state at a given time is characterized by the positions and velocities of all vehicles. The decision of any driver α, to accelerate or to brake depends only on his own velocity, and on the "front vehicle" immediately ahead of him. Specifically, the acceleration dv_α/dt of a given driver depends on his velocity v_α, on the distance s_α to the front vehicle, and on the velocity difference Δv_α (positive when approaching). The IDM is described by the following partial differential equations:

$$\dot{x}_{\alpha(t)} = \frac{\mathrm{d}x_\alpha}{\mathrm{d}t} = v_\alpha$$

[eq. 1]

$$\dot{v}_{\alpha(t)} = \frac{\mathrm{d}v_\alpha}{\mathrm{d}t} = a\left(1 - \left(\frac{v_\alpha}{v_0}\right)^\delta - \left(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha}\right)^2\right)$$

[eq. 2]

$$\text{with } s^*(v_\alpha, \Delta v_\alpha) = s_0 + v_\alpha T + \frac{v_\alpha \Delta v_\alpha}{2\sqrt{a\,b}}$$

[eq. 3]

The acceleration, which is described by *equation 2*, is divided into a "desired" acceleration a [1-$(^{v}/_{v0})^{delta}$] on a free road (first part of eq. 2), and braking decelerations induced by the front vehicle $(s^*(v_\alpha, \Delta v_\alpha) / s_\alpha)^2$, which is the second part of eq.2. The acceleration on a free road decreases from the initial acceleration a to zero when approaching the "desired velocity" v0.

The braking term is based on a comparison between the "desired dynamical distance" s^*, and the actual gap s to the preceding vehicle. If the actual gap is approximately equal to s^*, then the breaking deceleration essentially compensates the free acceleration part, so the resulting acceleration is nearly zero. This means, s^* corresponds to the gap when following other vehicles in steadily flowing traffic. In addition, s^* increases dynamically when approaching slower vehicles and decreases when the front vehicle is faster. As a consequence, the imposed deceleration increases with

- decreasing distance to the front vehicle (one wants to maintain a certain "safety distance")
- increasing own velocity (the safety distance increases)
- increasing velocity difference to the front vehicle (when approaching the front vehicle at a too high rate, a dangerous situation may occur).

The model parameters v_0, s_0, T, a, δ and b are the same for all the vehicles in the network and are defined as follows:

- ***desired velocity v_0***: the velocity the vehicle would drive at in free traffic
- ***minimum spacing s_0***: a minimum net distance that is kept even at a complete stand-still in a traffic jam
- ***desired time headway T***: the desired time headway to the vehicle in front
- ***acceleration a***
- ***comfortable braking deceleration b***
- ***Acceleration exponent δ***: fixed value usually set to 4

Additionaly, the user of the model has the potential of introducing a traffic jam in the network, thus making the simulation even more realistic. The introduction of the traffic jam is a manual process during which the user must define the exact position of the traffic jam starting and ending points on the road, and the reduced velocity that the vehicles in the traffic jam will experience. Also the distance among the vehicles in the traffic jam must be defined (and should be set smaller than the distance that the vehicles not experiencing a traffic jam, have among them) and a reduced desired velocity must be defined.

The initial situation of the model is defined by assigning random positions to the vehicles in the network, taken from a uniform distribution. The velocities of the vehicles are also sampled uniformly from a user defined interval (max and min allowed velocities). From that moment on, the IDM will be able to calculate the position and speed of every vehicle at any given time instant. For our simulator, we have chosen to implement a refresh rate of the network of 100 ms. That means that every 100 ms the positions and speeds of all the vehicles in the network are recalculated, as well as the distance of every vehicle from the eNB which is needed for LTE signal strength calculations (*see Section 4.3*). Normally, the IDM performs calculations on a per second basis, but for the purposes of this thesis project the calculation interval was set to 100 ms because it was calculated that this time interval would give us a sufficiently accurate image of the channel's conditions. If the interval was any larger, the model wouldn't adapt accurately enough to the changes of the channel, while a smaller interval wouldn't offer any further adaptation advantages than the 100 ms interval.

In order to fit the IDM in our simulation scenario we had to add a couple of extra features to it. Because the simulated road has a finite length and the simulation time is much longer than the time a vehicle needs to travel the whole length of the road, we implemented a *wraparound* scheme, which means that any vehicle that reaches the end of the simulated road is automatically re-inserted at the beginning of the road. In that way there is no limit in the simulation time that we want to consider. The other modification that we had to make was mandated by the fact that the IDM is defined for one lane of vehicles (vehicles one behind the other in a horizontal line) while we had the need to simulate a highway with multiple lanes in order to have a more realistic model of a highway, as is shown in ***Figure 4.1***. To overcome this problem, we implemented the IDM independently for every lane of the simulated road network. Since the movement prediction of the vehicles depends on the same equations, the resulting traffic pattern will be similar for all vehicles, thus producing an accurate prediction for the movement of the vehicles.

4.2.2 <u>ITS Beacons</u>

The ITS load (or ITS traffic) that is mentioned in *Section 4.1.1* and that is imposed on the LTE network, is nothing more than the beacons that the vehicular users of the network generate. Every vehicle on the highway transmits a beacon of predefined size with a fixed beaconing frequency. The most common value for the beacon size is 100 Bytes and the most common beaconing frequency is 10 Hz, but the values of these parameters change depending on the ITS application that is served. Here, we will examine only the case of the periodic beacon transmission from the vehicles and not the case of event triggered messages *(see Section 2.1.2*). The size and the frequency of the beacons might seem relatively small, but depending on the number of ITS users (vehicles) in the network, the aggregated ITS load imposed on the LTE cell is quite significant.

In our model, each vehicle picks a random initial time to generate its first beacon from a uniform distribution, and after the generation of the first beacon, all the subsequent beacons follow in fixed time intervals depending on the beaconing frequency (a beaconing frequency of 10 Hz leads to a beacon inter-arrival time of 100 ms). Then, the ITS users have to wait for the eNB to assign resources to them depending on the scheduling scheme that is implemented *(see Section 4.4.2*), in order to be able to transmit their beacon.

Through the monitoring of the ITS beacons, we will be able to determine the performance of ITS when using LTE as the communication technology. The normal path that an ITS beacon takes through the LTE network was described in *Section 4.1.1*, but as mentioned before, this model only simulates the function of the UL of LTE, thus the only part of that path that is simulated is the UE → eNB part. The rest of the path is not simulated, but some typical values regarding the delay of a packet travelling through an LTE network, have been taken into account from [8]. The DL transmission time, meaning the eNB → UE part of the path, had to be calculated too. A broadcast transmission was assumed on the DL, and as in real LTE networks the broadcasting bit rate (see *Section 4.4*) is adapted to the receiver with the weakest signal. So, the vehicle with the lowest bit rate (which is usually the vehicle situated farthest away from the eNB) at any given moment, defines the bit rate of the broadcast transmission and hence the DL transmission delay. By adding the UL transmission delay, the DL transmission delay and the core network delay we could calculate the Round Trip Time (RTT) delay of each beacon in the system.

The transition delay that LTE defines, which is the time needed for a UE to go from the idle state to the connected state and is usually around 100 ms (see *Section 2.3.3*), was not taken into account when calculating the beacon delay. When a UE hasn't transmitted or received any information for some period of time it goes into the idle state in order to save resources and battery time. Because of the fact that this period of time is not specifically defined and it depends on various parameters that are controlled by the operator of the LTE network, there is no specific value for it. For that reason, we chose to assume that all the users in our simulated network, remain at the connected state throughout the whole simulation run and thus, the idle – connected transition time was not taken into account.

4.2.3 <u>Background traffic</u>

As mentioned in *Section 4.1.1* the background traffic was modeled as data transmissions from the UEs to the eNB. The arrival of the background data calls followed a Poisson process with average arrival rate λ, and the data call size, was randomly sampled from a lognormal distribution with mean M and a coefficient of variation C. The position of the background call in the cell was selected randomly within the bounds of the LTE cell, and it's position didn't change throughout the whole transmission (zero mobility assumed for background traffic). Each background data call that arrives in the system enters a buffer and waits there until it is assigned resources from the eNB to start transmitting. When all the data have been sent to the eNB successfully, the entry for the specific data call is erased from the buffer. In this model, no background calls are blocked and they all enter the system buffer, but the time that they have to wait in the buffer before resource allocation, depends on the total load imposed on the network and the scheduling scheme being used. In other words, there is no admission control implemented, so a background call will always enter the system buffer, but might never leave it.

In the background traffic case, we only simulate the UL and we don't take into account what happens after the data reach the eNB. This is a simple way to incorporate background traffic in our simulator and monitor its behavior, without losing focus of our research. When a background call enters the buffer, the path loss, SINR and bit rate of that call are calculated the same way that they are calculated for the ITS users (see *Section 4.3*) and the necessary resources are assigned to it by the eNB. Since the location of background data calls doesn't change from the moment that they are generated until they have finished their transmission, there is no need for recalculation of their path loss and SINR.

4.3 <u>Propagation Environment</u>

In this section we will discuss the propagation characteristics of our model and how they affect the calculations made by the simulator. In order to calculate how the beacon transmissions are handled by the LTE UL, the path loss and *Signal to Interference and Noise Ratio* (***SINR***) of each vehicle is calculated according to the distance of the vehicle from the eNB at any given moment. From that, we can find the maximum bit rate that each vehicle can support and calculate the exact resources that each vehicle is going to need, in order to transmit its beacon to the eNB. It must be noted that by the term resources, we mean the minimum piece of time and frequency that the eNB assigns to a user, and is referred to as Physical Resource Block (**PRB**). The minimum resource allocation is always 1 PRB and it can never be less than that no matter the needs of the user. In LTE one PRB defines a block of resources that has a duration of 1 ms with a bandwidth of 180 kHz.

The path loss between the eNB and the vehicles is calculated in dB according to the Okumura – Hata model for rural areas which is described by the equation below [17].

$$PL = 69.55 + 26.16\log f_c - 13.82\log h_b + \left(44.9 - 6.55\log h_b\right)\log r - C \qquad \text{[eq. 4]}$$

$$C = 4.78\left(\log\left(f_c\right)\right)^2 - 18.33\log f_c + 40.94 \qquad \text{[eq. 5]}$$

where:

f_c : transmission frequency in MHz

h_b: height of the eNB in meters

r : distance from eNB in meters

The SINR for each user of the network depends on the path loss it is experiencing, the applied transmission power, as well as on the interference and thermal noise that it is experiencing. Because the transmission power of a user is calculated on a per PRB basis, the SINR is also calculated on a per PRB basis. Since the SINR depends on the path loss, that means that it changes as the vehicles move along the network and that is why it is important to recalculate it at regular intervals. It must be noted that before the path loss is used to calculate the SINR of users, it must be first converted from dBs to linear units. The recalculation in our model occurs with every update of the IDM (see *Section 4.2.1*), meaning every 100 ms. The SINR of every user in the network (both ITS and background users), is calculated according to the following equation:

$$\boldsymbol{SINR^{PRB}} = \frac{\boldsymbol{P_{Tx}^{PRB}/PL}}{\boldsymbol{I+N}} \qquad \text{[eq. 6]}$$

where:

$SINR^{PRB}$: SINR per PRB

P_{Tx}^{PRB} : UE transmission power per PRB

PL : Path loss (linear units)

I : Interference in Watt

N : Thermal Noise in Watt

A compromise that had to be made in our simulator was the fact that the simulated network consists of only one cell. That means that there are no neighboring cells creating inter-cell interference and for that reason, as an approximation, the inter-cell interference was considered fixed within the whole area of the simulated cell. The research presented in [20] and [21], showed that a representative value for the inter-cell interference was I = -116 dBm (2.25 $*10^{-15}$ Watts). Also, since the network was comprised of only one cell, the handover procedure (the procedure that takes place when a user leaves one cell and enters a neighboring one) was not taken into account and as a consequence, the handover delay was not included in the measurements for the beacon and packet delay.

Although the path loss was calculated for each user of the network, some other important propagation phenomena were ignored, such as shadowing and multipath fading. These phenomena would be quite important in a scenario modeling e.g. an urban environment, where there are a lot of buildings and objects that the transmission signal can bounce off, but their effect in the rural environment that we are modeling, is significantly less. Therefore, these phenomena are not modeled in our simulator, and the credibility of the simulator is not degraded significantly.

Besides the simplifications that are mentioned above, we had to make some educated assumptions regarding the values of some parameters, which are not defined by the LTE standard but depend on the network circumstances, the operator’s needs and other similar factors. One important such assumption, was that the simulated LTE network uses omni-directional antenna which means that no antenna gains were involved in our calculations. Apart from that, the minimum coupling loss and the level of the thermal noise had to be defined. The minimum coupling loss is the minimum loss any user will experience even if they are standing right next to the eNB, while the thermal noise is defined as the electronic noise generated by the thermal agitation of the charge carriers inside electronic devices, regardless of the applied voltage. After studying the research presented in [20] and [21], the minimum coupling loss was set to 70 dB and the thermal noise was set to N_{Th} = -116 dBm.

4.4 Radio Resource Management Modeling

In this section we will discuss how LTE allocates its resources to the users and what kind of measures it takes, to optimize the resource allocation. In order to do that, first we have to understand the way that our model calculates the bit rate of every user, since it plays a critical role in the PRB assignment. Once the SINR for every user of the network has been calculated (see *Section 4.3*), the bit rate of every user is calculated with the use of the Shannon bound which is $\log_2(1 + SINR)$ [17]. By finding out the bit rate of the users, which actually tells us how many bits can be sent in one PRB, we will be able to calculate exactly how many PRBs the user will need to transmit its beacon, since the beacon size is predefined. This procedure models the Adaptive Modulation and Coding (AMC) scheme of LTE and uses the equation presented below to calculate the bit rate of every user in the network.

$$\boldsymbol{Bit\ Rate^{PRB}} = \boldsymbol{B^{PRB}} \times (\boldsymbol{\alpha} \times \ \mathbf{log_2}(\mathbf{1} + \boldsymbol{SINR^{PRB}})) \qquad \text{[eq. 7]}$$

where:

$SINR^{PRB}$: SINR per PRB

B^{PRB} : Bandwidth per PRB (180 kHz)

α : Attenuation factor representing implementation losses

The attenuation factor is an approximation in order to simulate the implementation losses in the network. In [17] it has been shown that an appropriate value for the modeling of LTE UL is $\alpha = 0.4$, so this value is used also in our model.

The velocity of the vehicles must also be taken into account in the calculation of their experienced bit rate, as was explained in *Section 2.3.4*. By analyzing ***Figure 2.8*** we can calculate the effect of different velocity values on the experienced throughput and hence the experienced bit rate of the users. In our model, after the calculation of the original bit rate of every user with *equation 7*, the bit rate was decreased according to the user's velocity by adjusting it to the curves of ***Figure 2.8***. More specifically, the values that are used for the adaptation of the bit rate are the following:

- ***User velocity****: 1.39 m/s <= v <= 8.35 m/s* → ***bit rate reduction****: 4%*
- ***User velocity****: 8.36 m/s <= v <= 33.3 m/s* → ***bit rate reduction****: 12%*
- ***User velocity****: 33.3 m/s < v* → ***bit rate reduction****: 15%*

Based on the above calculation of the bit rate and the number of available resources, we will also explain the decision policy of our simulator regarding the number of resources allocated to the users. The number of resources that are assigned to the users is not exclusively dependent on the SINR and the bit rate, but other factors play a role, such as the available transmission power of the user, the velocity of the user and the scheduling scheme used by the network.

4.4.1 Transmit Power Control

During the design of the simulator we had to make an important assumption concerning the transmission power that the users will use, in order for their transmission to reach the eNB. Normally, LTE uses a very elaborate and complex scheme in order to assign power levels to each user, called *Transmit Power Control* (***TPC***). Because this scheme is rather elaborate and complex to implement, we incorporated a more convenient approximation of the TPC scheme, in our simulator, which can be viewed as an open loop power control scheme. In a LTE network, the eNB broadcasts the optimal target received power level per PRB and the UEs choose correspondingly their transmission power levels according to their path loss and the number of PRBs allocated to them at the time. In our model, we assume the users are always aware of the target received power level of the eNB, thus enabling them to calculate their optimal transmission power level in order for their transmission to reach the eNB. The received power level per Physical Resource Block (PRB) at the eNB was set at $P_0 = -78$ dBm, based on [20], [21] and [22]. The power level is indicated on a per PRB basis, because multiple PRBs arrive at the eNB simultaneously (in parallel) from different users, and they all must have the same power level when reaching the eNB, so as to avoid bad reception of PRBs due to interference caused by higher power levels.

Additionally, a decision about the transmission capabilities of the UEs had to be made, or in other words the quality of the hardware used by the users of the network had to be decided. LTE defines five different terminal classes, which vary in quality and capabilities. For the needs of this model, we assumed that each vehicle in the ITS network is equipped with the highest class terminals that are defined by the LTE standard. This is important because the class of the terminal defines the maximum transmission power that it can use. In this case the maximum transmission power of the UEs is $P_{UE\_MAX} = 23$ dBm. This is a very important parameter, since it actually puts an upper limit to the number of PRBs that are allocated to the users. In our model the eNB assigns resources to each user depending on the bit rate that the user can support. Nonetheless, even if the user is experiencing a very high SINR and consequently can support a very high bit rate, that doesn't mean that it is assigned as many PRBs as its bit rate can support, because the UE doesn't have the transmission power to use all of these PRBs. So the P_{UE_MAX} restricts the number of PRBs that are allocated to the user, so as not to waste resources of the system.

4.4.2 Scheduling Schemes

As mentioned before, the resources of the network, or PRBs, are assigned to the users by the eNB through the packet scheduling process. The resource assignments that the users of the network receive differ significantly according to the prioritization and differentiation scheme that is implemented in the network. The way that an eNB handles the priorities among the users and allocates the necessary PRBs for transmission, depends on the scheduling scheme that is implemented in the network. The scheduling scheme is a set of rules, which define the way that the eNB shares the available network resources among the users.

The LTE model serves both ITS and background traffic at the same time, and the priorities are determined by the scheduling scheme that is used. Three different scheduling schemes are implemented in this model:

- Dynamic scheduling (fair sharing)
- Dynamic scheduling (priority for ITS)
- Semi-persistent scheduling for ITS / dynamic scheduling for background traffic

The functionality of dynamic scheduling and semi-persistent scheduling will be explained in the following paragraphs, but first it is important to understand how the above mentioned scheduling schemes combinations operate. In the first case, the LTE network serves both the ITS and background traffic in the same way, utilizing a round robin scheme, which means that both of them have the same priority for transmission. In the second case, the scheduling is still made on a dynamic basis for both, but this time, the LTE network gives full priority to the beacons of ITS traffic over the data packets of the background traffic. That means, that the background traffic is served only when all the beacons of the ITS traffic, that have entered the system buffer, have been served and there are still available resources in the system. This scheduling process happens every 1 ms which is the scheduling interval for dynamic scheduling in LTE, and as a consequence the system buffer is also refreshed every 1 ms. It must be noted, that dynamic scheduling is needed for every single beacon transmitted in the network. That means that there is some control signaling overhead between the vehicle and the eNB in order to reserve the resources for transmitting the beacon. That is why, whenever dynamic scheduling is used, a *scheduling penalty* is added to the RTT of the beacon. This scheduling penalty is not used in the case of SPS, since the control signaling overhead in that case is negligible. In the third case, the ITS traffic is being scheduled for transmission according to the SPS rules that will be explained below, while the background traffic still uses dynamic scheduling which is the default scheduling in LTE. The ITS traffic still retains full priority over the background traffic, since the SPS reserves the resources for the ITS traffic, and the background traffic is allowed to use whatever resources are left over.

By default, LTE uses *dynamic scheduling* which means that the scheduling decisions are made every Transmission Tine Interval (TTI), which has a duration of 1 ms, for each packet transmission and for the possible retransmissions. Although this scheme provides full flexibility for optimizing resource allocation, which is very important in rapid time varying networks like vehicular networks, it also requires a lot of control overhead. Because each user is scheduled with control signaling, the control overhead may become a limiting factor for applications such as ITS and will result in a reduced traffic handling capacity. Moreover, the delay introduced to the total RTT of a packet by the scheduling request signal of the UE and the scheduling grant signal of the eNB is quite significant and is a big disadvantage for any time critical applications such as ITS. This is depicted in ***Figure 4.2*** below, where the LTE End-to-End delay is shown and the contribution of each step of the transmission path to this delay is given.

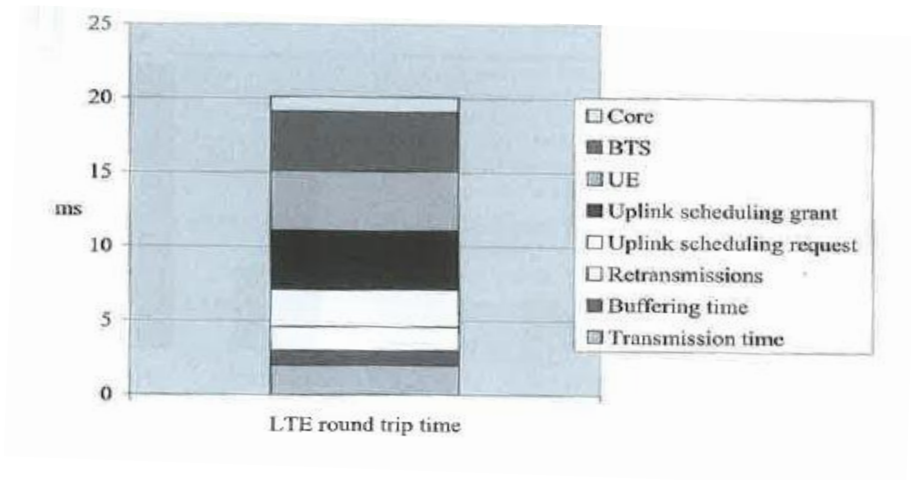


Figure 4.2: LTE Round Trip Time

Another scheduling scheme was designed for LTE, mainly keeping in mind the needs of the growing VoIP application. This scheduling scheme is called *Semi-Persistent Scheduling* (***SPS***) and can prove to be very useful for ITS networks too, because of the similarities with the VoIP application (small packet size, constant inter-arrival rate and stringent delay requirements).

The principle of semi-persistent scheduling includes two parts: persistent scheduling for initial transmissions and dynamic scheduling for retransmissions. At the beginning of each active period, the UE sends an uplink resource request to the eNB. On receiving the resource request, the eNB allocates a sequence of PRBs located with a certain periodicity between them, where the UE can send all its initial transmissions using a pre-assigned transport format. When needed, the eNB may reallocate different resources or reassign a different transport format to enable link adaptation. The allocation for initial transmissions is sent either on a control channel or in a MAC control Payload Data Unit (PDU). All the retransmissions are scheduled dynamically using the control channels. As illustrated in ***Figure 4.3*** below, all the colorized PRBs are allocated persistently for users' initial transmissions and PRBs in each color denote resources for one specific user. The remaining white PRBs can be used for all users' retransmissions or for other dynamic traffic flows by dynamic allocation. The persistent allocations (colorized PRBs) will repeat according to the periodicity until a new resource assignment is handed down by the scheduler or until a user becomes inactive and its resources are freed. The SPS is configured by higher layers like Radio Resource Control (RRC) and the periodicity is also signaled by RRC (the periodicity for VoIP applications is 20 ms). In this way the control channel capacity is no longer a problem for these applications since there is no need for control signaling for every single packet that needs to be transmitted. ***Figure 4.4*** depicts the difference between the two scheduling schemes and clearly show the gain in control signaling that is achieved by the use of SPS [2] [12].

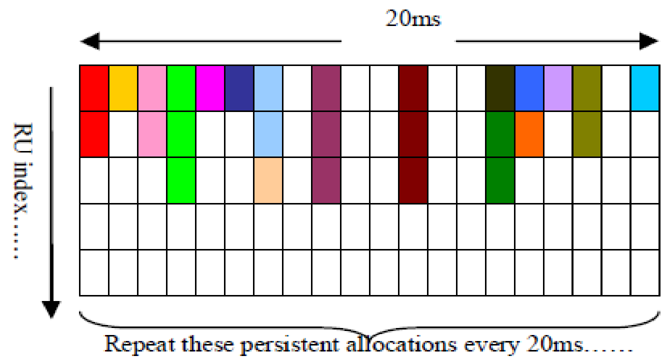


Figure 4.3: Semi-Persistent Scheduling

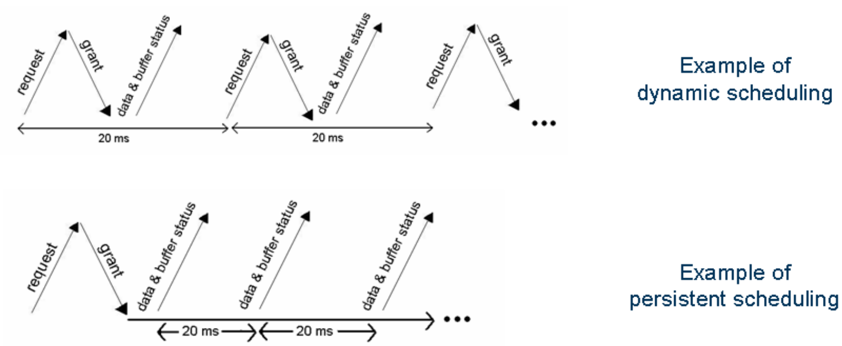


Figure 4.4: LTE scheduling schemes

In order to illustrate the benefits that can be gained by SPS we will examine the behavior of VoIP like applications in LTE, because of their similarity with ITS applications. The capacity of VoIP like applications in the LTE specification was examined with the use of simulators for three different codecs and for both dynamic and semi-persistent scheduling. The results were very conclusive. In the downlink channel, the performance of the dynamic scheduler is control channel limited and hence the SPS is able to show a significant capacity improvement in the order of ***50 %*** compared to the dynamic scheduler, in the case that the AMR 12.2 codec is used, which is the most common case. In the uplink channel, the performance of the dynamic scheduler is once again control channel limited whereas the SPS suffers much less from control channel limitation due to a looser control channel requirement. Therefore, the SPS is able to have ***14 %*** capacity gains over the dynamic scheduler in the AMR 12.2 codec case. The results of the simulations that show this huge improvement in capacity achieved with SPS are presented in ***Table 4.1*** below [2].

VoIP codec	AMR 5.9	AMR 7.95	AMR 12.2
Downlink capacity			
Dynamic scheduler, without bundling	210	210	210
Dynamic scheduler, with bundling	410	400	370
Semi-persistent scheduler	470	430	320
Uplink capacity			
Dynamic scheduler	230	230	210
Semi-persistent scheduler	410	320	240

Table 4.1: VoIP capacity in number of users for LTE at 5 MHz

Another general advantage that is gained by using Semi-Persistent Scheduling is that the upload transmission delay is decreased since the UEs don't have to perform random access any time they are not connected to the eNB and they want to transmit a packet, and thus they avoid the random access delay. Also there is a latency gain by the fact that the UEs will have to perform fewer transitions from idle to connected state (100 ms delay) since the scheduler will keep a UE in the connected state as long as there is no certain idle time. The periodical beacon transmissions from the vehicles participating in a vehicular network will likely keep the UE connected to the eNB, but as mentioned before, the transition delay is not taken into account in our model, not even for the background traffic [4]. In any case, the effect of the transition delay on the system's performance is negligible, since it only occurs once when the UE transits to the connected state.

From the facts presented above, we see that the main advantage of SPS is that it needs much less control signaling overhead than the dynamic scheduling and thus more of the available resources are used for data transmission, making SPS more efficient in that sense. The exact gain of SPS depends on various system parameters and implementation choices, so it is hard to define an exact percentage of gain for the simulations. The percentage of resources used for control signaling in every scheduling interval depends on many factors, such as the number of users using SPS, the number of users using dynamic scheduling, the scheduling interval used in SPS, the frequency with which the dynamic scheduler assigns resources, etc. The Cumulative Distribution Function (CDF) of the resources used for control signaling per TTI in the LTE UL, is another good indication of the advantages gained by SPS. This CDF is shown if ***Figure 4.5*** below [2].

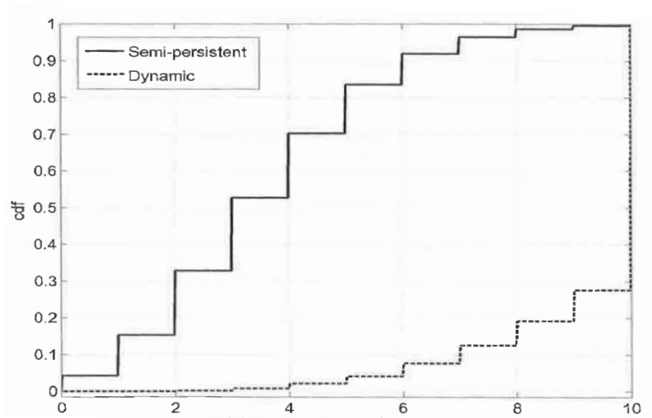


Figure 4.5: CDF of N^o of PRBs used for control signaling per TTI

Figure 4.5 clearly depicts that SPS needs much less resources for control signaling than dynamic scheduling. By observing the above graph, we can calculate the ratio of PRBs used for control signaling and PRBs used for data transmission in the LTE UL for the two scheduling schemes, and compare them in order to calculate the gain that SPS offers in control signaling overhead. This estimation shows that SPS uses 20 – 25% of the total control signaling resources that dynamic scheduling uses. Further literature research ([1] and [2]) shows that dynamic scheduling uses more or less, 16% of the total available resources for control signaling (8 resource blocks for control signaling from the total of 50 resource blocks per scheduling interval). The combination of the two facts presented above, motivates us to model SPS in order to use as little as 4% of the available resources for control signaling, which means that the remaining 96% will be available for useful data transmission. Recall that we assume 50 resource blocks per scheduling interval because we have chosen to implement the LTE standard for the 10 MHz bandwidth. Should another bandwidth be used, then the number of available PRBs, changes accordingly.

Although there are more factors affecting the performance of SPS, and therefore the control signaling gain, for the purposes of this simulator we have chosen to implement the above presented scheme so that the only factor that affects the SPS control signaling gain is the number of ITS users in the network. In the case that the ITS users (vehicles) use SPS while the background traffic uses dynamic scheduling, the more ITS users there are in the network, the more obvious the advantages of SPS will become. That is based on the principal of SPS, that there is no need for control signaling for every transmission since the necessary resources have already been assigned. On the other hand, the users that use dynamic scheduling need to communicate with the eNB every time that they want to transmit in order to get the necessary resources. As a consequence, when the number of users in a network that use SPS increases, the number of resources that are needed for control signaling decreases (as opposed to the case that every user uses dynamic scheduling). In other words, the ratio of ITS traffic vs background traffic directly affects the control signaling gain obtained by the use of SPS and translates into increased handling capacity.

A disadvantage of SPS is the slow adaptivity to the channel changes and the environment of the network. While dynamic scheduling occurs on a per *millisecond* basis and is always very well adjusted to the circumstances of the channel, the SPS occurs on a basis of a few seconds at a time and the users maintain the same PRBs and transport format throughout this period, until they are reassigned new PRBs and transport format by the semi-persistent scheduler. In this period of a few seconds, the channel may have changed dramatically, especially in the case of environments with severe shadowing or multipath fading, and as a result the resource allocation may no longer be appropriate and it can lead to a great number of block errors or a waste of resources.

The main reason for the beacon losses due to SPS' bad adaptation to the channel, is the fact that at the moment of resource allocation, each node has specific needs in resources in order to transmit its beacon, depending on the distance from the eNB and the SINR it experiences. The semi-persistent scheduler assigns to each node exactly the number of PRBs it needs at the time. But because of the high mobility of the nodes, these needs change very fast. Especially in the case that a node moves away from the eNB, it will experience higher path loss, lower SINR and lower bit rate than it had at the moment of resource allocation. As a consequence, the PRBs that were assigned to this node are no longer enough for it to transmit its beacon and this results, into a failed beacon transmission, which will lead to a retransmission (see *Section 4.4.3*).

This problem can be tackled in two ways. The first one is to define a very small SPS period (in the order of 1 sec or even less) so that the changes in the channel during this period are not so severe and there is better adaptation to the channel. Of course, such a solution drastically decreases the control signaling gain that SPS offers, since its operational time scale gets closer to that of the dynamic scheduler's. Another disadvantage of this solution is that it doesn't entirely solve the channel adaptation problem of SPS, it just reduces its effects. Even with SPS periods as small as 0.5 sec, there are still a few beacons lost per user due to bad adaptation, which in some cases, such as ITS applications, can lead to degraded performance especially if the application has very low tolerance for lost beacons.

The other solution to tackle this problem is to accommodate in advance for the changes that may take place in the channel. That means that at the time of resource allocation, the semi-persistent scheduler assigns 1, 2 or even more PRBs to each user, than it actually needs. This redundancy in PRBs increases the chances that the users of the network will have enough resources to transmit their beacon even if the channel circumstances have changed from the time of resource allocation. Of course, as it can be imagined, this solution also means that the total capacity of the network is decreased, since the users of the network are assigned more resources than they actually need, most of the time. But in systems like ITS, if this redundancy scheme makes sure that there are no SPS losses, then it might be worth it.

Both of the above presented solutions are supported by our simulator. Unfortunately, there is no information about how many extra PRBs per user are necessary or what is the optimal SPS scheduling period for ITS applications. So, in order to find out, we will use the simulator and test the effects of different PRB allocations per user and different scheduling periods, on the performance of the system. From the results obtained from these simulations we will be able to decide and justify the most appropriate amount of extra PRBs per user in combination with an appropriate SPS period.

4.4.3 <u>Retransmission Scheme</u>

A retransmission scheme was implemented in order to simulate the block error rate of the network. In ITS, delayed or failed beacons is one of the major concerns which indicates the quality of the network. In LTE, packets are never really lost, but they are retransmitted, which affects the transmission time and the available resources significantly. That is why, a realistic retransmission scheme was necessary in order to make the model more accurate. A literature research in [1], [2] and [6] indicated that a retransmission ratio (or packet loss) of 1% for the ITS traffic and 10% for the background traffic was very realistic according to the specifications of the two applications. There is a trade-off between the packet loss or retransmission ratio and the experienced SINR and bit rate of the users. In order to accommodate for the lower loss percentage of the ITS users the SINR curve had to be adjusted to this lower loss percentage [1], which means that the ITS users will experience lower SINR (and consequently bit rate) but fewer losses than background traffic. In our model, after the SINR is calculated as explained in *Section 4.3*, 0.5 dB is subtracted from the SINR in order to accommodate for the lower loss (retransmission) ratio and as a consequence, the bit rate of each user is also slightly reduced Each time that a retransmission occurs, a retransmission penalty of *8 ms* is added to the RTT of the beacon and the necessary resources for the retransmission are reserved.

4.5 <u>Simulation Environment</u>

A simulator this complex includes a lot of system parameters. Some of them are constants, since their value has been predefined by the standard or for commercial purposes a specific value has been agreed upon, and some of them are variables. The variables comprise the input of the simulator, as they are the ones to decide which exact scenario is simulated. Moreover, they allow for precise control over the simulator, and testing for different outcomes depending on the needs of the research. The simulator was designed in such a way so that it offers easy access to some of the most important variables. The *Graphic User Interface* (GUI) of the simulator is shown below in ***Figure 4.6***.

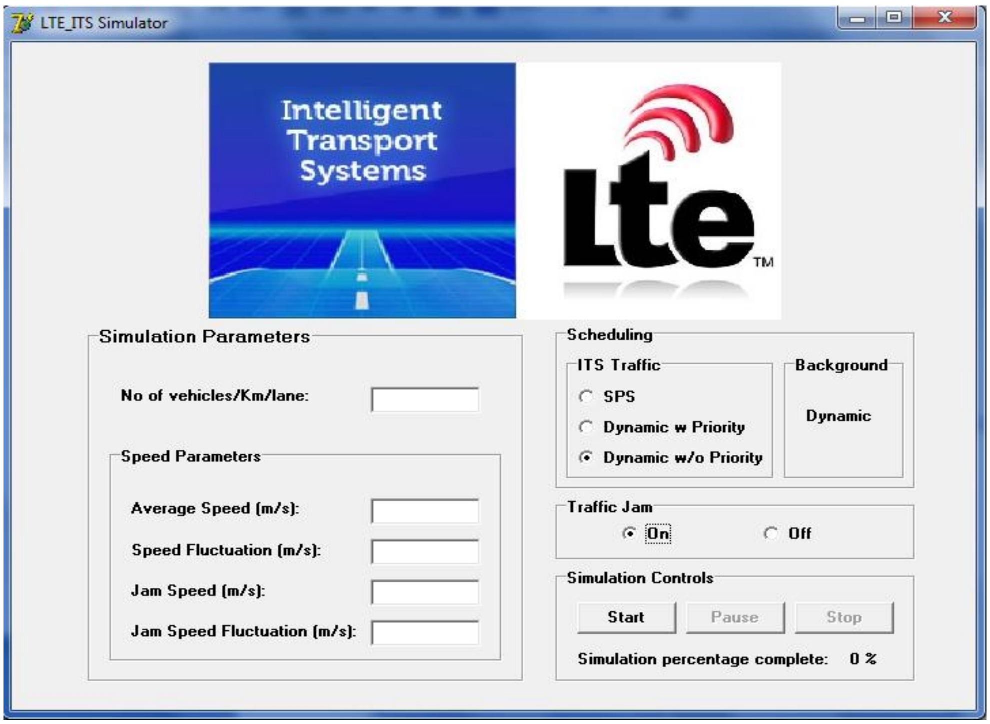


Figure 4.6: Simulator's Graphic User Interface

As we can see, the simulator offers immediate control over the most basic parameters such as the number of vehicles in the network, their velocity, the scheduling scheme used, etc., while there are a lot more variables that can be adjusted in the simulator's code. A full list of the system parameters is given in ***Appendix A***.

The simulation process is organized by an event calendar which contains four distinct events and which comprises the heart of the simulator. After the initial situation of the system has been defined as described above, the event calendar takes over, and the four events take place according to their individual timing and the values of the parameters of the network. These four events are:

- ***Road Network Update***: Every *100 ms* the position and speed of every vehicle in the network is being recalculated as well as all the other metrics that depend on them such as distance from eNB, path loss, SINR, attainable bit rate etc.

- ***Background Call Arrival***: This event is not periodic, as it depends on the random sampling of exponentially distributed inter-arrival times. The average arrival rate of the distribution is λ and it is user defined. When this event occurs, all of the necessary metrics are calculated (SINR, path loss, bit rate, etc.) and a new entry is made in the system buffer, awaiting for the assignment or resources for transmission.

- ***ITS Beacon Generation***: The periodicity of this event is also a system variable and is the same for every vehicle. The exact timing of beacon generation though, is different for every vehicle and depends on the initial random assignment. The most common values for beaconing frequency are 10 or 20 Hz. When this event occurs, the beacon enters the system buffer and awaits transmission and also at that moment it is sampled whether a retransmission will be needed for that specific beacon.

- ***Scheduling & Transmission***: This event occurs every *1 ms* in the dynamic scheduling case while its periodicity in the SPS case is a system variable. When this event occurs all the beacons and background data calls in the system buffer are scheduled for transmission and the available resources are shared among them according to the scheduling scheme used. When the scheduling is done, the users with resources assigned to them, transmit their data and the output measures are calculated (delay, block error rate, throughput etc.).

The reader should keep in mind, that because of the necessary simplifications that were made to the model and the aspects of the system that were not implemented at all (see *Sections 4.1 – 4.4*), the following results constitute an approximate evaluation of the system's performance. That means that, even though the results of the simulator are realistic, the actual performance of a real LTE network within the context of ITS, will be a little bit different but always within the same order of magnitude of the presented results.

5

Simulation Results & Analysis

In this chapter, we gather, analyze and compare the results of the simulations, in order to draw some useful conclusions about the use of LTE in ITS. Because of the extended number of simulation runs, the volume of the produced results was quite big, and so it would be confusing to present all the results tables and graphs in this chapter. That is why, only the most important results and graphs are presented in this chapter, but a full list of the results and graphs that were produced during the simulation runs, are presented in ***Appendix B***. In *Section 5.1* the experimental setup used for the measurements is presented as well as the performance metrics that were outputted by the simulator while in *Section 5.2* the performance of LTE is evaluated in terms of beacon delay and system capacity. In *Section 5.3* the behavior of the system to the variation of the network's parameters is examined and in *Section 5.4* the performance of LTE under different scheduling schemes is evaluated. Finally, in *Section 5.5* the performance of LTE in the context of ITS is compared to the performance of 802.11p and the suitability of the two standards for vehicular communication is evaluated.

5.1 Experimental Setup

In order to fully understand the potential and capabilities of the LTE standard, and to get a full image of its performance in ITS applications, the simulation runs were divided into three distinct experiments, each one aiming to evaluate a different aspect of the system. The three simulation experiments and their goals are presented below.

- ***LTE Performance Evaluation***: In this phase of simulation runs, only one scheduling scheme is used (Dynamic Scheduling - Fair sharing) and the values of all the variables are kept fixed, except for one which is the variable under consideration. In this way we will be able to evaluate the performance of LTE from the results that will be produced and the exact effect that each variable has on the system will be explored. The variables under examination in this phase are: *Number of vehicles, average velocity of vehicles,* *beacon size, beacon frequency, background call size & arrival rate (λ)* and *cell range*. At the end of this phase, we should have a pretty good understanding of the performance of LTE in ITS scenarios and a good knowledge of its behavior in response to the changes of the network's parameters.

- ***Scheduling Schemes Evaluation***: In this phase of simulation runs, all the values of the parameters remain the same throughout the simulation runs, and the three scheduling schemes that were described in *Section 4.4.2* are used. Also, different simulations will be carried out for the case of SPS with different values for the SPS properties (SPS period, number of extra PRBs). At the end of this phase, we should have a good understanding of the advantages and disadvantages of every scheduling scheme, as well as which scheme is more suitable for use in ITS applications. Also, the most suitable values for the SPS properties should be found and justified.

- ***Comparison with 802.11p***: The goal of this phase is to carry out simulations under similar circumstances and with the same values for the network's parameters, as the ones used to evaluate the performance of 802.11p standard in [13]. In this way the results generated by the LTE simulator will be directly comparable with the results obtained in [13] and very useful conclusions can be drawn, concerning the relative performance of the two standards in ITS applications.

It must be noted that every single simulation carried out in these three experiments, was repeated four times with four different random seeds, and the mean of these four runs was taken as the final result of that simulation, in order to enhance statistical accuracy. In order to increase our confidence in the measurements, the variance of the separate measurements was calculated as well as the 95% confidence interval compared to the average value of the beacon delays and background throughput that were measured with different random seeds. Naturally, because of the large number of simulation runs, the confidence interval varies a bit between measurements for different simulation scenarios, but always remains within satisfying levels. For all the results that are shown in this chapter, the 95% confidence interval is smaller than 1% - 5% of the displayed mean value.

5.1.1 Performance metrics

One of the most important aspects of the simulator's design is the output that it produces, since the output data are the ones that will help us draw the conclusions and understand the behavior of the system. This simulator outputs a variety of performance metrics, each one with a specific purpose and each one helping us understand a different aspect of the system. The different performance metrics are presented below:

- ***End-to-End beacon delay***: This is the most important indication of the system's ability to support ITS applications. The delay of each beacon transmitted in the network is measured and an average beacon delay per user is calculated as well as the average beacon delay for the whole network.

- ***Percentage of beacons that meet ITS criteria***: The number of beacons that were delivered successfully within the ITS timing requirements is measured. Two thresholds are taken into account for the different ITS requirements (50 ms and 100 ms) and the probability that a beacon will be delivered successfully within those thresholds is calculated. By setting this threshold according to the ITS applications requirements, we can test which applications can be served by the system with adequate quality.

- ***Total Load on the network***: This performance metric outputs the percentage of the network's available resources that are being used both for data transmission and for signaling. By definition, this metric can never have a value above 100%. This metric must not be confused with the offered load to the network by the ITS or the background traffic which in cases, can be more than 100% of the network's capacity.

- ***Control signaling load***: This metric measures the percentage of the available resources that is being used for control signaling purposes and not for data transmission.

- ***Cumulative Distribution Function (CDF) of the beacons delay***: The CDF of the beacons delay is calculated by measuring the transmission time of every single beacon transmitted in the network. The number of beacons that experienced the same delay is calculated and the CDF is produced. This metric helps us understand the distribution and variation of delay between the different beacons.

- ***Background traffic throughput***: The throughput of every background call in the system is calculated by dividing the call size with the transmission time of the call. The average value of these measurements gives us the average throughput of the background traffic.

- ***Background traffic QoS***: In order to have a quality metric regarding the background traffic, the number of background calls that experience throughput below a certain threshold was measured. These thresholds were chosen to be 1000, 500 and 100 kbps, and in that way we can predict the probability of a background call receiving certain QoS. This metric in combination with the mean experienced background throughput will give us a good impression of the background traffic behavior.

It must be noted that there was no warm up period implemented before the gathering of our results. This is due to the small background load implemented in our measurements. Because the background load is so small and the number of ITS users per simulation doesn't change, the system buffer is at balance right from the beginning of the simulation. At any point in time, there is at most 1 background call in the buffer, being served, and the number of ITS users being served is constant.

5.2 LTE Performance in ITS

In this section we will attempt to establish whether the LTE performance is satisfactory for ITS applications. In other words, we will discover if LTE can meet the strict ITS requirements that have been put forth, while at the same time maintaining an acceptable level of Quality of Service for the regular LTE users (background traffic). The parameters values that are shown in ***Table 5.1***, were used throughout the simulations presented in this section, unless specifically mentioned otherwise.

Parameter	*Value*	*Parameter*	*Value*
N° of lanes	4	**Beaconing frequency**	10 Hz
Road-length	2000 m	**Beacon size**	100 Bytes
Cell radius	1000 m	**Average Speed**	30 m/s
Height of eNB	30 m	**Speed fluctuation**	6 m/s
N° of Bck Calls arrived	3600	**Simulated time**	1800 sec
Bck call arrival (λ)	2 / sec	**Avg Bck call size**	800 kbits

Table 5.1: Parameter values for LTE performance evaluation

5.2.1 Beacon Delay & Capacity

As mentioned before, ITS applications are time critical applications and that is why the most important performance measure concerning the ITS applications is the End-to-End beacon delay. For most ITS applications the time boundary that the beacon delay has to meet is somewhere between 50 and 100 ms (*see Section 2.1.3*), but there are a couple of very demanding applications which need a beacon delay below 50 ms. According to the End to End beacon delay that LTE offers, we will be able to determine which applications can be supported by the standard.

The beacon delay depends on many parameters of the network, but most of them have a fixed value when the network is operating. The parameter that really affects the beacon delay and can change in real time is the network load, which is why it was decided to test the resulting beacon delays against different offered loads to the network. In that way, the capacity of the network is also tested. The easiest way to modify the network load is by modifying the number of users that are being served by the network. During the simulations phase, a number of simulation runs were carried out for different numbers of ITS users and the mean beacon delay of the vehicles was measured. The scheduling scheme used in this experiment is Dynamic scheduling with the same priority for both ITS and background traffic, meaning that all the users of the system are served in a round robin manner, and the results are presented in ***Table 5.2*** below.

N° of vehicles in the network	*Load on the network*	*Mean Beacon Delay (ms)*	*Probability T_{beacon} > 50 ms*	*Probability T_{beacon} > 100 ms*
40	35%	18.4	0	0
120	42%	18.4	0	0
240	53%	18.3	0	0
360	62%	18.4	0	0
480	72%	18.4	0	0
600	83%	18.5	0	0
720	92%	19	0	0
768	97%	47	0.149	0.005

Table 5.2: LTE measurements for Beaconing Frequency = 10 Hz

In order to be able to fully appreciate the transition of the beacon delays in relevance to the network load and the change in the rest of the metrics it is useful to create graphs based on the above results. ***Figure 5.1*** below depicts the mean beacon delay experienced by the vehicles in the network, while ***Figure 5.2*** depicts the probability that a beacon will be delayed more than 50 or 100 ms respectively. Finally, ***Figure 5.3*** depicts the total load on the network in relevance to the number of ITS users (vehicles).

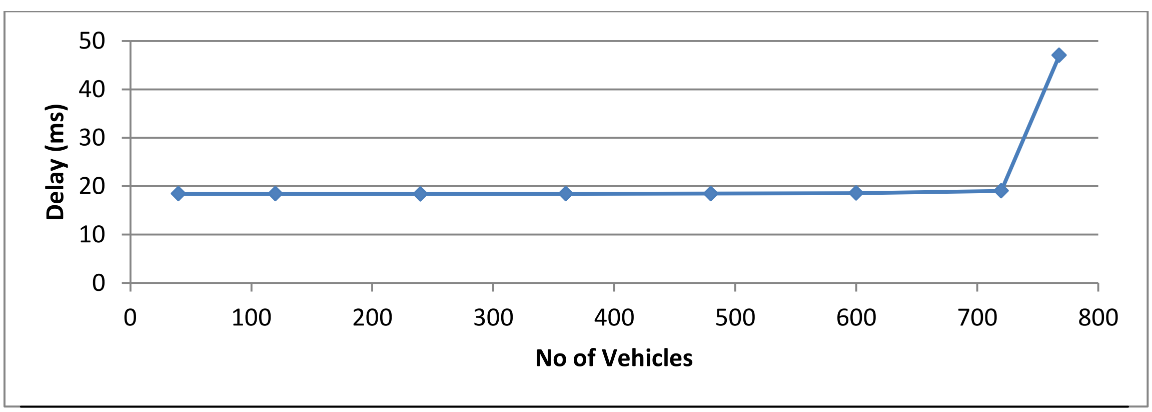


Figure 5.1: Mean beacon Delay vs N° of ITS users in the network

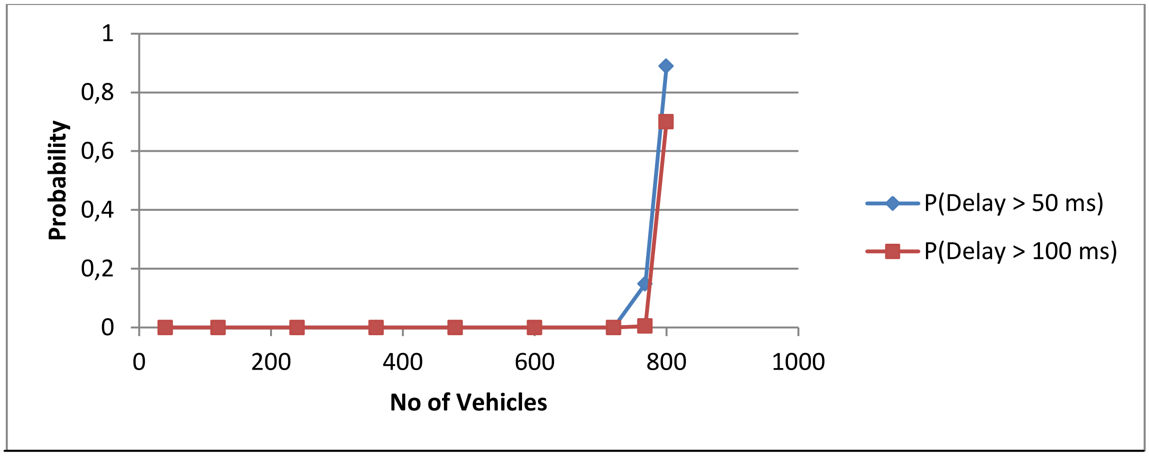


Figure 5.2: Probability that the experienced beacon delay will be higher than X ms

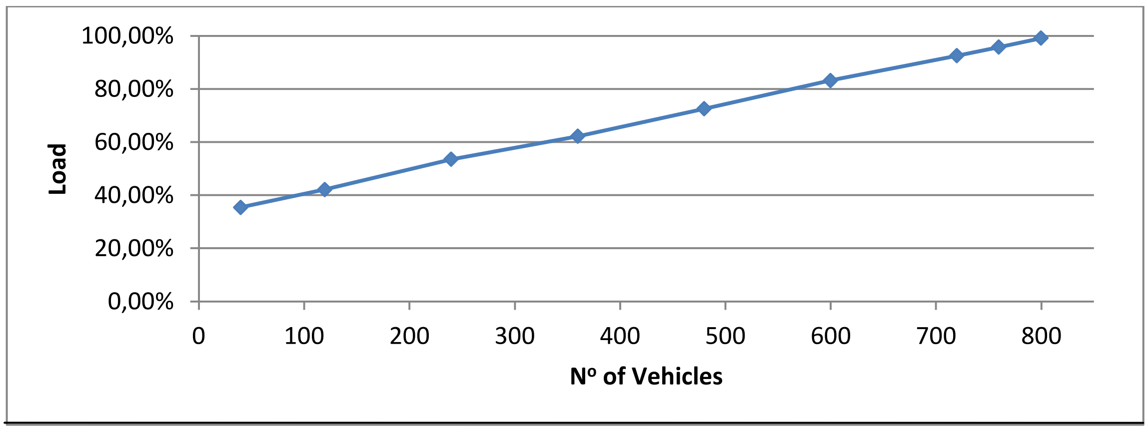


Figure 5.3: Total network load vs Nº of ITS users in the network

As we can see from the graphs above, the beacon delay offered by LTE is for the most part, well below the ITS imposed upper bounds. Under normal load conditions, the beacon delay is around 18 ms and it increases slightly as the load imposed on the network, increases. Even with a load as high as 95%, the beacon delay doesn't surpass 21 ms, but for any further increase of the load beyond 95% we observe that the performance of LTE degrades significantly, the beacon delay becomes very high and some of the beacons start to experience delays larger than the ITS application requirements. The above observations, mean, that LTE can easily serve ITS applications until its limit for capacity is reached. As the load of the network gets close to 100%, the performance of LTE degrades abruptly and can no longer serve the ITS applications. That happens, simply because there are no more resources in the 10 MHz bandwidth, to serve the increasing number of users.

Apart from the mean beacon delay it is important to know if any beacons were over the 50 or 100 ms boundaries that are defined for ITS applications, because even if the average beacon delay is satisfactory, there is always the chance that a few beacons were over these limits, which can prove fatal for some ITS applications. From ***Figure 5.2***, we can see that as long as the network load is below 92% the probability of a beacon exceeding those limits is zero. After that point, with any increase of the offered load, the probability of a delayed beacon increases even if the mean beacon delay is below 50 ms. The closer we get to the capacity limit of the network, this probability becomes very significant. These results show that LTE can be very trustworthy for beacon delivery within the necessary time limits, as long as the total load imposed on the network is not close to the network limit.

As far as the capacity of the system is concerned, the conclusions derived from the above graphs are very encouraging. The Background load was kept constant throughout these simulations at 2 background data calls per second, and a total of 3600 calls were completed during each simulation run. By consulting ***Figure 5.***3, we observe that the background load on the network amounts for about 32% of the total load (theoretical point on the Y axis when N^o of vehicles is zero) and it remains fixed at amount throughout the simulation runs. From that point on, the total load increases only with the increase of the ITS load (number of vehicles) and it is almost linear with the number of ITS users in the network. We observe that when the number of ITS users is significantly large, the ITS load amounts for the majority of the total load offered to the network. By taking into account ***Figures 5.1*** and ***5.2***, we can conclude that LTE can serve in a satisfactory way, close to 700 ITS users while at the same time it also serves the background traffic. For more users than that, the strict ITS requirements can no longer be fulfilled, but this number of ITS users is already very satisfactory. The effects of the increasing number of ITS users on the QoS of the background traffic will be examined in the next sub-section.

Due to the fact that some ITS applications, demand an increased beaconing frequency of *f = 20* Hz, it was deemed necessary to repeat the same simulations and find the beacon delays and the capacity of the system for the case of 20 Hz. All of the other parameters have the same values as before. The results of these simulation runs are presented below in ***Table 5.3***.

N^o of vehicles in the network	***Load on the network***	***Mean Beacon Delay (ms)***	***Mean Background Throughput (kbps)***
40	38,41%	18.3636	4078
80	45,73%	18.3349	3592
160	60,12%	18.4643	2670
240	73,95%	18.403	1803
320	87,18%	18.7946	974
360	94,04%	19.7652	523
384	98,05%	23.2538	102

Table 5.3: LTE measurements for beaconing Frequency = 20 Hz

In order to draw some useful conclusions from the above results and to be able to compare them with the results from the 10 Hz beaconing frequency case, the two set of results were plotted together in the graphs that are shown below. ***Figure 5.4*** depicts the mean beacon delay experienced in the network for the two cases of beaconing frequency, while ***Figure 5.5*** depicts the probability of a beacon exceeding the 50 and 100 ms time thresholds in the two cases.

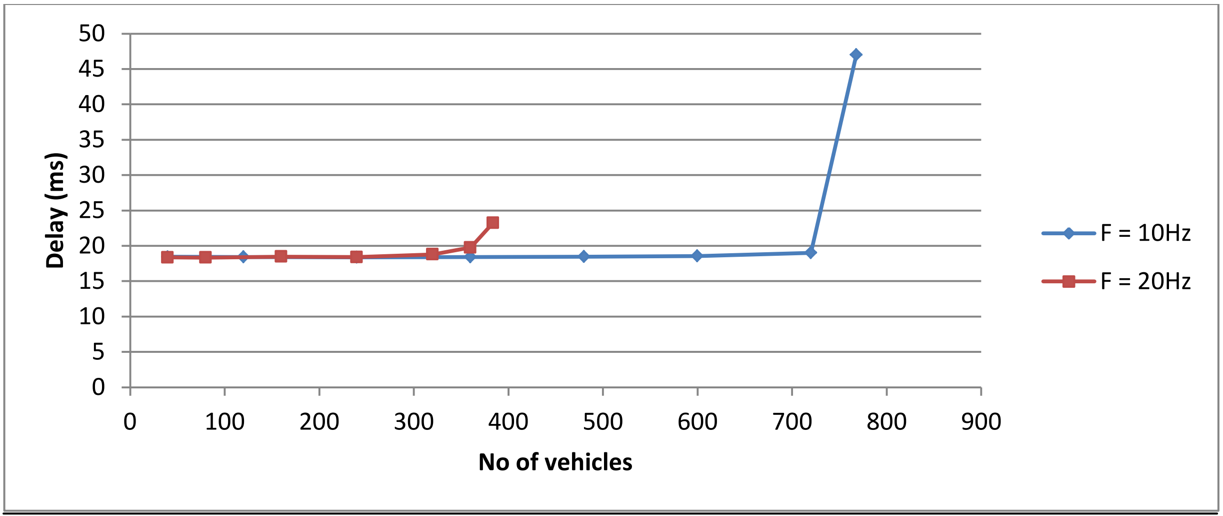


Figure 5.4: Comparison of mean beacon delays

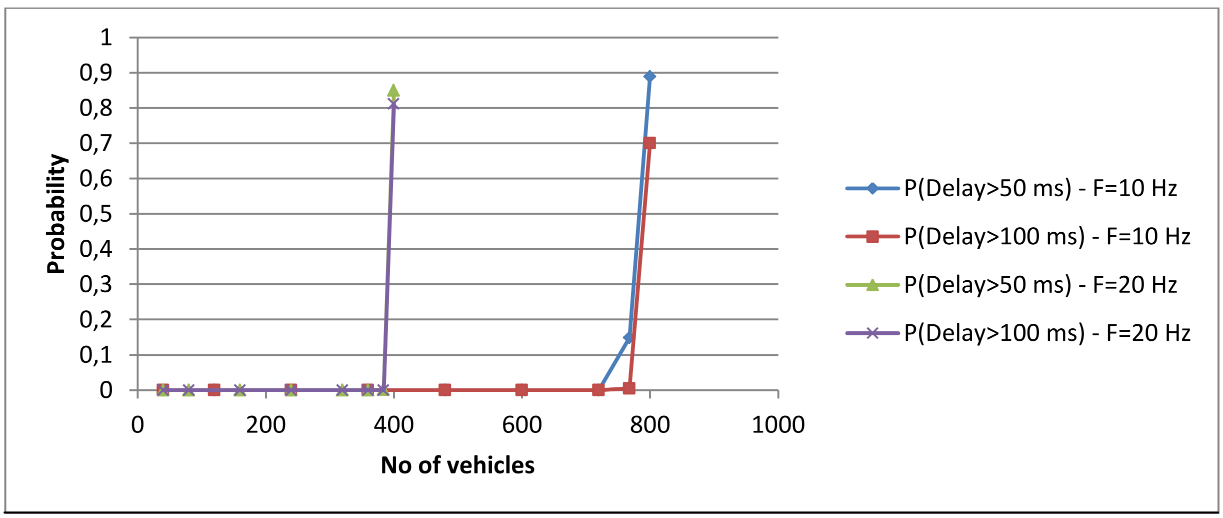
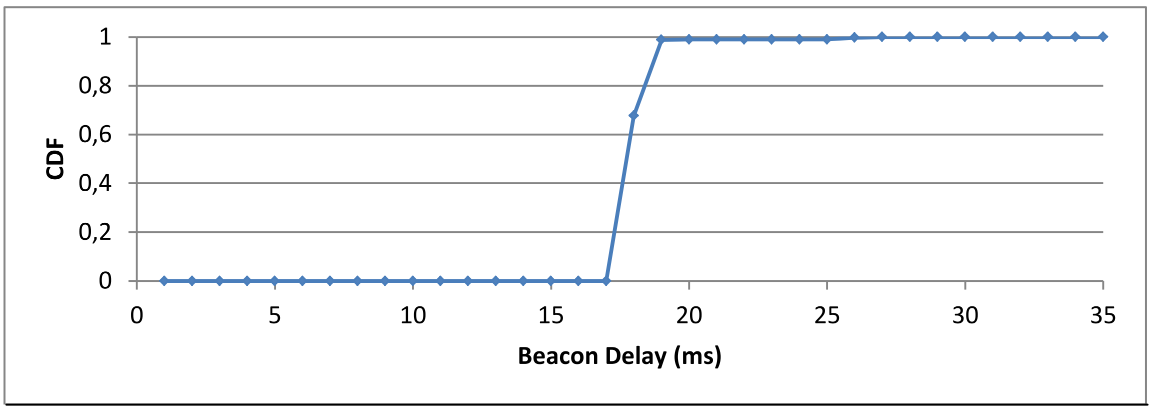


Figure 5.5: Comparison of probability of beacon delay > X ms

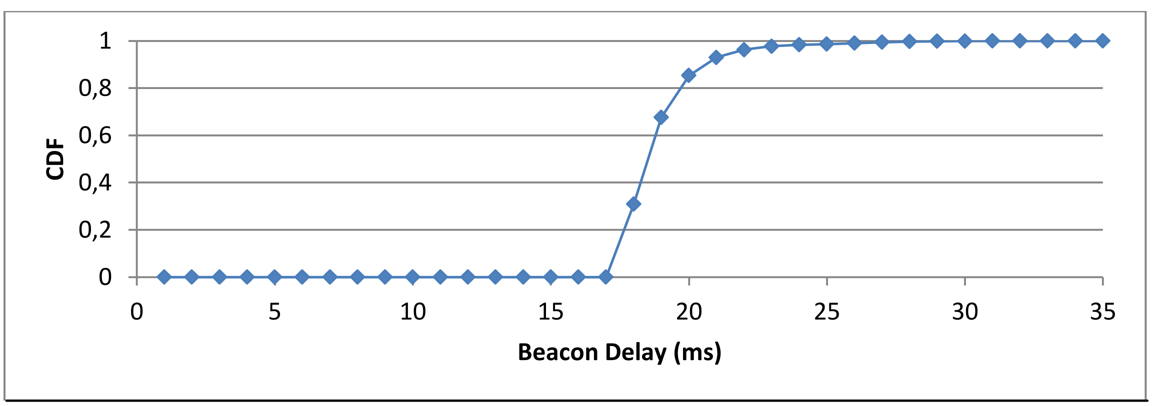
By observing the graphs that are presented above, we see that the behavior of the system is similar in both cases, but its capacity, in terms of number of vehicles supported, has significantly reduced in the case of the 20 Hz beaconing frequency. It is clearly shown that the network reaches its limits for a much smaller number of ITS users. This is of course very logical, since in the case of *f = 20* Hz, each vehicle sends out double the amount of information that it did in the case of *f= 10* Hz and since the ITS load is almost linear with the total load and capacity of the network, for a large number of ITS users, the capacity of the network is almost halved, as was expected. So, in the case of *f = 20* Hz, about 350 ITS users can be served satisfactory by the LTE network.

As far as the beacon delay is concerned, we see that it follows a similar behavior. As long as the network is not overloaded and operates below 94% of its capacity, the delays that are experienced in the network are in the order of 19 to 20 ms, which is a very satisfactory performance. When the number of users in the network (or the network load) becomes too big, then the performance of LTE drops quickly and the majority of the beacons no longer meet the strict ITS timing requirements.

In order to obtain a full understanding of the performance of LTE in ITS scenarios, especially when it comes to the beacon delays, it would be very useful to have more data about the beacons except for the mean beacon delay and the percentage of failed beacons (failed in terms of meeting the ITS requirements). That is why, after every simulation run the *Cumulative Distribution Function* (CDF) of the beacons delay was calculated. By examining the CDF along with the rest of the results, we will have a full image about the way that the beacons are distributed in the time domain and we will be able to determine whether the system can support specific ITS applications. ***Figure 5.6*** below, shows the CDFs of the beacon delays for the 10 and 20 Hz beaconing frequency cases and for an ITS load of 360 vehicles.



a) f = 10 Hz (360 vehicles)



b) f = 20 Hz (360 vehicles)

Figure 5.6: Beacon Delay CDF for a) f = 10 Hz and b) f = 20 Hz

__Figure 5.6__ above, confirms the previously made conclusions about the behavior of the system. It is clearly shown that in the case of *f= 10* Hz the system can handle the ITS users much easier since almost all of the beacons are delivered within less than 19 ms, while in the case of *f= 20* Hz, the increased load on the network causes some beacons to experience larger delays, but even so, all of the beacons experience a delay less than 27 ms which is well within the requirements of ITS. What is interesting to note is that no matter how little the load on the network is, no vehicle will ever experience a beacon delay less than 18 ms (see *Figure 5.1*). This is due to the transmission path that every beacon has to travel from the transmitter to the eNB and from there to the receiver (see *Section 4.1.1*). The UL transmission delay, the DL transmission delay, the core network delay, the processing delay etc. can never add up to less than a specific lower bound, which in this case is 18 ms, even if all the resources of the network are available.

5.2.2 Background Traffic Performance

In the previous section, we investigated the effect of the increase of ITS users on the latency of the ITS beacons and the total load on the network. Apart from that, it is very useful to examine the effect of the ITS users on the service of the background traffic, since this is also a very important aspect of the system. Even if the system meets the ITS requirements for the beacon delays, if it cannot support the background traffic at the same time, then its performance is not satisfactory and the ITS applications will not be supported by LTE. From the same simulations that were carried out in *Section 5.2.1*, we get the results that are shown in the following graphs for the case of *f = 10* Hz. *__Figure 5.7__* shows the mean throughput of the background data calls versus the number of ITS users in the network, while *__Figure 5.8__* shows the percentage of the arrived background calls that were served (and completed). Finally, in order to have a qualitative estimation of the background traffic, the probability of a background call being served with a throughput less than 100, 500 and 1000 kbps is shown in *__Figure 5.9__*.

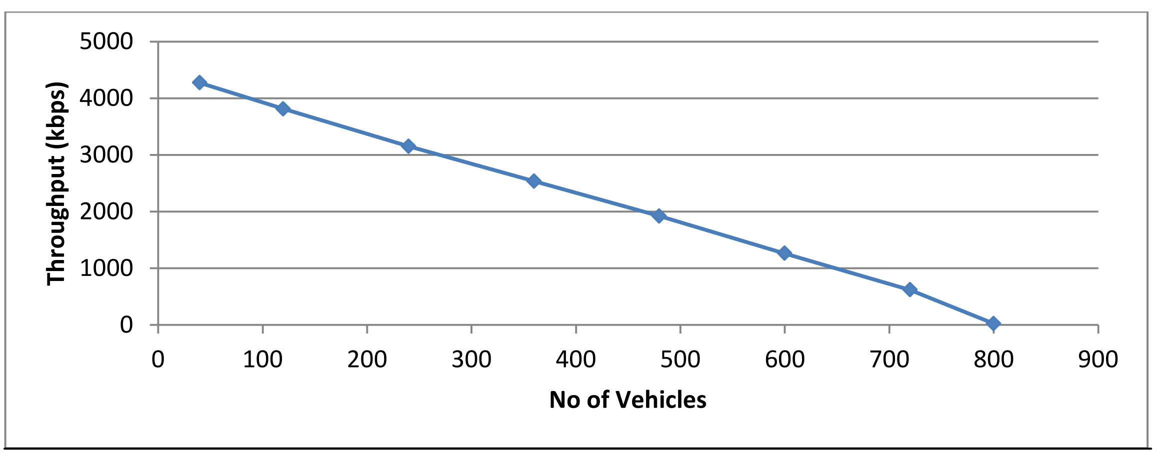


__Figure 5.7: Mean Throughput of background traffic for f = 10 Hz__

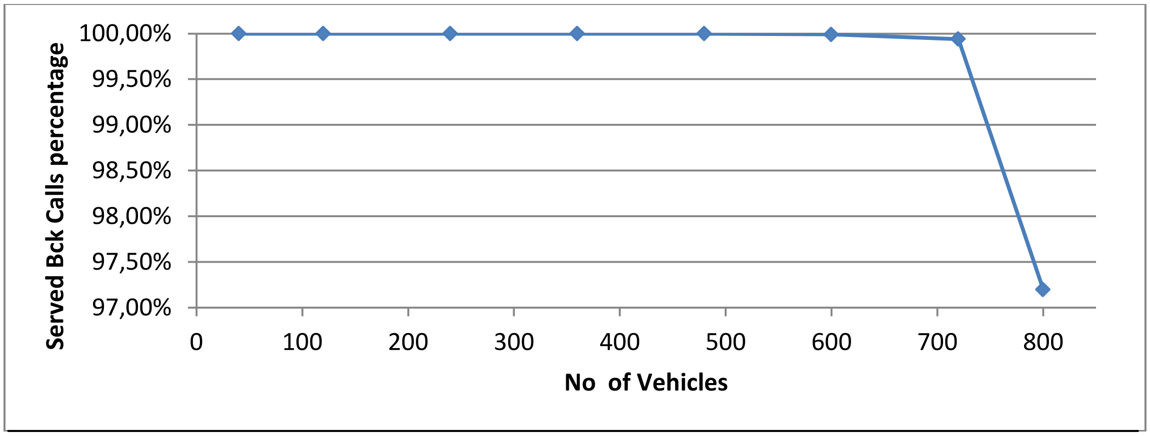


Figure 5.8: Percentage of served background traffic for f = 10 Hz

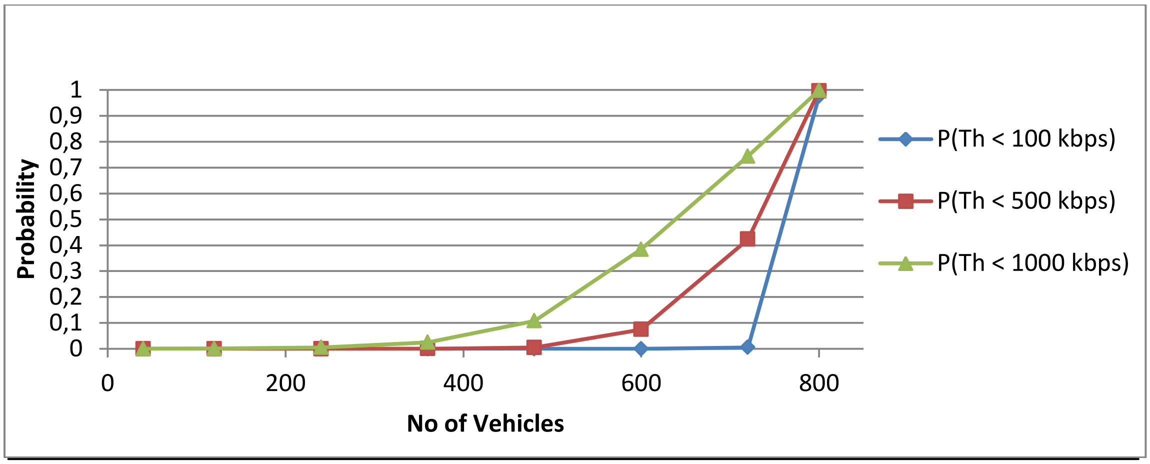


Figure 5.9: Probability of a background call Throughput < X kbps for f = 10 Hz

By observing the above graphs, we can see that as the number of the ITS users in the network increases (as does the load), the mean throughput of the background traffic drops significantly. Of course this was to be expected, since the increasing amount of ITS traffic, claims more resources from the network, and so, there are not enough resources to serve the background traffic. Additionally, we see that the background traffic service ratio does not drop significantly even for network loads higher than 90%. ***Figure 5.8*** can be misleading in that way, and can drive someone to the wrong conclusion, that even if the network is close to full capacity more than 97% of the background traffic will be served. This result has to do with the simulation parameters that were chosen. Because the average background data call that is being simulated has a size of around 800 kbits, which is the size of an average data call, the network can serve those calls very quickly because of LTE's high data rate. The average duration of such a call, under normal circumstances, is around 2 to 3 sec. In the case that the network is close to its full capacity, the call duration increases because of the reduced available resources, and reaches durations around 6 to 8 sec. But even so, the background call is completed because of the much longer simulation time which is 1800 sec. This fact, in combination with the fact that a very large number of background calls are simulated (around 3600), results in most of the calls being completed, except from the ones that arrived in the system a few seconds before the end of the simulation. That is why the percentage of served background calls is so high, even for an overloaded network.

A more representative graph about the background traffic, which will help us understand the system's behavior, is shown in ***Figure 5.9***. In that graph, we can see that the probability of a background call experiencing reduced Quality of Service (throughput), increases drastically with the increasing number of ITS users. This graph is very useful, because most of the applications used on a cellular network, have certain QoS requirements that have to be met at all times. Nevertheless, we can see that LTE's performance is still very satisfactory and it can accommodate for around 400 ITS users, while at the same time making sure that almost all the background data calls experience more than 1000 kbps of throughput.

It was not deemed necessary to also present the results for the $f = 20$ Hz case, since the behavior of the system is the same and the difference is the same as in the previous sub-section. That means that the curves on the graphs are similar, but the capacity of the system has been halved, thus accommodating for around 200 ITS users while ensuring a minimum throughput of 1000 kbps for the background traffic. The results for this case are given in ***Appendix B***, along with the results from all the simulation runs that were carried out.

Impact of varying background traffic

Apart from the above simulations, the behavior of the system was tested for an increased background traffic load (increased background call arrival rate and/or increased background call size). In this series of simulations the ITS load was kept fixed (360 ITS users, 10 Hz beaconing frequency, 100 Bytes beacon size) and the background load was varied in order to establish the service that ITS and background traffic receive in that case. ***Figure 5.10*** shows the experienced mean beacon delay in the system and ***Figure 5.11*** shows the probability of a beacon exceeding the 50 and 100 ms thresholds. As far as the background traffic is concerned, ***Figure 5.12*** shows the mean throughput experienced and ***Figure 5.13*** depicts the probability of a background call experiencing throughput less than 100, 500 and 1000 kbps respectively.

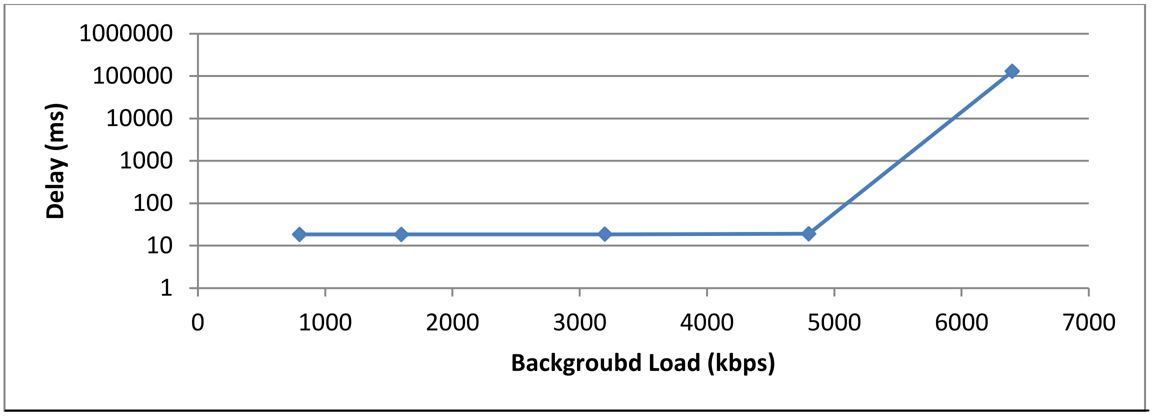


Figure 5.10: Mean beacon delay vs background load

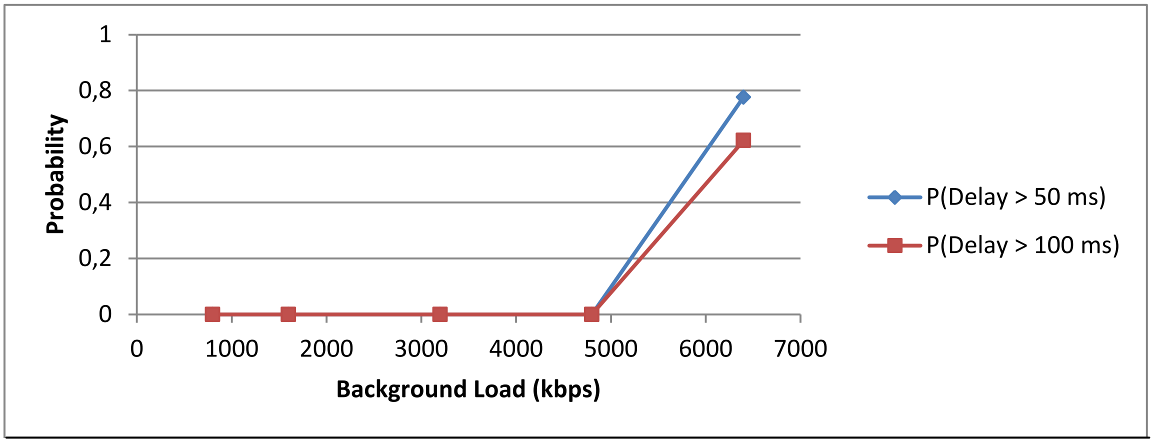


Figure 5.11: Probability that the experienced beacon delay will be higher than X ms

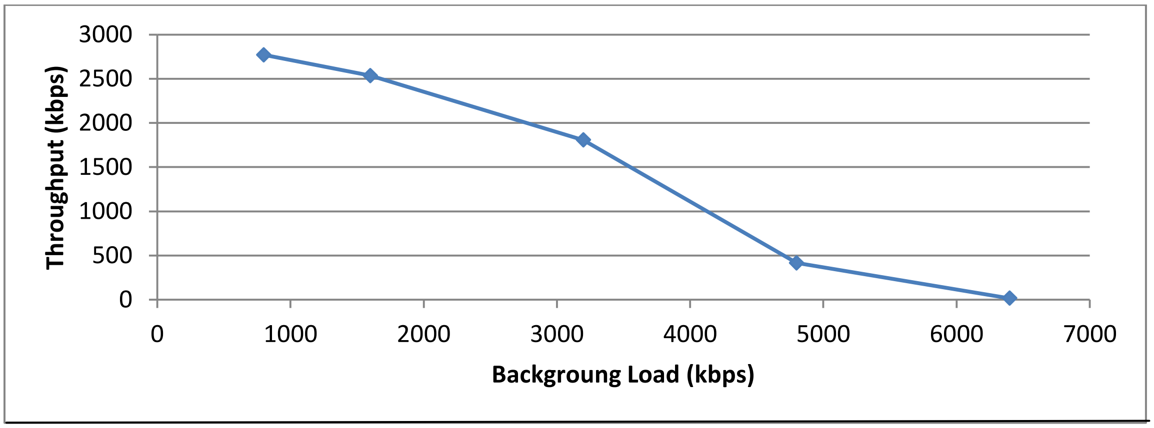


Figure 5.12: Mean background throughput vs background offered load

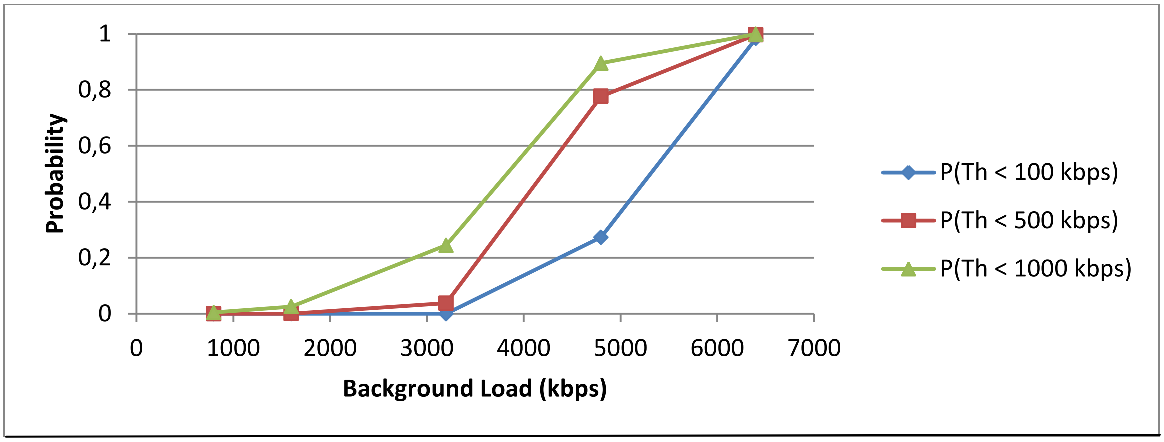


Figure 5.13: Probability of a background call Throughput < X kbps

From ***Figures 5.10*** and ***5.11*** we observe that the behavior of the system is similar with the previous cases. LTE maintains a steady and satisfactory performance (beacon delays below 20 ms and zero probability of failed beacons) for the ITS users, up until a certain point, where its performance degrades abruptly (the results in ***Figure 5.10*** are presented on a logarithmic scale). This point is always the network's capacity limit and in this case it is reached when the background offered load is around 5000 kbps. Beyond this point the beacon delay and the failure probability reach very high values and the ITS requirements are not met anymore. The analytical results for this experiment are presented in ***Appendix B***.

From ***Figures 5.12*** and ***5.13***, we see that the throughput and QoS that the background users experience drop fast with the increase of the offered background load. That was of course expected since after a certain point the available resources are no longer sufficient to serve all the background users with the appropriate quality. We can observe that after the offered background load has surpassed the 3000 kbps, the experience throughput drops extremely fast and the probability that a call will not receive sufficient throughput to accommodate for its QoS needs are increased drastically.

By studying the results and graphs that were presented in this section, we can calculate the ideal values for the network's parameters in order to get a satisfactory performance, depending on the focus of our network. Depending on the number of ITS users and background users in the network, we have a pretty clear image of the network's performance and behavior and its capacity limits which shouldn't be exceeded.

5.3 Parameters Impact on the System

In this section, we will evaluate the effect that the various network parameters have, on the network's performance. By keeping the values of all the parameters in the network fixed, and by varying only the value of the parameter under investigation, we can see how the network "reacts" to the change of every variable. The results of this series of simulations, will also prove helpful to determine the optimal values for the network's parameters, depending on the environment circumstances and the desired focus of the network (focus on ITS or background traffic). This section doesn't focus on the absolute performance of the system (beacon delays, capacity in terms of number of supported users) but rather on the relative impact that the variation of a parameter has, on the system's performance, as it was measured in *Section* 5.2.

5.3.1 Beaconing Load

Beaconing load refers to the combination of the beaconing frequency and the beacon size that is being used for the ITS applications. The beaconing load is actually the product of the beaconing frequency and the beacon size and it gives us the amount of data that an ITS user transmits into the network per second. Taking that into account, we arrive at the conclusion that these two parameters affect the network in the same way, since for instance, the doubling of the beaconing frequency or the doubling of the beacon size, both result in the doubling of the ITS load. Because of this similarity, the effect that these two parameters have on the network is identical and for that reason only one of them will be examined in this sub-section, but the results and conclusions that will be drawn are the same for the other one. Here, we will examine the effect of the beacon size, but the results for the beaconing frequency can be found in ***Appendix B*** with the rest of the simulation results.

For the previous simulations we have used a fixed value for the beacon size of 100 Bytes. In order to establish the behavior of LTE when the beaconing load changes, we varied the beacon size and the results of the simulations are presented in ***Table 5.4***. The probability that the beacon delay will be higher than 50 and 100 ms is plotted against the beacon size in ***Figure 5.14*** and the probability of the background throughput being less than specific thresholds, is shown in ***Figure 5.15***.

Beacon Size (Bytes)	Beaconing load / user (Bytes/s)	Load on the network	Mean Beacon Delay (ms)	Mean background Throughput (kbps)
50	1000	55.50%	16.7583	3012
100	2000	73.95%	18.4031	1803
150	3000	93.72%	20.9301	526
160	3200	96.67%	31.207	226
170	3400	99.20%	24884	44

Table 5.4: Simulation results for various beacon sizes

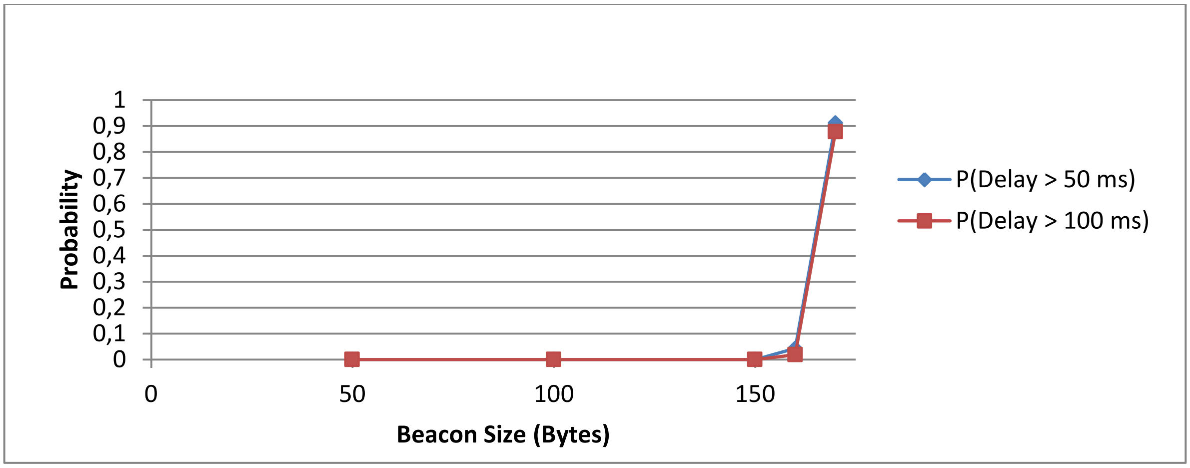


Figure 5.14: Probability that the experienced beacon delay will be higher than X ms

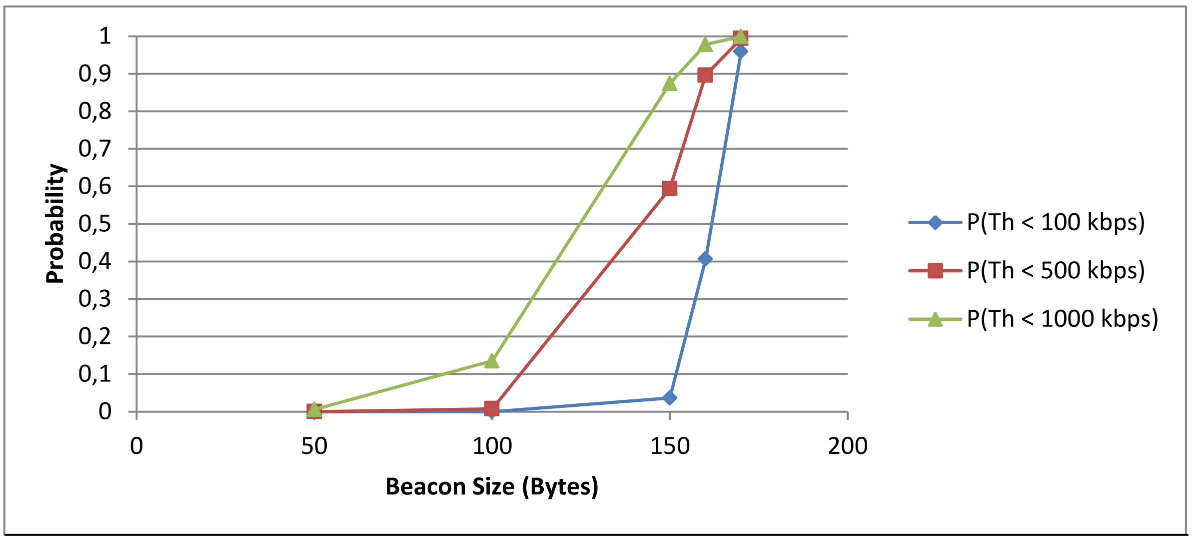


Figure 5.15: Probability of a background call Throughput < X kbps

From the results and graphs that are presented above, we can see that the beaconing load plays a very important role in the performance of the whole system. That can be justified by the fact that even a slight increase of the beacon size (or the beaconing frequency) leads to a significant increase of the total ITS load offered to the network, since the increased beaconing load is used by all the vehicles in the network. We can see that for a beaconing frequency of $f = 20$ Hz (which is the case simulated here) a beacon size greater than 120 Bytes, leads to significant decrease in the background experienced throughput and hence to a severe degradation of the QoS for the background traffic. Moreover, an increase of the beacon size beyond 160 Bytes, leads to extremely high beacon delays and an increased probability of failed beacons (see ***Table 5.4***), which means that the ITS requirements can no longer be met. Thankfully, a beacon size of 100 Bytes is sufficient for the vast majority of the ITS applications, and even if it's not, most ITS applications use a much lower beaconing frequency (usually 10 Hz) which would allow an increase to the beacon size without significantly degrading the performance of LTE.

5.3.2 Vehicle Velocity

As we mentioned in *Section 2.3.4*, the mobility of the nodes is an important factor in the LTE network. The high mobility that characterizes ITS networks was taken into account in our model by adjusting the throughput of the mobile users to their speed, according to the curves of ***Figure 2.8*** (*see Section 4.4 – equation 7*). The higher the velocity of a vehicle, the less bit rate it will be able to support, thus the experienced throughput will be decreased. It must be noted that the throughput that is reduced due to the velocity of the vehicles, is the throughput of the ITS users and not the background throughput, which has been used as a performance metric in this thesis. In this sub-section we will find out, the degree to which the high mobility of the nodes, affects the performance of the LTE network, by simulating under different vehicle velocities. The simulations were carried out for 240 ITS users (vehicles) in the network with a beaconing frequency of $f = 20$ Hz. ***Figure 5.16*** depicts the mean beacon delay experienced by the ITS users for different average velocities and ***Figure 5.17*** shows the effect of the average vehicle velocity on the background throughput (*attention*: not the ITS throughput which we actually reduce ourselves due to increasing velocity)

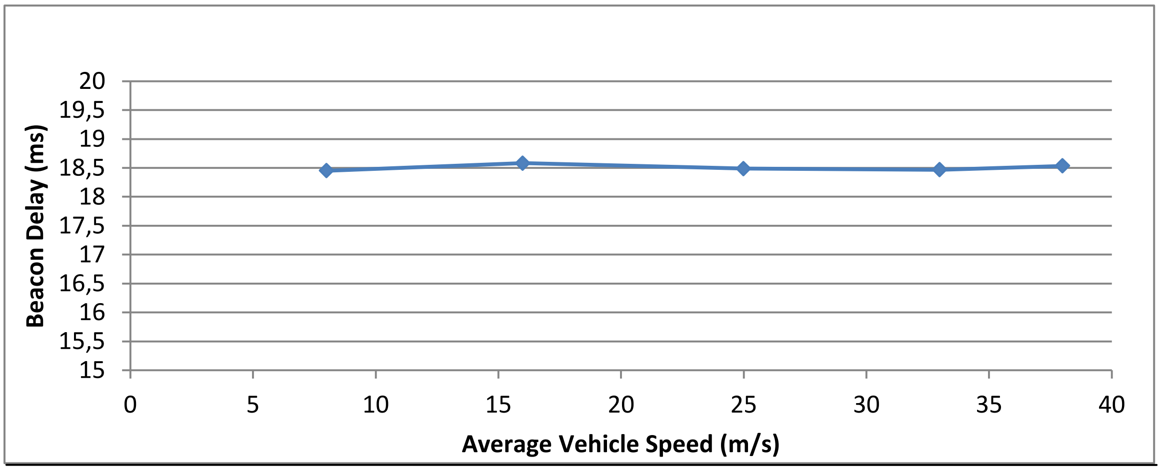


Figure 5.16: Mean beacon delay vs vehicle velocity

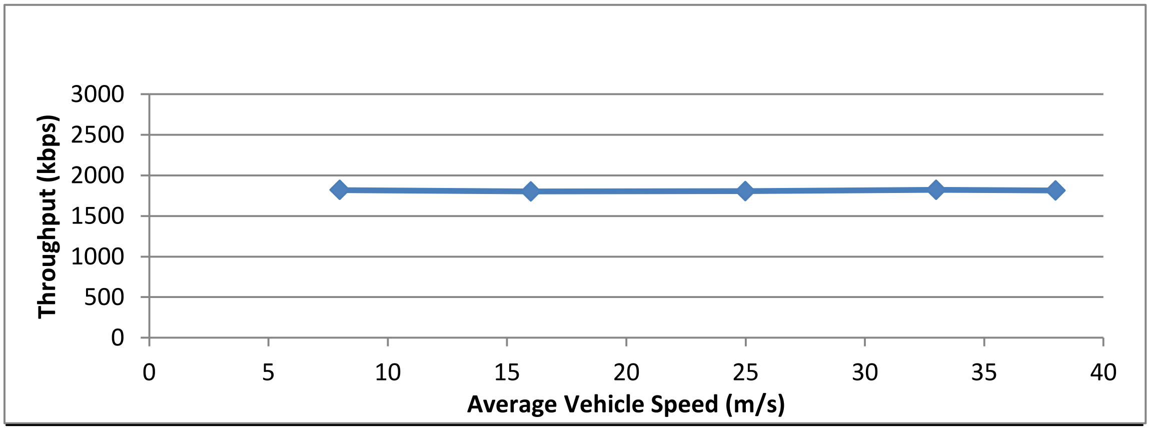


Figure 5.17: Mean background Throughput vs vehicle velocity

From the simulation results and the graphs that are presented above, we can immediately observe that the velocity of the vehicles, doesn't affect the performance of the LTE network as much as the other parameters do. The beacon delay of the ITS users is virtually unchanged, no matter the speed of the vehicles. That happens because, even though there is a decrease in the throughput of the ITS users due to the increased speed, that throughput is still more than enough to transmit their small sized beacons within the necessary time limits. The effect of the vehicles velocity has already been accounted for in our model, as explained in *Section 4.4*. The decrease in ITS throughput, would normally mean that the users would need more resources assigned to them in order to successfully transmit their beacon, but thanks to the innovative design of LTE, the decrease in throughput is very small, so there is no need for extra resources in order to transmit small packets like the ITS beacons. This is also obvious by the fact that the network load has remained almost unchanged throughout these simulation runs.

Figure 5.17 depicts the throughput of the background traffic and not the throughput of the ITS traffic (which is actually reduced). The background traffic is assumed to have very low mobility (pedestrians – up to 3 km/h) which is why there are no significant variations to it, throughout this simulation series. Perhaps, the effect of the vehicle's speed will become more apparent in an overloaded network where every single resource counts, but for a normal network load (which was simulated here), the effect of the speed is negligible. It must be noted, that in reality the vehicle velocity is expected to have a greater effect than this, on the performance of LTE, but it is not obvious from our results due to the simplifications that were made in our model (See *Chapter 4*).

5.3.3 <u>Cell Radius</u>

One very important parameter for the performance and efficiency of the network is the dimension of the LTE cell. Usually different cell sizes are used depending on the environment, the population, the structures and the QoS necessary in a specific area. For the ITS network, especially the rural environment case that we are examining, it is very important to find the ideal cell size, so as to accommodate as many users as possible while at the same time making sure that everyone meets their QoS requirements. Moreover, depending on the environment, an optimal cell size is very important for technical and financial reasons, since depending on the cell size, more or less cells are needed to cover the same geographical area, and more or less handovers have to be performed. In order to find an optimal cell size for our simulation scenario, a series of simulation runs were carried out, simulating different cell sizes (variation of the cell radius). During those simulations, the offered ITS load to the network remained the same, by maintaining the same number of ITS users and the same beaconing load in the network (*480 ITS users, f =10 Hz, Size = 100 Bytes*) and the offered background load was kept also fixed by maintaining the same inter-arrival rate for the background calls (2 calls/sec). ***Table 5.6*** presents the results of the simulation runs, which are also depicted in the following figures***. Figure 5.18*** shows the probability that a beacon will take more than 50 or 100 ms to be delivered and ***Figure 5.19*** shows the probability that a background call will experience throughput less than 100, 500 and 1000 kbps respectively.

Cell Radius (m)	***Network Resources Used***	***Mean Beacon Delay (ms)***	***Mean background Throughput (kbps)***
500	60,73%	17,4788	3352
1000	72,54%	18,4594	1920
1500	84,65%	19,473	987
2000	87,11%	23,6284	278
2225	99,11%	2585	20

Table 5.5: Simulation results for various LTE cell sizes

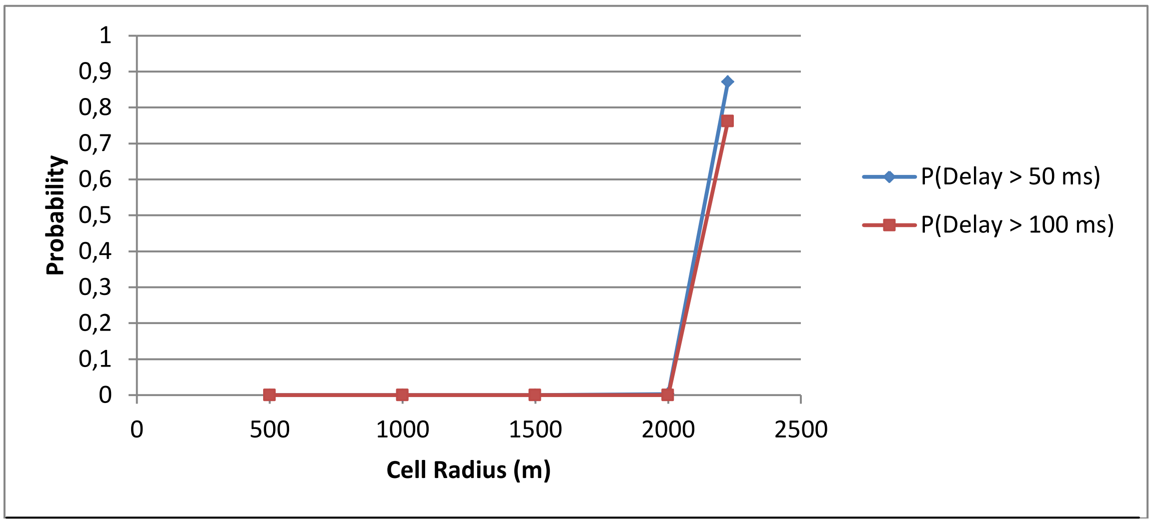


Figure 5.18: Probability that the experienced beacon delay will be higher than X ms

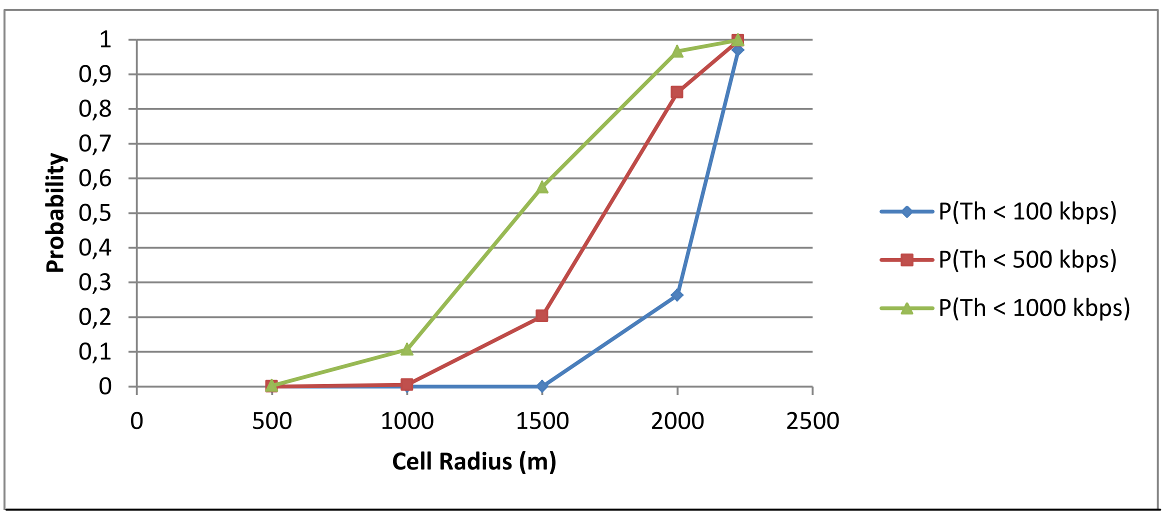


Figure 5.19: Probability of a background call Throughput < X kbps

As we can see from the results and the graphs that are presented above, the variation of the cell size has a significant impact on the performance and behavior of the LTE network. As the cell radius becomes larger than 2000 m (cell diameter of 4 km) the load on the network reaches its full capacity, and the ITS users can no longer be successfully served, since the beacon delay and the beacon failures (number of beacons over the 50 and 100 ms time threshold) become extremely large. The effect that the variation of the cell radius has on the background traffic is more or less the same. As the cell radius increases, the throughput experienced by the background users decreases drastically, and especially after the 2000 m mark, the service provided is unacceptable, since almost all of the background calls, experience extremely low throughput.

The above behavior of the LTE network can be explained by considering the role that the distance between eNB and UE, plays in a cellular network. As the cell radius increases, the average distance of the vehicles from the eNB increases accordingly. That means that the vehicles experience much greater path loss, which leads to decreased SINR and consequently to a decreased bit-rate. A decreased bit-rate means that a user can send a decreased amount of information per time unit, or that in order to send the same amount of information it will need more resources. As the bit-rate of the ITS users gets extremely low due to the increased distance from the eNB, they need more and more resources in order to transmit their beacons. When that happens, the limited amount of available resources leads to extremely high beacon delays and consequently beacon failures, and since the background users compete for the same resources with the ITS users, it leads to significantly reduced throughput for the background users, since there are no available resources. The need for more resources by the users as the cell radius increases also means that the capacity of the system decreases and can accommodate for a reduced number of users, since the increased need for resources from users far away from the eNB, leads to shortage of available resources.

5.4 Scheduling Schemes Performance

As mentioned before, there are a number of different scheduling schemes and a number of different ways to combine them. The three combinations of scheduling schemes that were implemented in our simulator were mentioned in *Section 4.4.2*, and in this section the performance and behavior of these scheduling schemes will be evaluated. Through this examination of the different scheduling schemes, we hope to find which one is more suited for use in ITS networks by offering the best possible service to the ITS users, while at the same time maintains a satisfactory performance for the background traffic. Before, evaluating the performance of the schemes, the details for the implementation of SPS must be set and particularly the values of the properties that will help us tackle the problem of failed beacons due to the bad adaptation to the channel of SPS, as described in *Section 4.4.2*. In the following sub-sections, the optimal values for the properties of the Semi-Persistent Scheduling will be decided and its performance with these values will be evaluated and compared to the other scheduling schemes.

5.4.1 SPS Properties

In order to tackle the SPS losses problem we have to find the appropriate values for the SPS resource assignment period and the redundancy of the PRBs assigned to the users. The trade off of the SPS period is that if it is too small then the advantages of SPS in control signaling will not be apparent and if it is too big then there will be a lot of failed beacons because of the slow adaptation of the scheduling scheme to the channel. At the same time, if the redundancy used is too large, then the capacity of the system will be significantly reduced and the number of ITS users that will be able to be served will be also reduced. In order to find the most appropriate values that will lead to the most efficient use of the SPS scheme a series of simulation runs were carried out for different values of the SPS period and extra PRBs. The results are presented in ***Table 5.6***, while ***Figure 5.20*** depicts the percentage of lost beacons per ITS user (lost in the sense that there were not enough PRBs assigned to the user due to bad adaptation to the channel of SPS) in relation to the SPS period and the amount of extra PRBs used and ***Figure 5.21*** shows the percentage of the system's resources that are being used for different amounts of extra PRBs.

	Extra PRBs = 0		Extra PRBs = 1		Extra PRBs = 2	
SPS Period (sec)	Avg Lost Beacons/vehicle	Total Load	Avg Lost Beacons/vehicle	Total Load	Avg Lost Beacons/vehicle	Total Load
1	1.38%	58.82%	0.00%	66.03%	0.00%	71.23%
5	6.34%	58.63%	0.00%	65.87%	0.00%	71.33%
10	11.69%	58.92%	0.006%	65.98%	0.00%	71.27%
20	20.90%	58.33%	0.92%	65.56%	0.0018%	70.95%
30	27.24%	58.62%	3.62%	66.10%	0.0669%	71.15%

Table 5.6: Simulation results for different SPS properties

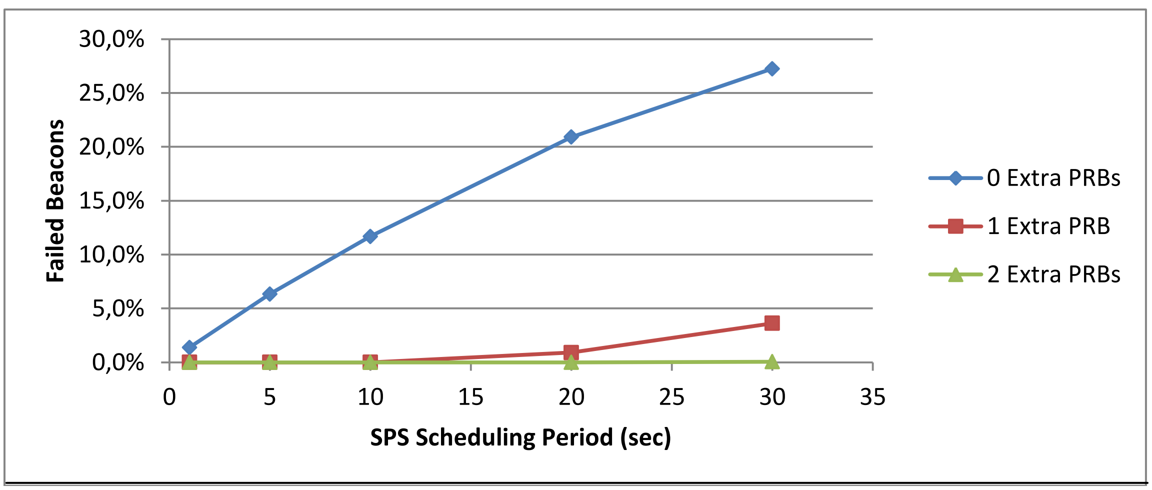


Figure 5.20: Average failed beacons per ITS user vs SPS period & redundancy

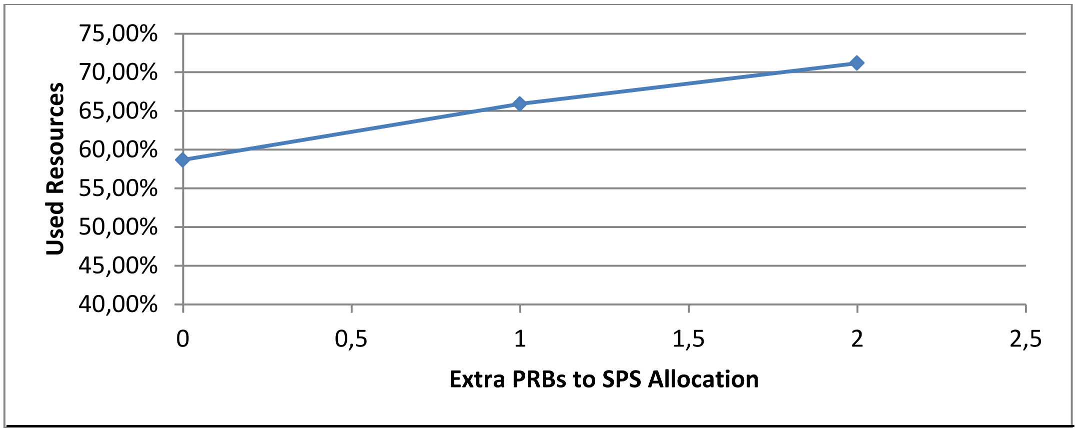


Figure 5.21: Used system's resources (Load) vs extra PRB allocation

From the results and graphs that are presented above, a lot of important conclusions can be drawn about the function of SPS. From ***Figure 5.20***, we can see that if no redundancy is used during the resource allocation process, the percentage of beacons that are lost (not enough resources to be transmitted) is quite large. Even for a very small SPS period of *1 sec*, a few beacons are lost, which would result in a failed ITS application, since there is very little tolerance for losses in ITS. This fact alone, stresses the need for some measures in order to avoid the failure of beacons. By assigning 1 extra PRB per user, we see that the performance of the system improves significantly, since there are almost no failed beacons even for a SPS period of *10 sec*. By assigning 2 extra PRBs per user, the performance improves even further and there are no lost beacons even for very large SPS periods such as *20 sec*, but of course that comes at the price of increased load imposed on the network, as is shown in ***Figure 5.21***. From this figure we can observe that for every extra PRB that is assigned to the ITS users, there is an increase of 6% to 7% of the network load, which means that more resources are needed to transmit the same amount of beacons and hence, the capacity of the system drops, since less users can be accommodated by the network.

The increase of the network load seems to have a proportional relationship with the number of PRBs assigned to each user for its beacon. We can verify the above results by calculating the exact load imposed on the network. As mentioned in *Section 5.2.1*, the background load is fixed and amounts for about 32% of the total load imposed on the network (32% of the available resources are needed to accommodate the background traffic). So the variation in the total load, originates only from the variation in the ITS load, which is easily calculated. The average assignment of PRBs per user for a single beacon, in the case that no extra PRBs are assigned, is 3.5 PRBs/beacon. Taking into account the number of ITS users in the network (360 vehicles), the beaconing frequency (10 Hz) and the total available resources of the network (50 PRBs every millisecond) we come to the conclusion that the ITS load imposed on the network for the case of 0 extra PRBs is:

*ITS load = (3.5*10*360) / (50*1000) = 25.2%* *(0 Extra PRBs)*

In the case that 1 extra PRB is assigned to every user, the average PRB assignment per user also increases by 1 and becomes 4.5 PRBs/beacon, while in the case of 2 extra PRBs per beacon, the average PRB assignment becomes 5.5 PRBs/beacon, as expected. With these data we can calculate the ITS load for the case of 1 and 2 extra PRBs:

*ITS load = (4.5*10*360) / (50*1000) = 32.4%* *(1 Extra PRB)*

*ITS load = (5.5*10*360) / (50*1000) = 39.6%* *(2 Extra PRBs)*

From the above calculations, we can see that our experimental results are verified, since for every increase of the PRB assignment by 1 PRB per beacon the ITS load on the network increases by 7.2%. The background load remains fixed around 32% of the total load but small fluctuations can be observed by the fact that the background call size and location, are selected randomly (see *Section 4.2.3*) which affects their bit rate and their experienced throughput. As a consequence, the total load on the network, experiences a variation very close to that of the ITS load, namely 7.2%, which validates the results of our simulator.

By taking all of the above results into account, we see that by assigning 1 extra PRB to each ITS user, we might "loose" 7.2% of the system's resources but the impressive decrease of the lost beacons makes it worth the while. On the other hand, a further increase of the redundancy, leads to an additional 7.2% loss of resources, but the performance improvement is not so significant anymore. Moreover, the "2 extra PRBs" solutions, presents its advantages mostly for very high SPS period values (> 10 sec), which are not needed or used frequently in such applications. By taking into account the above results, we reached the decision that a SPS period of 10 sec and a redundancy of 1 extra PRB per user, should be used to evaluate and compare the performance of SPS in the next set of simulation runs. In that way, we will be able to profit from SPS's advantages, without compromising too much, of the system's capacity.

5.4.2 Scheduling Schemes Comparison

In order to be able to compare how the different scheduling schemes perform, we have to test them under the same network conditions. In that way, by comparing the beacon delay, the network load and the background traffic throughput, we will be able to determine which one of the scheduling schemes is more suitable for ITS applications. The experimental setup was chosen to be the same as the one used for the original LTE performance assessment in *Section 5.1.1* and the same setup was repeated for every scheduling scheme separately. The analytical output of the simulator is not presented here because of the large volume of the outputted results, but it is given in ***Appendix B***. ***Figure 5.22*** below, shows the mean beacon delay that ITS users experience for each one of the scheduling schemes.

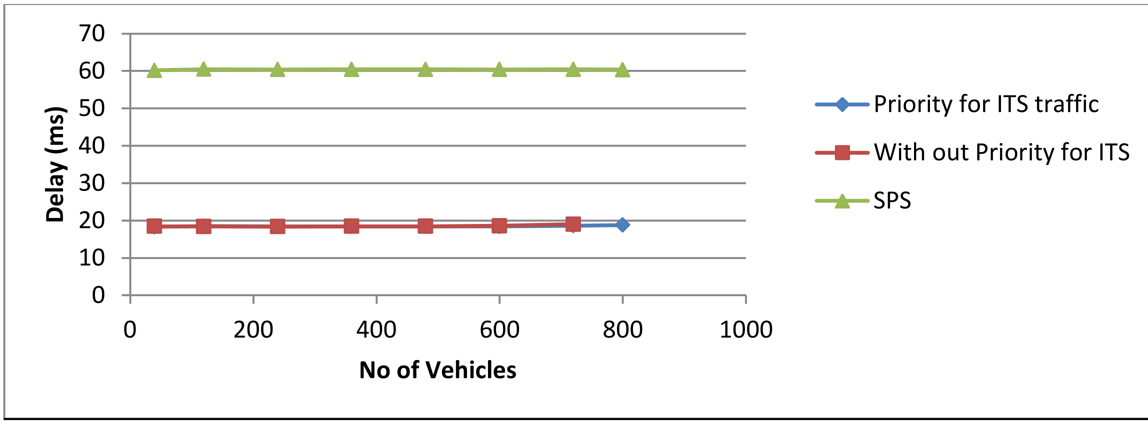


Figure 5.22: Mean Beacon Delay for different scheduling schemes

From the graph that is presented above it becomes clear that SPS behaves in a totally different way than the dynamic scheduling schemes. As long as the number of ITS users in the network is not overwhelming (overloaded network) the two dynamic scheduling schemes offer beacon delays around 20 ms while the SPS offers delays around 60 ms. That is not because SPS doesn't perform well or because it doesn't operate efficiently, but it happens because of the way SPS is structured to function (see *Section 4.4.2*). In the ITS case, the beaconing frequency is 20 Hz (1 beacon per 50 ms), which means that a beacon is generated every 50 ms by each vehicle. The Semi-Persistent scheduler is aware of that and makes use of that property. The problem arises from the fact that the minimum timing requirement for beacon delivery in ITS is also 50 ms. The Semi-Persistent scheduler assigns the resources to the users, keeping in mind that it has to assign enough resources to each vehicle in order to be able to transmit one beacon every 50 ms (beaconing frequency). The exact timing of the resources assigned to its user is random, the only restriction is, that the time interval from the beacon generation to the time were the user gets its resources, must be, under 50 ms. Unfortunately, that means that most of the time this time interval is around 35 to 40 ms and that only represents the UL buffering time. By adding the rest of the delays that a beacon encounters through a network (UL transmission delay, core network delay, DL transmission delay, etc) the End-to-End delay of the beacon adds up to around 60 ms, which is also obvious from ***Figure 5.22***.

In order to make the SPS mean beacon delay drop below 50 ms, we should instruct the Semi-Persistent scheduler to assign resources to ITS users with smaller time intervals (for instance every 15 or 20 ms) so that the RTT delay would add up to less than 50 ms. Unfortunately, if we do that, each user will have resources for transmitting a beacon every e.g. 20 ms, but it will only have a beacon to transmit every 50 ms (beaconing frequency), which means that a large amount of the available resources would be wasted. It is an unfortunate coincidence that both the beaconing frequency and the ITS requirement are 50 ms, for some ITS applications. For such applications the SPS would not be an appropriate choice. On the other hand, most ITS applications have a timing requirement for beacon delays around 100 ms, which can easily be handled with a beaconing intervals of 50 ms. Of course if we use a beaconing frequency of 10 Hz (1 beacon per 100 ms) we will end up with the same problem. In order to overcome this problem, we have to increase the beaconing frequency a bit, so that the beaconing interval is a bit lower than the ITS timing requirement. Of course that will lead to wasting some resources, but that is a compromise that we must accept, and which can be balanced out by the advantages that SPS offers in terms of control signaling overhead.

As far as the two dynamic cases are concerned, there are no obvious differences in the performance when the network operates under a normal load. Since there are enough resources for everyone, the priority doesn't really play an important role, since everyone will be served. By consulting the full results table and graphs that are presented in ***Appendix B***, we see that the difference is observed when the network's capacity limit is approached, where there are not enough resources to go around for everyone. In the case where the ITS users have priority, they are served first and that is why there is room for more ITS users than in the case with no priority. But of course, that comes with the price of slowly starving the background traffic from resources.

Some other interesting measures that we should look at, are the network load and the control signaling overhead. These two measures combined will give us an idea about the capacity improvement that is achieved with SPS. ***Figure 5.23*** below, depicts the total network load for each scheduling scheme and ***Figure 5.24*** shows the control signaling overhead that each scheme needs. ***Figure 5.25*** shows the portion of resources that are used for actual data transmission (useful resources) and not for control signaling, for each scheme.

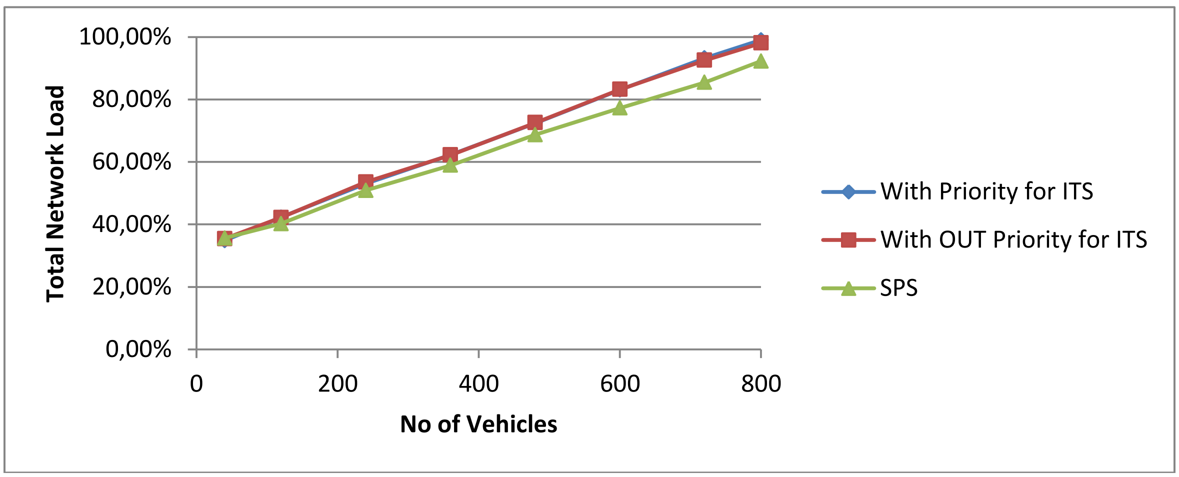


Figure 5.23: Total network load (data & control signaling) vs N^o of ITS users

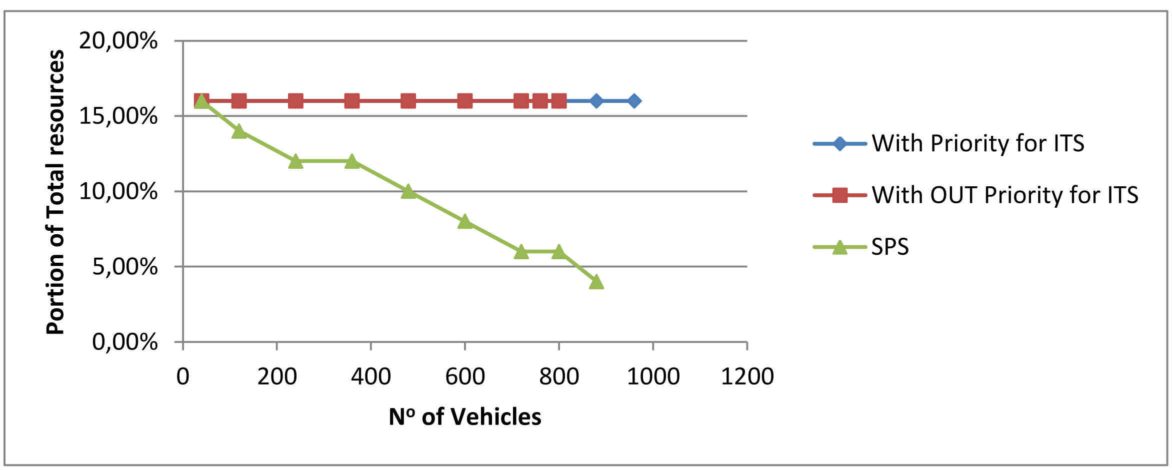


Figure 5.24: Resources used for Control Signaling

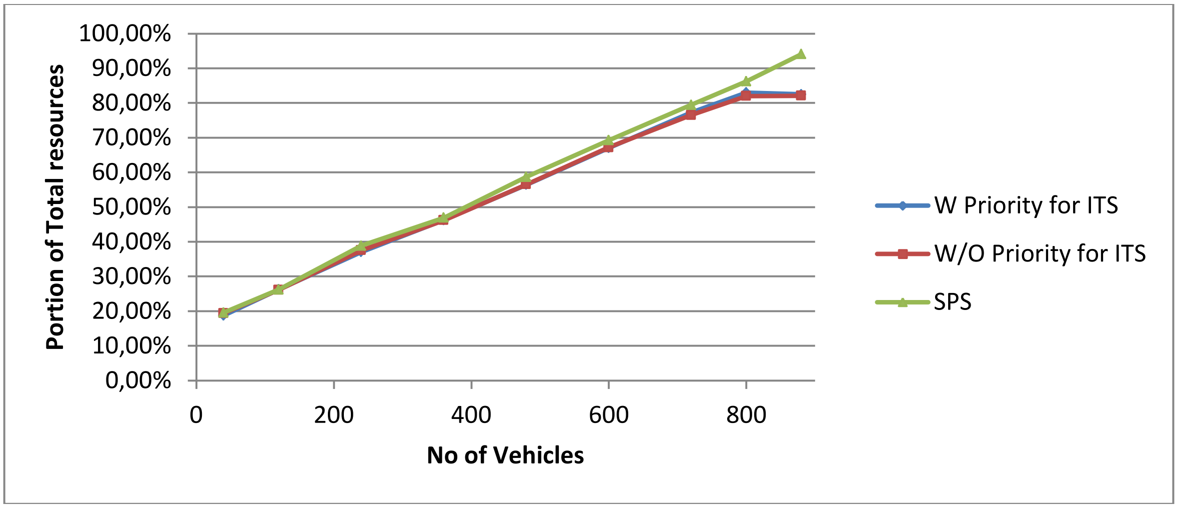


Figure 5.25: Resources used for data transmission

By observing ***Figure 5.23***, it seems that all scheduling schemes make more or less the same use of the available resources, since the differences between them are insignificant and for a specific number of ITS users they appear to use the same amount of resources. By investigating ***Figure 5.24*** and ***5.25***, we see that this is not exactly the case. Even though the two dynamic scheduling cases present identical behavior, the SPS case is quite different and offers great capacity improvement, especially close to the capacity limit of the network. The fact that the amount of resources needed for control signaling decreases with increasing number of ITS users was explained in *Section 4.4.2*. That is also obvious in ***Figure 5.24*** and it was expected, since the portion of total users who use SPS in the network, increases and that means that the total needs of the network for signaling, decrease significantly. As we can see, in both the dynamic cases the control signaling overhead, consumes 16% of the available resources, while in the SPS case the amount of resources needed for control signaling can drop as low as 4% of the total available resources. This fact, offers a great advantage to the SPS which can be seen in ***Figure 5.25***. The resources that would normally be used for control signaling are now used for transmitting data, which means that the throughput of the system increases and so does its capacity. Since more data per time unit can be send with SPS, more ITS users can be accommodated in the network.

Before being able to make up our minds about the different scheduling schemes, there is one more thing that we must examine, namely, their effect on the background traffic. ***Figure 5.26*** below, shows the mean throughput experienced by the vehicles in the network for the different scheduling schemes. We observe that all three scheduling schemes present the same behavior and serve the background traffic in a similar way, but the performance of the SPS is a bit better since it offers slightly higher throughputs. This is a direct result of the increased capacity offered by SPS. Since some of the available resources that are used for control signaling in the dynamic schedulers case, are used for data transmission in SPS, there are more available resources after the ITS traffic has been served and thus the experienced throughput of the background traffic is slightly higher. The two dynamic scheduling cases, present identical performance, since the offered load by the background traffic is quite small, and the background data calls are served with the same throughput, irrespectively of the existence of a priority scheme or not, due to the small amount of resources needed in order to transmit the relatively small sized background data calls (see *Section 5.2.2*).

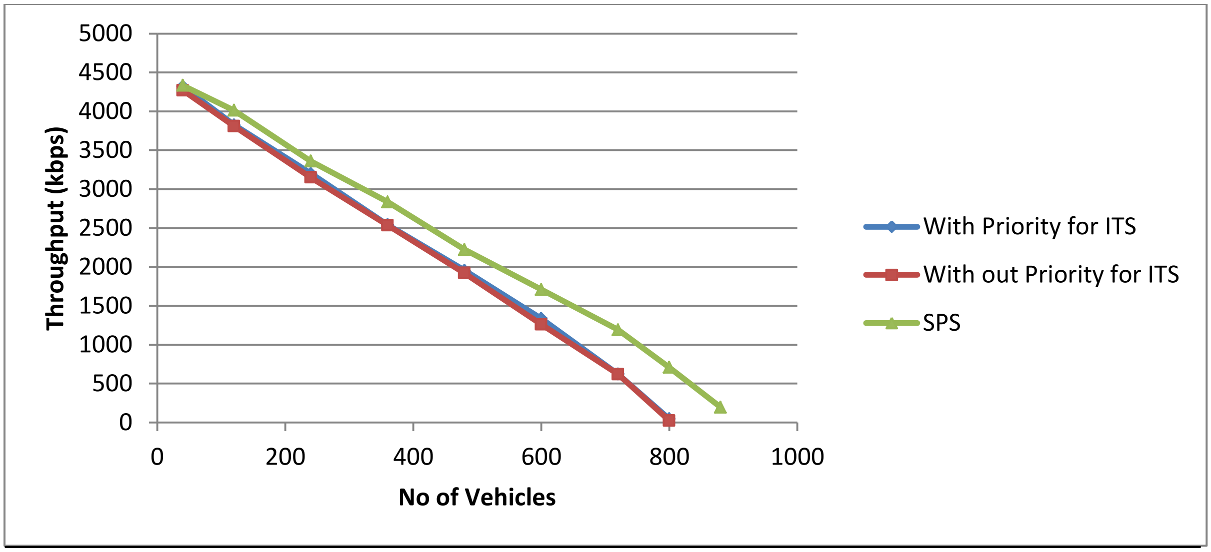


Figure 5.26: Mean background throughput for the 3 scheduling schemes

In order to be able to see the difference between the way that the dynamic scheduler with priority for ITS and the dynamic scheduler with fair sharing, are serving the background traffic we must increase the background offered load. ***Figure 5.27*** below, depicts the mean throughput experienced by the background traffic for the case of an increase background call inter-arrival rate (λ = 4 data calls per sec). As expected, while the two schedulers offer the same throughput to the background traffic in the case of an unloaded network (small number of users), when the total load on the network increases (large number of users) the dynamic scheduler with priority for ITS traffic, performs worse with respect to the background throughput. This is completely justified since the scheduler gives absolute priority to the ITS traffic and only serves the background traffic when all of the ITS users have completed their transmissions. When the load on the network is high, the effect of the shortage of available resources is only depicted in the decreased background traffic throughput.

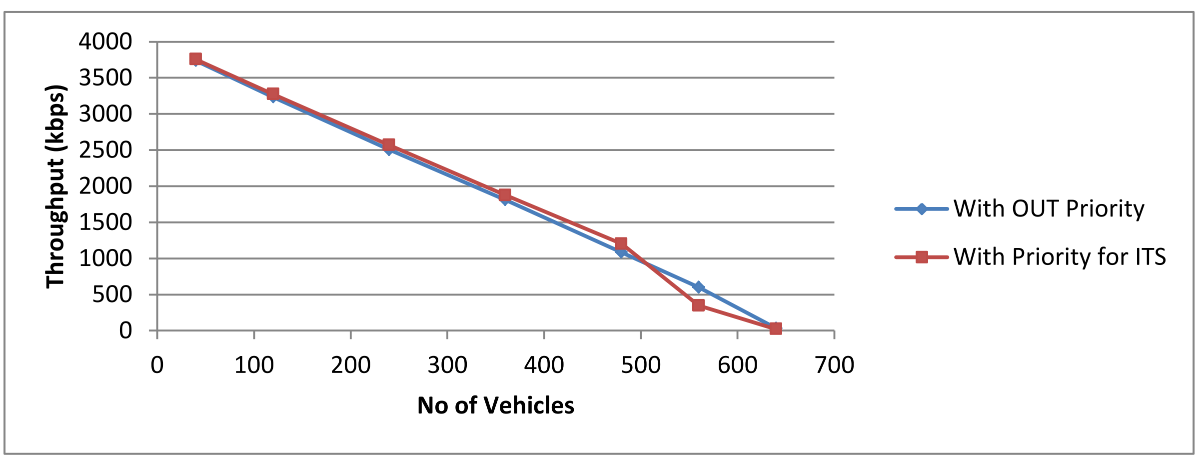


Figure 5.27: Mean background throughput for λ = 4 data calls / sec

5.5 Comparison of LTE & 802.11p

The results that were presented and analyzed in the previous sections, give us a good understanding of LTE's performance and behavior in an ITS environment. In order to be able to determine whether or not there is any future in ITS for the LTE standard, we must compare its performance with the performance of the current communication standard that is being used in ITS, meaning, the 802.11p standard. In order to be able to perform such a comparison, the two standards must be tested under the exact same conditions. The work carried out in [13] provides us with many results, about the functionality of 802.11p in an ITS environment. The work presented in [13] was carried out by the author of this thesis, in the context of an internship project, using the ITS Communication Analyzer (ITSComAn) Simulation tool, provided by TNO. At this point, the LTE simulation tool will be used to evaluate LTE's performance under the same conditions as the ones that 802.11p was tested under, and compare the results at the end. Two distinct cases were simulated for both standards representing operation under lighter (300 ITS users) and heavier load (450 ITS users). The exact simulation parameters and the variable values that were used for the evaluation of both protocols, are shown below in ***Table 5.7***.

Parameter	*Value*	*Parameter*	*Value*
N^o of lanes	3	**Beaconing frequency**	10 Hz
Road-length	1000 m	**Beacon size**	100 Bytes
N^o of vehicles/lane/km	100 / 150	**Average Speed**	30 m/s
Height of eNB	30 m (LTE)	**Speed fluctuation**	6 m/s
Transmit Frequency (MHz)	900(LTE) / 5890(11p)	**UE transmit power (dBm)**	23 (LTE) / 20 (11p)
Contention Window (slots)	1023 (802.11p)	**Modulation scheme**	QPSK (802.11p)

Table 5.7: Simulation Parameters for LTE & 802.11p comparison

The output of the ITSComAn simulator for the 802.11p case, consists of three graphs which are shown below, for the two cases of network load that were simulated. ***Figure 5.28*** depicts the output of the ITSComAn simulator for the case of the lighter load (300 ITS users). That output consists of the mean beacon delay experienced by each vehicle separately (each vehicle has its own ID number), the mean beacon drop rate experienced by each vehicle and the average Frame Delivery Ratio (FDR) in relevance to the distance between sender and receiver. ***Figure 5.29***, depicts exactly the same graphs, only for the case of the heavier simulated load (450 ITS users).

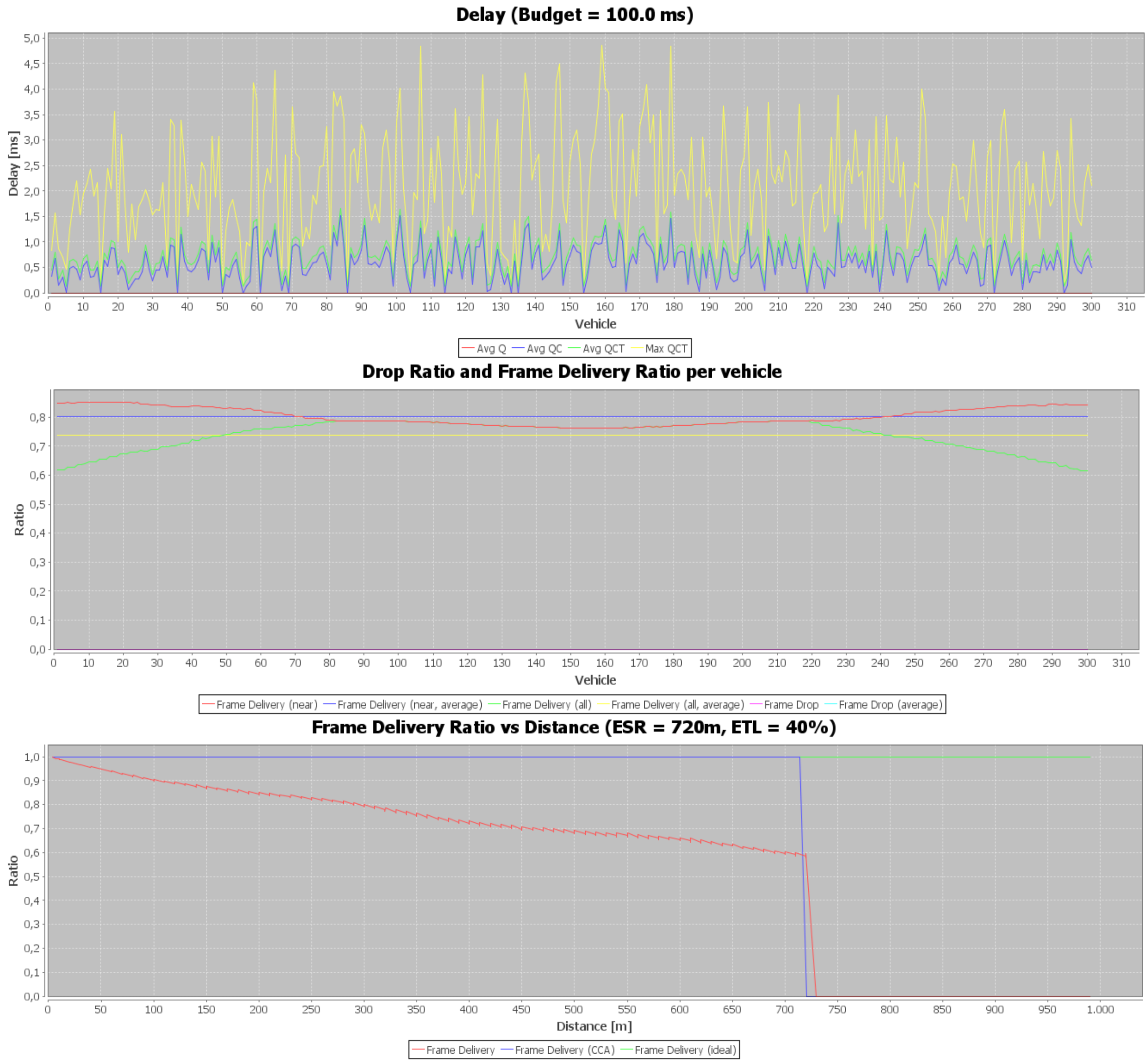


Figure 5.28: Simulation results for 802.11p for a light load (300 ITS users)

The yellow line of the delay graph represents the maximum total delay of a beacon from the time it is generated at the transmitter side until the time it is delivered to the receiver, while the green line represents the average total beacon delay that each vehicle experiences. The blue line represents the average contention delay experienced by the vehicle, meaning the time from the beacon generation until the user gets access to the channel by competing with the rest of the users (wireless Ad-hoc network property). In the drop ratio and FDR graph the red line represents the ratio of successfully delivered beacons compared to the number of sent beacons, but only for the vehicles within the communication range or Estimated Sensing Range (ESR) of the transmitter, which in this case is 720 m. The blue line represents the FDR for vehicles within the ESR of the transmitter, averaged over the number of these vehicles and the green line represents the FDR that each vehicle experiences, not only in the ESR of the transmitter, but throughout the whole network. Finally the yellow line represents the FDR for all the vehicles in the network, averaged over the total number of vehicles. In the FDR vs distance graph, the red line represents the mean FDR in relevance to the distance of the receivers from the transmitter, and the blue line represents the maximum FDR achievable under ideal circumstances, for the specific simulation parameters.

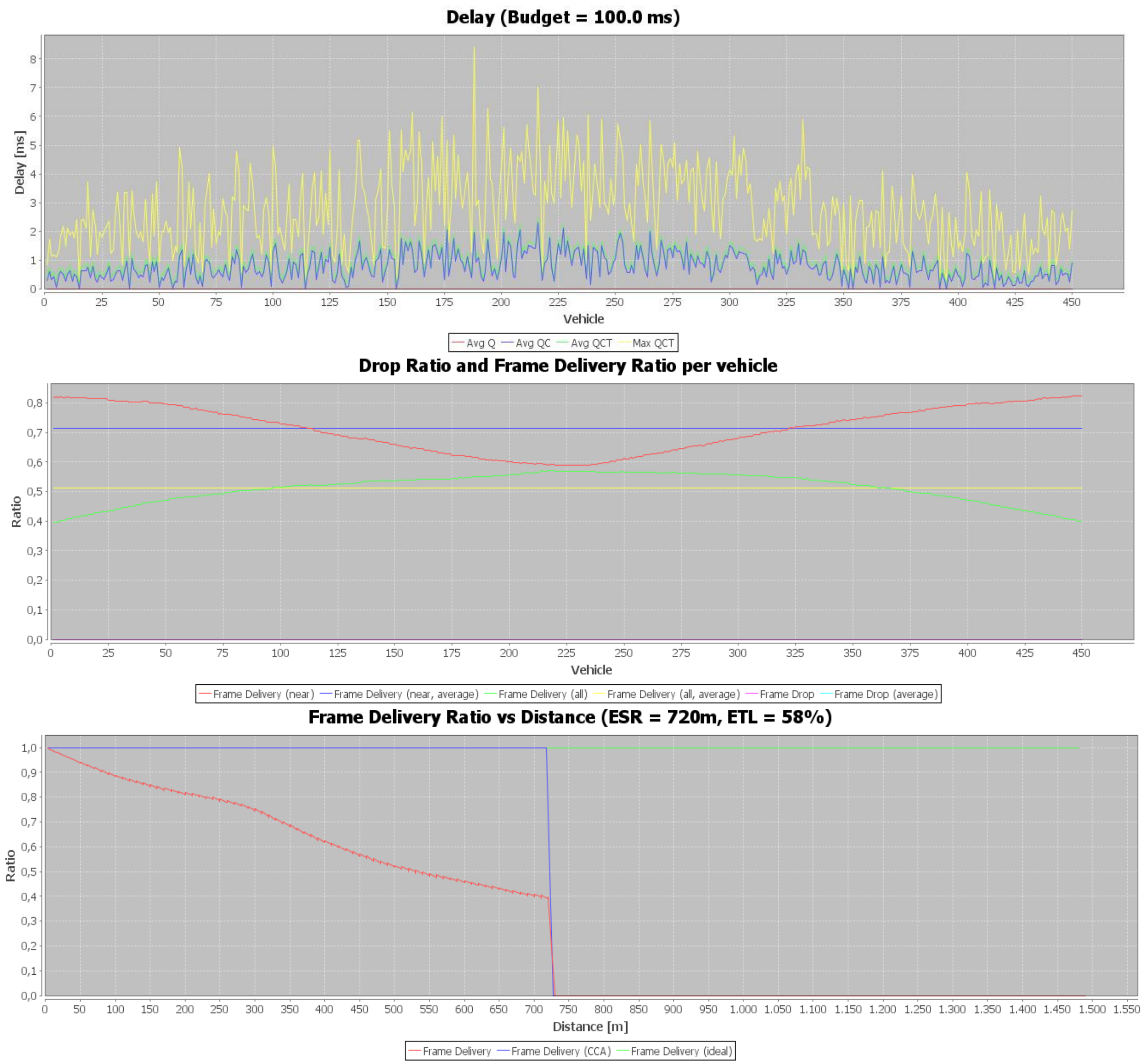


Figure 5.29: Simulation results for 802.11p for a heavy load (450 ITS users)

The first thing we notice is that in 802.11p there is a strong effect by the boundaries of the simulation, causing different performance experience for the users in the middle and the users at the boundaries of the simulation scenario. This is caused by the fact that the interference in the middle of the simulated network is greater than at the edges of the networks because there are more neighboring nodes. In order to minimize the boundary effect and to get reliable results, we only take into account the values and results from the users in the middle of the network, since in reality there is no such boundary effect. A very important aspect, that should be made clear, is that the ITSComAn simulator, does not simulate background traffic, so the 802.11p standard has to cope only with the ITS traffic in these simulation series, thus experiencing a decreased load compared to the LTE simulation under the same conditions.

From ***Figures 5.28*** we observe that even for the light network load case the ITS users experience some loss of beacons (FDR = 80 – 90%) and the ratio of successfully delivered frames drops fast with increasing distance from the transmitter. For the heavy load case (***Figure 5.29***), the experienced frame delivery ratio drops even further and the FDR vs distance graph becomes steeper, which means that even nodes close to the transmitter will experience greater beacon losses. It is interesting to notice, that in the FDR vs distance graph, the inclination of the graph changes at about one third of the ESR of the nodes, and the loss of frames becomes more severe after that point. This is due to the fact that at that distance the hidden node terminal effect "kicks in" which deteriorates the delivery ratio of frames due to the extra collisions. When the distance of the transmitter from the receiver is small, the signal is too strong, and interference from other users is minimal, so it is difficult for a node to experience the hidden node problem. But, as the distance between transmitter and receiver becomes greater, then other signals from other transmissions might interfere, and the chance of a node not sensing another node transmitting increases. It is interesting to observe that in both cases (light and heavy load), the experienced beacon delay of the users is extremely small (below 10 ms) which is a great characteristic for ITS traffic.

The same simulations were carried out with the LTE simulator for ITS, in order to compare the performance of the two standards. The simulation parameters and conditions were matched to the ones used in the ITSComAn simulator as much as possible (some details could not be exactly matched because of the structural differences between the two simulators) and the results are shown below. Of course the output of the LTE simulator is quite different from the 802.11p simulator, mainly because of the infrastructure that LTE has, instead of the infrastructure-less manner of operation of the 802.11p. In LTE there is no Frame Delivery ratio, since all of the frames are eventually delivered, even with an extra delay. As mentioned before a 1% retransmission scheme has been implemented, simulating the loss and retransmission of 1% of the transmitted beacons (see *Section 4.4.3*). The fact that no frames are lost and that such a low percentage of retransmissions can be implemented is an advantage of LTE that originates directly from its infrastructure. In any case, the FDR of a LTE network is always 100%, even if some beacons experience increased delays. Moreover there is no need for a FDR vs distance graph in LTE, since the eNB can communicate with any vehicle in the cell with no problem, and the service remains more or less the same even if the vehicle is positioned at the edge of the cell. Because of the reasons mentioned above, the only comparable measure between the two simulators is the End-to-End beacon delay experienced by the ITS users. ***Figure 5.30*** below shows the average End-to-End beacon delay experienced by each ITS user for the light load case (300 ITS users), using the three different scheduling schemes.

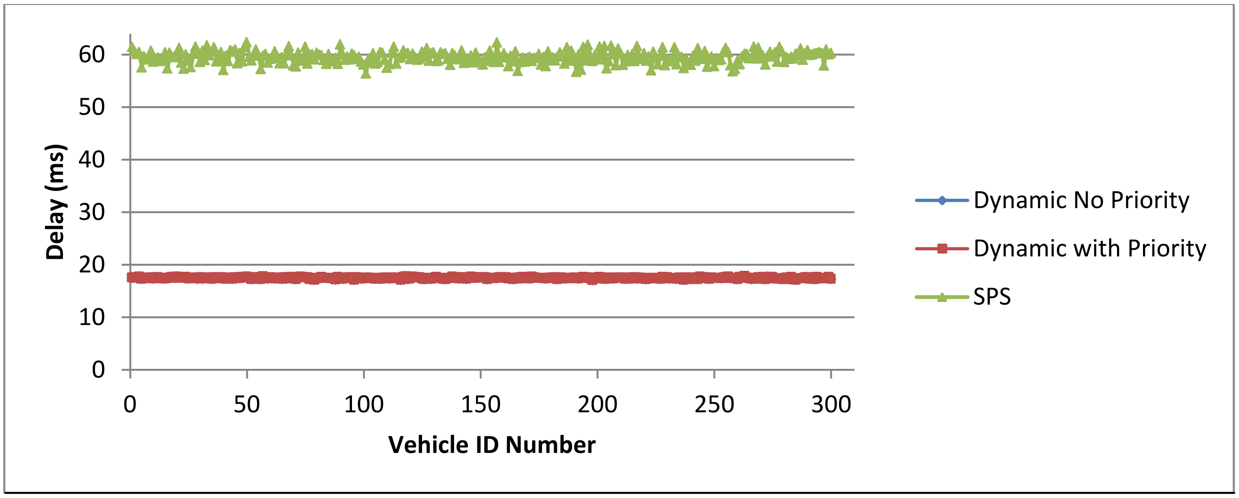


Figure 5.30: Mean beacon delay per vehicle using LTE with 300 ITS users

It is important to note, that in the graph presented above, each number on the horizontal axis (X Axis) represents a specific vehicle, beginning from the first vehicle at the start of the road (*Vehicle ID = 1*) and finishing with the last vehicle at the end of the road (*Vehicle ID = 300*). Moreover, we must note that the measurements for the Dynamic scheduling case with no priority for the ITS users (blue line) are not apparent in the above graph, because they coincide greatly with the measurements for the Dynamic scheduling with priority for ITS users, and thus the blue line of measurements is "hidden" behind the red line of measurements. This happens because the scale of the axis is too large to distinguish small details and differences in the measurements. The same simulation runs were carried out for the case of the heavier load (450 ITS users), and the results are presented below, in ***Figure 5.31***.

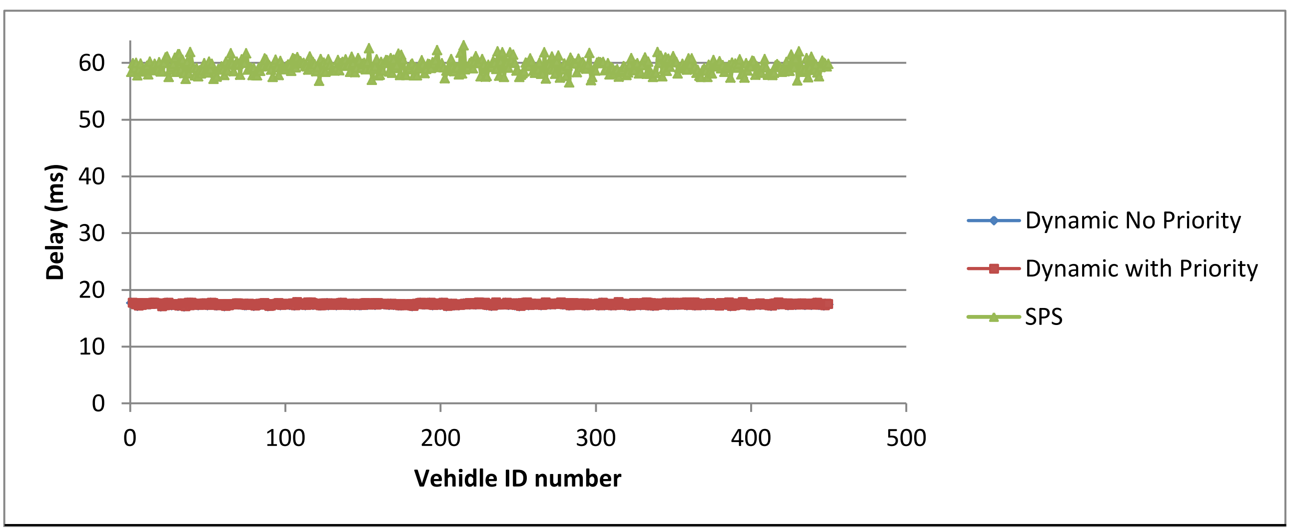


Figure 5.31: Mean beacon delay per vehicle using LTE with 450 ITS users

From the graphs that are presented above, some very important conclusions about the performance of the two standards can be drawn. First of all, we see that when the network operates under normal conditions (under light load), the 802.11p standard can offer extremely low End-to-End beacon delays, in the order of 2-3 milliseconds. That happens because the communication is direct between the transmitter and the receiver, and the beacon doesn't have to go through all the steps that it has to go through, in the LTE case (see *Section 4.1.1*), which are time consuming. Another observation about the beacon delay is that in the 802.11p case, there is some deviation in the beacon delays that the vehicles experience, while in the LTE case the deviation of the beacon delay from vehicle to vehicle is insignificant. As mentioned before, this is due to the basic difference of the two standards, meaning the use of infrastructure or not. Since the eNB organizes the transmissions in the cell in the LTE case, it makes sure that all users are more or less treated the same, that is why they all experience a beacon delay very close to the mean value which is 17.5 ms for the dynamic cases and 59 ms for the SPS case. On the other hand, the beacon delay in 802.11p depends on the network circumstances at the moment that the vehicle is trying to transmit. If there are other vehicles transmitting close to it, then it will have to back-off and wait until the medium is free for transmission. This process can enlarge the channel access time (contention delay) significantly and consequently the whole beacon delay time. The absence of a coordinator in 802.11p (such as the eNB in the LTE case), means that the nodes (vehicles) have to organize themselves, which leads to larger variation in the channel access delay, and hence the beacon delay.

As far as the capacity of the two standards is concerned, LTE appears to be able to handle a greater number of users than 802.11p. Taking into account the results that were presented in this section, we can see that 802.11p already presents a degraded performance for 450 users (***Figure 5.29***) as the percentage of lost beacons is very high (40%), even though the beacon delays remain in satisfactory levels. The fact that only 60% of the transmitted beacons are received by the intended receivers, indicates that the strict ITS requirements can no longer be met. On the other hand, from the results presented in *Section 5.2.1* we see, that under the same network circumstances LTE can accommodate for up to 700 ITS users, while serving background traffic too, and the performance remains within the ITS required limits. This is a clear indication that LTE offers greater capacity than 802.11p and the percentage of capacity improvement depends on the network parameters.

By increasing the offered load to the network, we see that the LTE copes much better with the increased load than 802.11p does, and we should keep in mind that LTE serves background calls at the same time, while 802.11p doesn't. From ***Figure 5.29***, we can see that the increased load leads to a minor increase in the beacon delays (up to 8 ms) in the 802.11p case, but it also leads to severe degradation of the FDR. A significant amount of beacons are dropped (30% – 40%), as the FDR has gone down to 60% for the users in the middle of the network, and the distance that they can reach has decreased, meaning that less vehicles receive the beacon. All of the above phenomena are caused by the increased interference due to the increased number of ITS users. The 802.11p has significant scalability issues, as was proven in [13] and it requires special handling mechanisms, such as *Transmission Power Control* (TPC) in order to cope with an increased number of users in the network. The increased contention times, the increased number of packet collisions and the increased interference, degrade its performance and increase the beacon delays significantly. On the other hand, LTE handles the increased traffic more efficiently, thanks to the coordination provided by the eNB, and that is why it is able to serve a larger number of users.

It must also be noted that 802.11p has a much smaller communication range than LTE because of its ad-hoc nature. As it can be seen by the FDR vs Distance graphs, the communication range of 802.11p is ideally around 700 m, but actually much less (around 200 m for an acceptable beacon delivery ratio), while in *Section 5.3.3* we showed that LTE ensures in time delivery for ranges up to 2000 m. Finally it must be noted that, in contrast with LTE, when a beacon is lost in the 802.11p case, there is no retransmission attempt and instead the transmitter will wait for the next beacon to be generated and transmitted. This is based on the notion that by the time a retransmission is made it will be too late and the information on the beacon will be outdated since a new beacon, with more recent information will have been generated. In the LTE case, a beacon retransmission only takes 8 ms, because it has been accounted for, in the original design of the system (retransmission scheme), thus increasing the possibilities that the beacon will reach its destination in time and the ITS requirements will be met. On the other hand, because of the retransmission scheme, the average information age in LTE is increased compared to 802.11p. So even if beacons are never lost because of the retransmission scheme, the information they carry could be outdated and hence useless.

It is important to stress out that the above presented results constitute a very high level comparison of the two communication standards, which aims at giving a rough image about their performance. In order to obtain some better founded conclusions about the performance and suitability of the two standards for ITS, a more complete comparison is needed which will examine all of the systems aspects. After all, apart from the technical characteristics of the standards, other aspects must be taken into account such as the fact that the deployment of LTE requires a huge and expensive infrastructure network, while 802.11p is much cheaper and easier to deploy.

6

Conclusions & Further Work

6.1 Conclusions

The research and results presented in this thesis, aim at offering a first look at the performance and behavior of LTE, when used in an ITS scenario, and to conclude whether the use of LTE for ITS applications is viable and whether further research is necessary in order to determine the possible applications of such a solution. In this chapter, we draw some general conclusions about the use of LTE and 802.11p for communications in ITS networks, based on the results that were presented above and we will try to answer the research questions that were put forth, at the beginning of this thesis.

By studying the results that were presented in the previous chapter, we can conclude that LTE can meet most of the requirements of ITS applications, assuming that the network's limits in terms of capacity have not been reached. When this point is reached the performance of LTE degrades significantly and can no longer meet the ITS requirements. The latencies and capacity offered by LTE under normal network conditions, make it an ideal candidate for use in Intelligent Transportation Systems and at the same time it can accommodate for the background traffic data calls, without compromising the offered QoS beyond certain acceptable limits. LTE can serve a large number of ITS users (up to 700 depending on the network's parameters and focus) and at the same time serve a substantial amount of background data traffic which in our research was taken to be 1.6 Mbps (2 data calls per second of average size 800 kbits – see *Section 5.2*). The effect of the background traffic is not very dominant in the behavior of the system, especially in the case that the number of ITS users is significant and the ITS load represents the majority of the total load offered to the network. Of course, if the background traffic load increases significantly, then the ITS traffic will not be able to meet the necessary requirements, unless some priority scheme has been placed in action.

The differentiation and prioritization of ITS traffic over the background traffic, is important in order to accommodate ITS applications, since it will ensure that the ITS beacons will receive the best service possible from LTE and that they will be served before the background traffic data packets. In this way LTE has the possibility to serve more ITS users as the load offered to the network gets closer to its capacity (increased ITS capacity and reduced background capacity). The implementation of Semi-Persistent Scheduling in ITS applications can offer some great advantages in terms of capacity of the system, but the fact that the beacon inter-arrival time and the beacon delivery requirement are the same in some ITS applications, make it hard to “harvest” these advantages in ITS implementations. The SPS capabilities can be fully exploited when the scheduling scheme is used for ITS applications with not so stringent timing requirements, since the inter-arrival time of the beacons will remain the same (50 -100 ms) while the beacon delivery requirements will be much higher (100 – 500 ms).

The main advantages offered by LTE originate from the fact that it is an infrastructure based standard, which allow it to mitigate many of the problems that 802.11p faces, such as contention delay, beacon collision, beacon losses, interference among users, etc. That is also the reason that LTE manages to maintain a satisfactory performance even for very high network loads but when it operates close to its full capacity, the beacon delays exceed the ITS requirements and/or the QoS requirements of the background traffic are no longer met. The general performance of LTE degrades gracefully with increasing load, but as far as ITS requirements are concerned, they are only met up until a certain point (in terms of network load) and after that point the ITS applications can no longer be supported in a satisfactory manner. The LTE behavior is similar with the 802.11p behavior, where the performance also degrades gradually with the increase of the offered load, but in the 802.11p case there is no specific point of failure for the ITS traffic since some users may meet the ITS requirements (probably the ones closer to the transmitter) while at the same time some others may not. Moreover, LTE appears to be able to accommodate for more users in the same bandwidth because of the fact that the whole organization, scheduling and function of the network is based on the eNB, which makes sure that the available resources are used in the best way possible.

By comparing the performance of the two standards, we saw that 802.11p can offer much lower beacon latencies than LTE, due to its direct way of communication, in the case that the network is not operating close to its capacity. On the other hand, LTE offers larger capacity (700 ITS users vs 400 ITS users for 802.11p) and larger communication range (2000 meters vs 700 meters for 802.11p). Of course, the larger the communication range the larger the load that is imposed on the network due to the increased average distance of the UEs from the eNB. Moreover, LTE hardly suffers from beacon losses due to collisions and it seems to be able to guarantee a minimum QoS (beacon delays) under specific network conditions, to all the users of the network, while with 802.11p the experienced QoS of beacons, can vary significantly.

In light of the above results we conclude that the best solution for communications in a ITS network, would be a combination of the 802.11p and the LTE standards. The 802.11p is more suited to serve the first class of ITS applications, namely the Cooperative road safety applications, because of its extremely low beacon latencies, while LTE is perfectly suited to serve the other two classes of ITS applications, meaning the Cooperative traffic efficiency class and the Cooperative local services and internet class (see *Section 2.1.3*). These two classes of ITS applications have looser latency requirements (> 100 ms), which LTE has no problem meeting without compromising the QoS offered to background traffic, as shown by the results presented in the previous chapter. At the same time, since LTE will be handling a big portion of the ITS load, the 802.11p standard will have no scalability or capacity issues, and will be able to offer the extremely low beacon latencies that are required by the first class of ITS applications.

6.2 Further Work

The work presented in this thesis, produced some very interesting results, which can become the basis for further studies on the subject. First of all, the enhancement and improvement of the model that was created for this thesis can lead to even more accurate results which in turn will lead to better founded conclusions about the support of ITS applications. By modeling in detail the downlink of LTE and the core network, and by including in the model all the LTE features and natural phenomena that had to be left out of this version of the simulator, we could reach very accurate conclusions about the exact delays and the exact capacity of LTE in the ITS environment. The overall conclusions that were drawn above, about the performance and behavior of LTE in the context of ITS will still be valid, but some more precise values for the network parameters can be defined and some specific case studies, simulating realistic traffic scenarios can be examined.

Another interesting direction, would be to create a model, simulating the combined application of 802.11p and LTE standards and evaluate how it performs in a ITS environment. This combination of the two standards seems to be the most promising solution when it comes to communicating in a vehicular environment, and a detailed model of such a system, would provide the necessary data that could turn the providers and manufacturers attention to such a solution.

Finally, it would be very interesting to verify the data outputted by such simulations, and compare them with real life measurements. The existence of test sites for both LTE and 802.11p in The Netherlands, would allow for a thorough test trial, which would produce real life results about the capabilities of the two standards. By analyzing the real life data, the simulation results could be verified and the simulators themselves could be “tuned” in order to output more realistic data. Such a tool would be very useful for predicting the behavior and performance of future ITS networks and would provide the manufacturers with a good estimation of the expected performance of a ITS network under any conditions.

The Intelligent Transportation System is a breakthrough which will revolutionize the way that people drive and behave on the road. At this moment, most of the research concerning the communications protocol to be used in ITS revolves around the 802.11p standard. This thesis project has demonstrated, that the Long Term Evolution standard is another viable candidate, which can easily handle, at least, some of the ITS communications load. This fact alone constitutes a driving force for further research, and proves that the LTE solution or the Hybrid solution (combination of LTE and 802.11p) for communications in ITS, deserve more attention from all the parties involved in the ITS development.

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Appendix

A. Simulation Parameters

In this section, a list of the model's constants and variables that were used throughout the simulations, is presented.

{--Traffic Model Parameters--}

Delta	*= 4;*	*{Intelligent Driver Model parameter}*
RoadLength	*= 2000;*	*{meters}*
RoadWidth	*= 4;*	*{meters}*
Num_Lanes	*= 4;*	*{Number of lanes in the highway}*
Veh_Length	*= 3;*	*{meters}*
Acceleration	*= 0.8;*	*{acceleration in m/s2}*
Braking	*= 1.8;*	*{deccelaration in m/s2}*
TimeHeadway	*= 1.2;*	*{Desired time headway to the vehicle in front is secs}*
MinSpac	*= 1.5;*	*{Minimum net distance between vehicles in Slots}*
Sim_Time_Sec	*= 1800;*	*{Total Simulation time in sec (Including Warm Up)}*
V0High	*= 30;*	*{Speed limit for vehicles in free road}*
V0Low	*= 18;*	*{Speed limit for vehicles in jammed road}*
EPSILON	*= 0.00000001;*	*{Dummy low number}*
lambda	*= 2;*	*{Poisson process variable}*

{--ITS Parameters--}

Beaconing_Freq	*= 10;*	*{The Beaconing frequency of the vehicles in Hz}*
Beacon_Size	*= 100;*	*{The total size of the Beacon in bytes}*

{--LTE Network Parameters--}

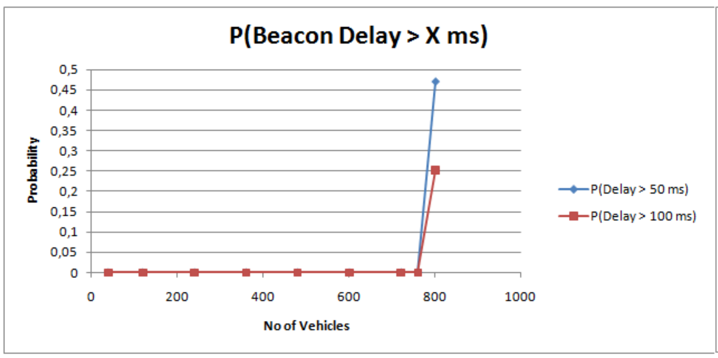
NumBts	*= 1;*	*{Number of LTE Base Stations}*
fc	*= 900;*	*{Frequency of LTE in MHz}*
cellBW	*= 10;*	*{Cell Bandwidth in MHz}*
HeightBst	*= 30;*	*{Height of eNodeB}*
UL_Spectral_Eff	*= 0.8;*	*{UpLink Spectral efficiency of LTE in bps/Hz }*
P0	*= -78;*	*{Min received Power per PRB at the eNB in dBm}*
alpha	*= 0.7;*	*{Pathloss compensation factor α}*
PueMax	*= 23;*	*{Max transmission power of UEs in dBm}*
ThNoise	*= 2.25E-15;*	*{Thermal noise in Watts}*
Interference	*= 2.25E-15;*	*{Inter-cell interference due to neighboring cells in Watts}*
PRBperTTI	*= 50;*	*{Available PRBs per TTI (1 ms intervals)}*
PUCCH_PRBs	*= 8;*	*{PRBs used for control signaling in Dynamic scheduling}*

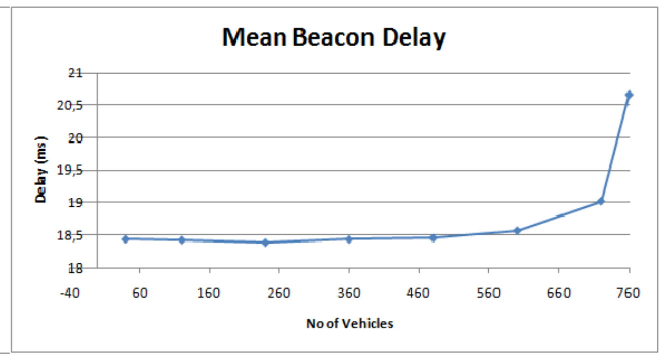
```
Saved_SPS_PRBs      = 6;         {Max Nº of PRBs that can be saved from control
                                 signaling  when SPS is used}
Avg                 = 800000;    {Mean of LogNormal distribution (in bits)}
Cov                 = 1.5;       {Coefficient of variance}
Sch_Penalty         = 0.0065;    {Delay for the scheduling request & grant in sec}
eNB_proc_Delay      = 0.004;     {eNB processing delay per packet in sec}
UE_rpoc_Delay       = 0.004;     {UE processing delay per packet in sec}
Core_Delay          = 0.002;     {LTE Core network delay in sec}
Buff_Delay          = 0.001;     {UE Buffering delay per packet in sec}
Speed_Factor1       = 0.04;      {Vehicle speed <= 30 km/h, throughput reduction = 4%}
Speed_Factor2       = 0.12;      {Vehicle speed >= 30 km/h, throughput reduction = 12%}
Speed_Factor3       = 0.15;      {Vehicle speed >= 120 km/h, throughput reduction =
15%}
Bck_Loss_factor     = 0.1;       {Packet loss facotr for Background traffic  =  10% packet
                                 loss}
ITS_Loss_factor     = 0.01;      {Packet loss facotr for ITS traffic  =  1% packet loss}
ReTxPenalty         = 0.008;     {Retransmission delay penalty of 8 msec}


{--Time Units definitions--}

TimeUnit100         =  0.1;      {Time Unit of 100 ms (1/10 sec)}
TimeUnit50          =  0.05;     {Time Unit of 50 ms (1/20 sec)}
TimeUnit20          =  0.02;     {Time Unit of 20  ms (1/50 sec)}
TimeUnit1           =  0.001;    {Time Unit of 1   ms (1/1000 sec)}
TimeUnitSPS         =  10;       {Time Unit of SPS Resource Assignment in sec}
```

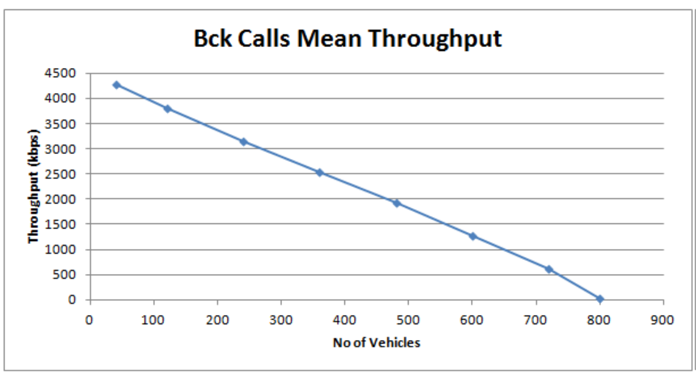
B. Analytical Simulation Results

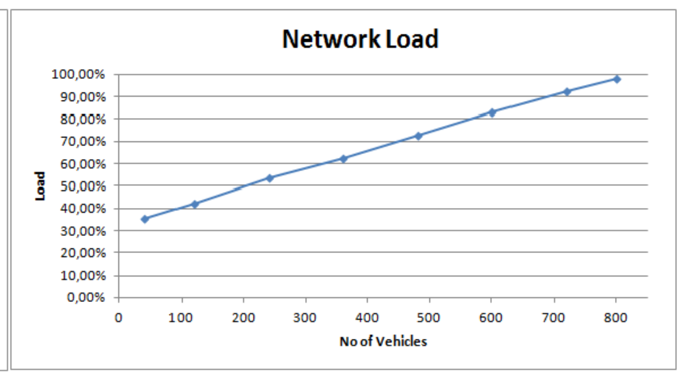
Parameter: N° of Vehicles (10 Hz)

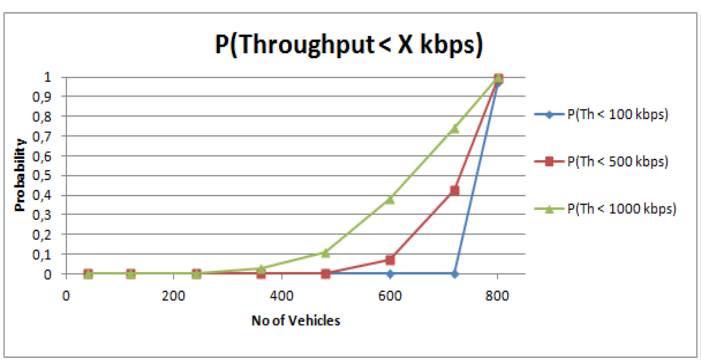
No of veh/lane/km	Total No of vehicles	Mean beacon delay (ms)	Percentage > 50 ms:	Percenage > 100 ms:	Load on the Network:	Calls Served/Arrived:	Throughput (kbps):	Percentage < 100 kbps:	Percentage < 500 kbps:	Percentage < 1000 kbps:
5	40	18,4392	0	0	35,42%	100,00%	4270	0	0	0
15	120	18,4276	0	0	42,15%	100,00%	3810	0	0	0,0009
30	240	18,3874	0	0	53,53%	100,00%	3150	0	0	0,0057
45	360	18,4362	0	0	62,20%	100,00%	2535	0	0,0004	0,0253
60	480	18,4594	0	0	72,54%	100,00%	1920	0	0,0048	0,1078
75	600	18,5707	0	0	83,17%	99,99%	1261	0	0,0745	0,3842
90	720	19,024	0	0	92,51%	99,94%	619	0,0053	0,4232	0,744
96	768	47,03	0,149	0,005	97,42%	98,69%	117	0,724	0,952	0,9916
100	800	7121	0,889	0,7	98,01%	97,20%	24	0,976	0,9967	0,999

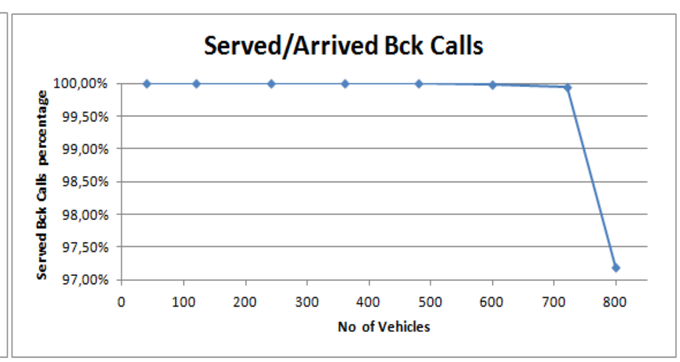






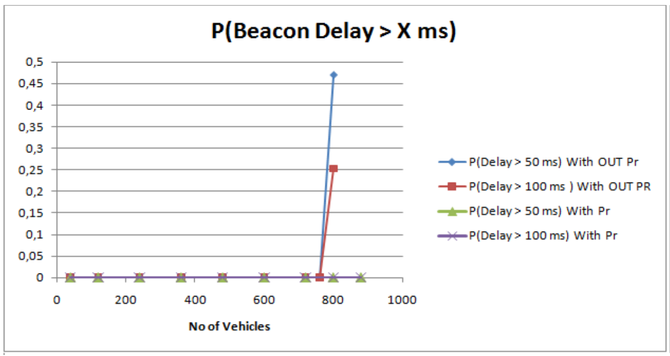


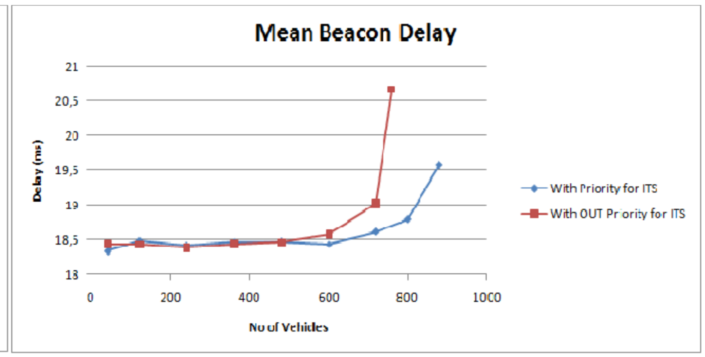


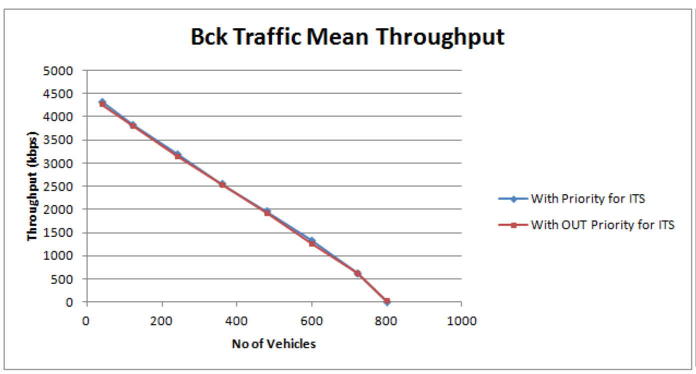


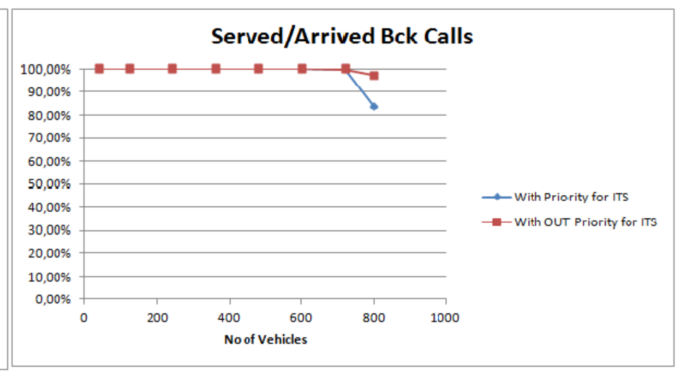
Parameter: N° of Vehicles (10 Hz – Priority for ITS)

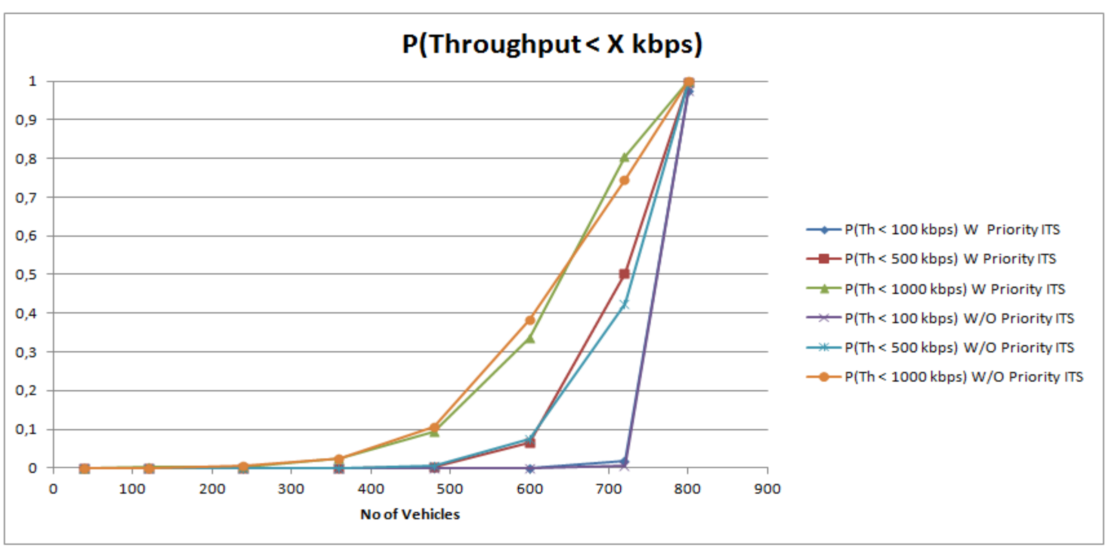
No of veh/lane/km	Total No of vehicles	Mean beacon delay (ms)	Percentage > 50 ms:	Percenage > 100 ms:	Load on the Network:	Calls Served/Arrived:	Throughput (kbps):	Percentage < 100 kbps:	Percentage < 500 kbps:	Percentage < 1000 kbps:
5	40	18,3392	0	0	34,78%	100,00%	4320	0	0	0
15	120	18,4797	0	0	42,26%	100,00%	3826	0	0	0,0013
30	240	18,4124	0	0	53,05%	99,99%	3200	0	0	0,0034
45	360	18,4606	0	0	62,23%	100,00%	2541	0	0,0003	0,024
60	480	18,4734	0	0	72,45%	100,00%	1955	0	0,003	0,095
75	600	18,4307	0	0	83,03%	99,98%	1338	0	0,067	0,3379
90	720	18,6139	0	0	93,24%	99,92%	622	0,02	0,5028	0,8058
100	800	18,7964	0	0	98,03%	83,88%	15	0,976	0,996	0,999





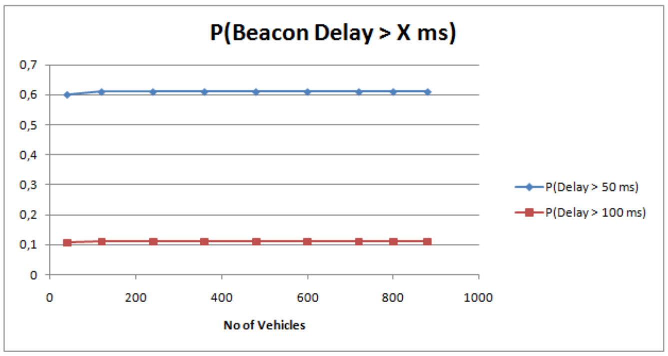


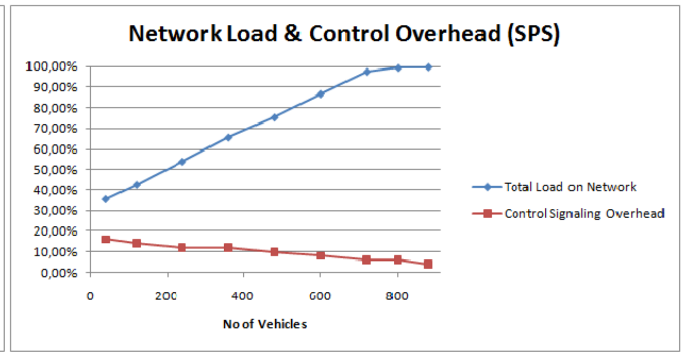


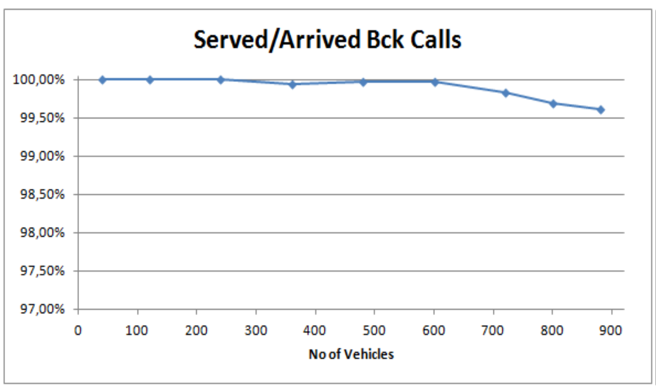


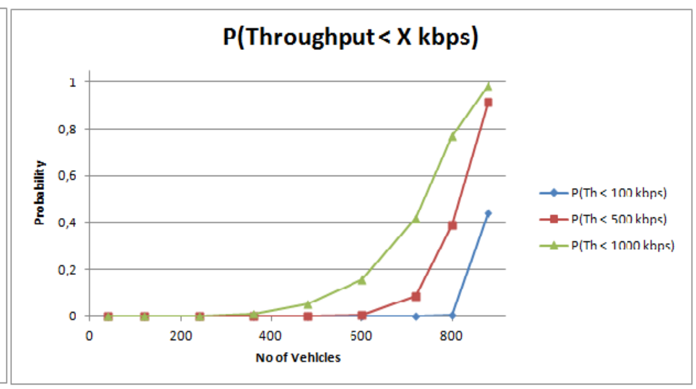
Parameter: N° of Vehicles (10 Hz - SPS)

No of veh/lane/km	Total No of vehicles	Mean beacon delay (ms)	Percentage > 50 ms:	Percenage > 100 ms:	Control Overhead	Load on the Network:	Calls Served/Arrived:	Throughput (kbps):	Percentage < 100 kbps:	Throughput < 500 kbps:	Percentage < 1000 kbps:
5	40	60,1971	0,6	0,10625	16,00%	35,61%	100,00%	4334	0	0	0
15	120	60,4813	0,61	0,11	14,00%	40,22%	100,00%	4013	0	0	0,00047
30	240	60,3854	0,61	0,11	12,00%	50,87%	100,00%	3359	0	0	0,002
45	360	60,4324	0,61	0,11	12,00%	58,94%	99,95%	2836	0	0	0,0129
60	480	60,4315	0,61	0,11	10,00%	68,71%	99,98%	2223	0	0,0004	0,053
75	600	60,4151	0,61	0,11	8,00%	77,27%	99,97%	1709	0	0,0069	0,1541
90	720	60,4372	0,61	0,11	6,00%	85,44%	99,83%	1192	0	0,084	0,4188
100	800	60,3646	0,61	0,11	6,00%	92,25%	99,70%	709	0,0055	0,3918	0,7687
110	880	60,3618	0,61	0,11	4,00%	98,07%	99,61%	196	0,443	0,9143	0,9863



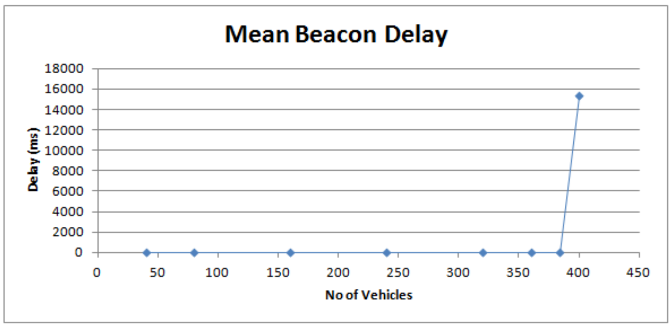


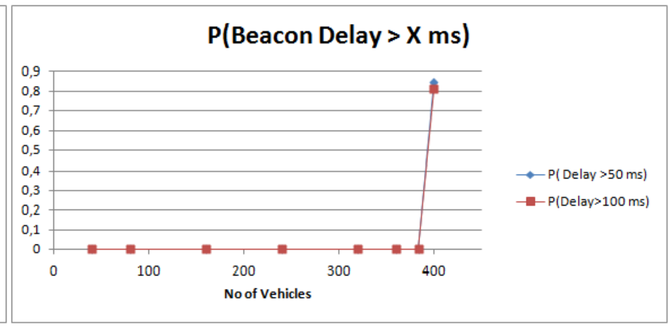


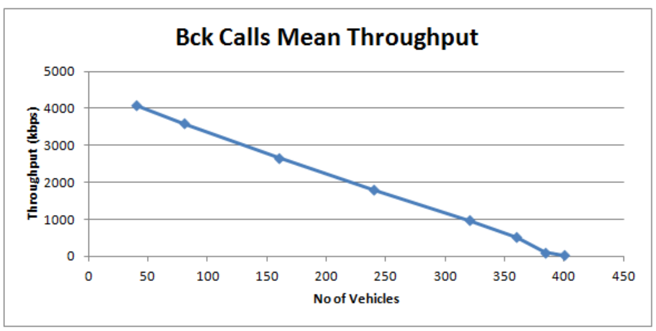


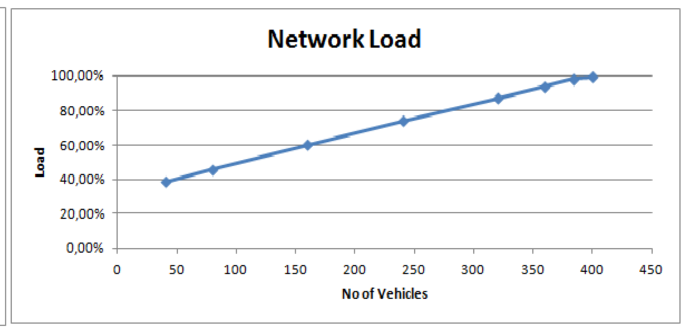
Parameter: N° of Vehicles (20 Hz)

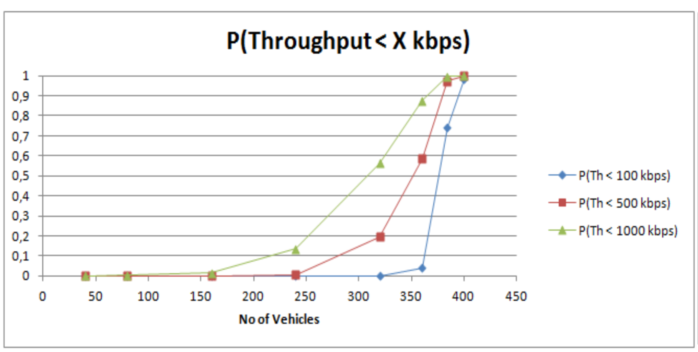
No of veh/lane/km	Total No of vehicles	Mean beacon delay (ms)	Percentage > 50 ms:	Percenage > 100 ms:	Load on the Network:	Calls Served/Arrived:	Throughput (kbps):	Percentage < 100 kbps:	Percentage < 500 kbps:	Percentage < 1000 kbps:
5	40	18,3636	0	0	38,41%	100,00%	4078	0	0	0
10	80	18,3349	0	0	45,73%	99,98%	3592	0	0	0,003
20	160	18,4643	0	0	60,12%	100,00%	2670	0	0	0,015
30	240	18,403	0	0	73,95%	100,00%	1803	0	0,007	0,135
40	320	18,7946	0	0	87,18%	99,95%	974	0	0,196	0,563
45	360	19,7652	0,00000077	0	94,04%	99,90%	523	0,04	0,586	0,875
48	384	23,2538	0,001765	0	98,05%	99,70%	102	0,741	0,973	0,996
50	400	15354,9155	0,8498	0,812	99,26%	98,04%	27	0,981	0,998	1

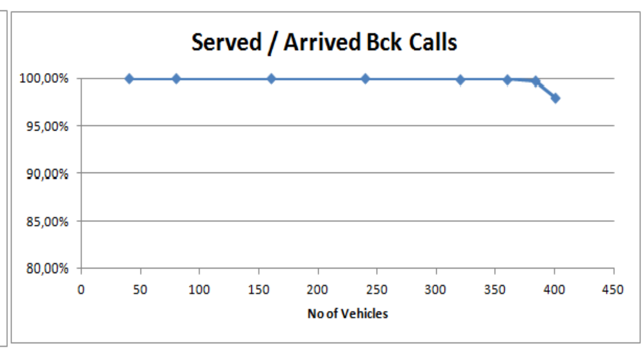






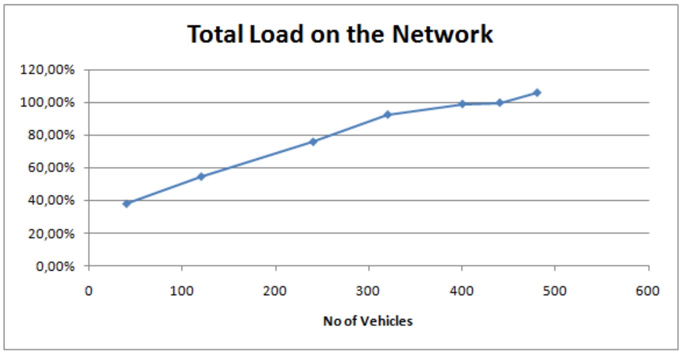


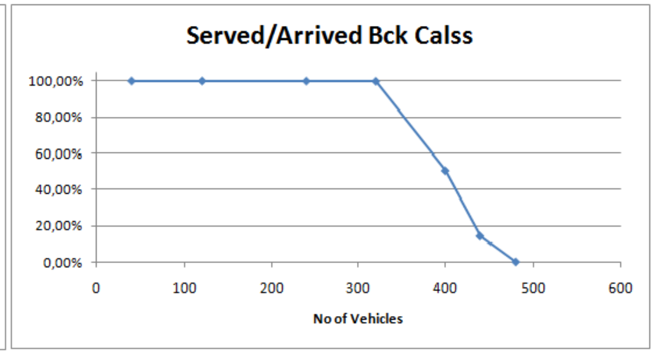


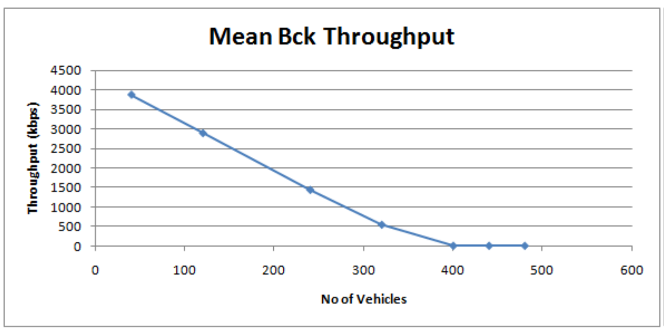


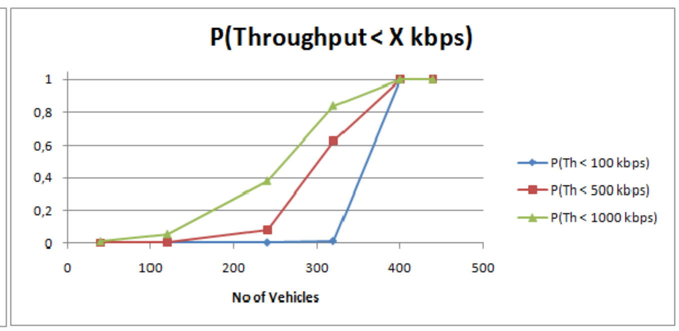
Parameter: N° of Vehicles (20 Hz - SPS)

No of veh/lane/km	Total No of vehicles	Mean beacon delay (ms)	Percentage > 50 ms:	Percenage > 100 ms:	Control Overhead	Load on the Network:	Calls Served/Arrived:	Throughput (kbps):	Percentage < 100 kbps:	Percentage < 500 kbps:	Percentage < 1000 kbps:
5	40	35,2333	0,1998	0	14,00%	37,83%	100,00%	3883	0	0	0,0088
15	120	35,3719	0,208	0	12,00%	54,40%	100,00%	2894	0	0,000975	0,05502
30	240	35,3561	0,20845	0	10,00%	75,64%	99,94%	1437	0	0,0814	0,3801
40	320	35,4514	0,2098	0	8,00%	92,29%	99,87%	542	0,00935	0,6279	0,842
50	400	35,4266	0,2084	0	6,00%	98,77%	50,34%	3,2	0,9984	1	1
55	440	35,433	0,2083	0	4,00%	99,59%	14,16%	1,6	1	1	1
60	480	35,416	0,1974	0	4,00%	105,68%	0,00%	0	0	0	0



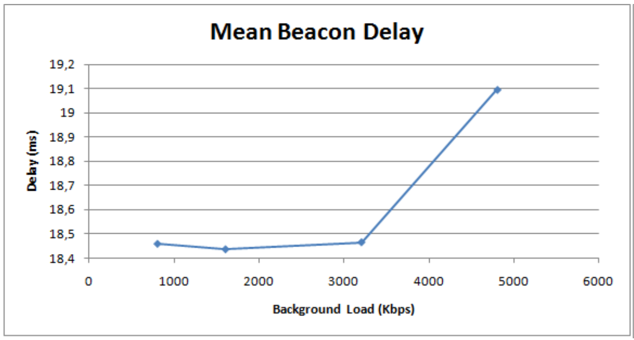


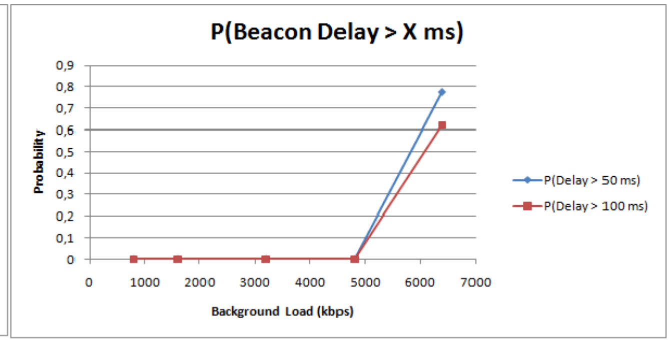


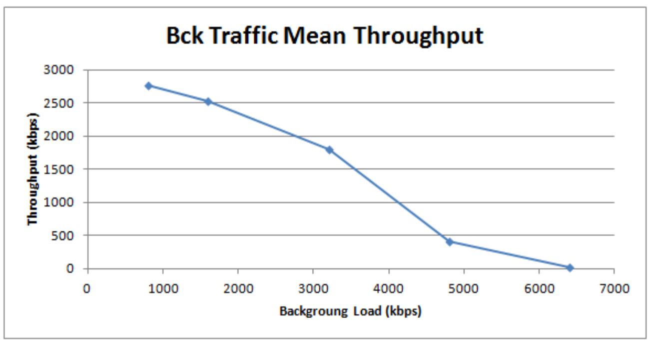


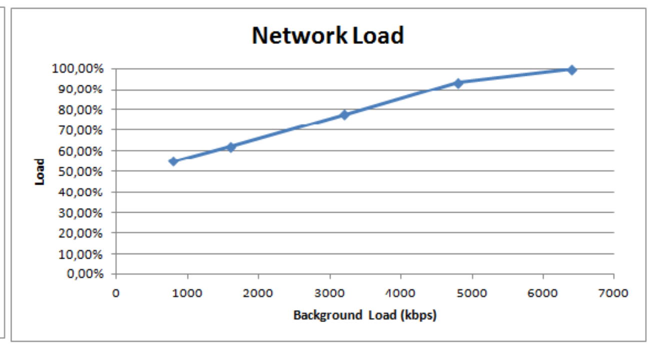
Parameter: Background traffic

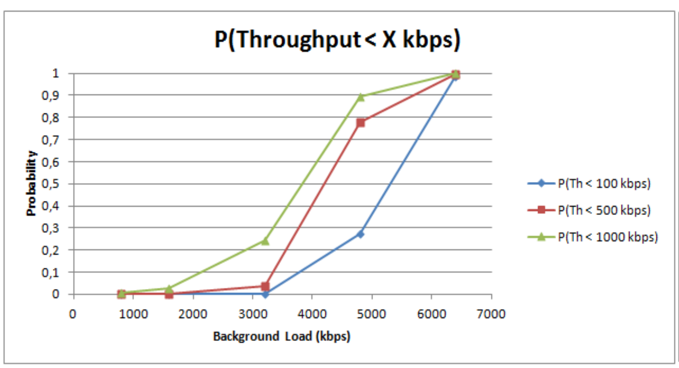
Avg Bck Call Size	Arrival Rate (λ)	Background Load (kbps)	Mean beacon delay (ms)	Percentage > 50 ms:	Percenage > 100 ms:	Load on the Network:	Calls Served/Arrived:	Throughput (kbps):	Percentage < 100 kbps:	Percentage < 500 kbps:	Percentage < 1000 kbps:
800	1	800	18,4592	0	0	55,01%	100,00%	2769	0	0	0,0045
800	2	1600	18,4362	0	0	62,20%	99,98%	2535	0	0,0004	0,0253
800	4	3200	18,4654	0	0	77,78%	99,97%	1806	0	0,0373	0,2446
800	6	4800	19,0967	0	0	93,34%	99,95%	415	0,2728	0,7766	0,8949
800	8	6400	128267	0,776	0,621	99,69%	93,90%	15	0,984	0,997	0,999

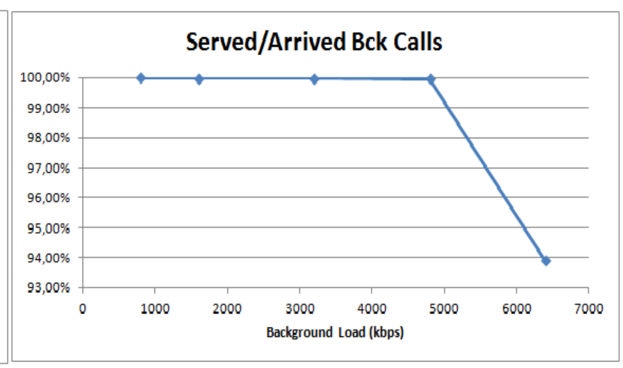






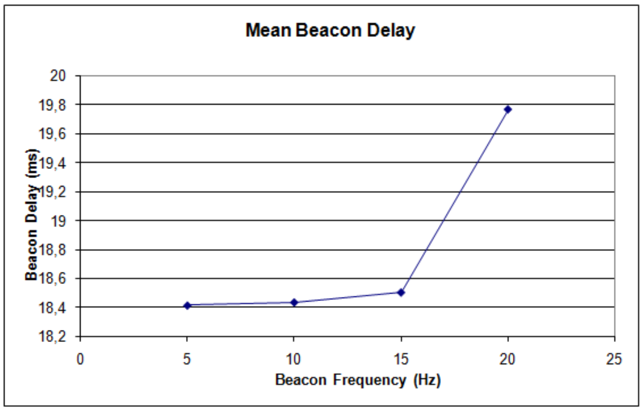


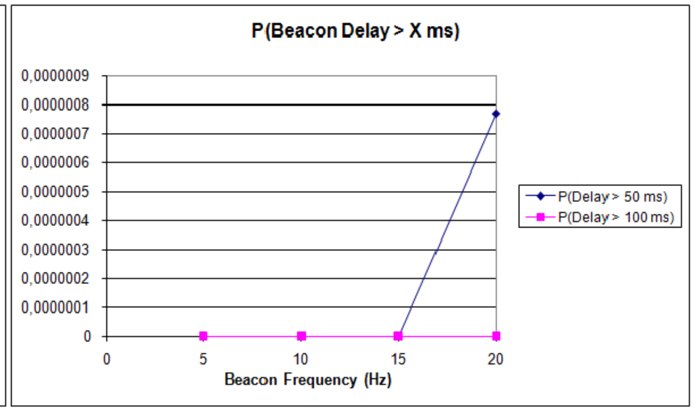


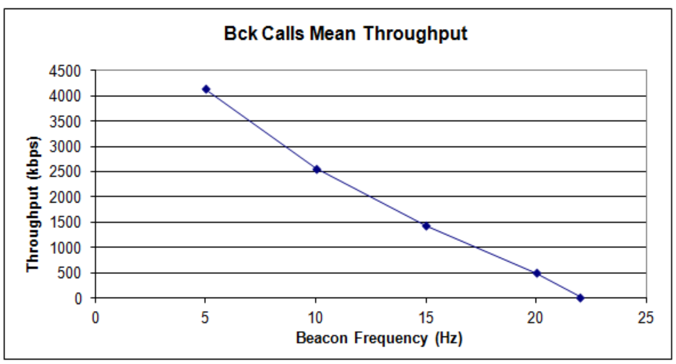


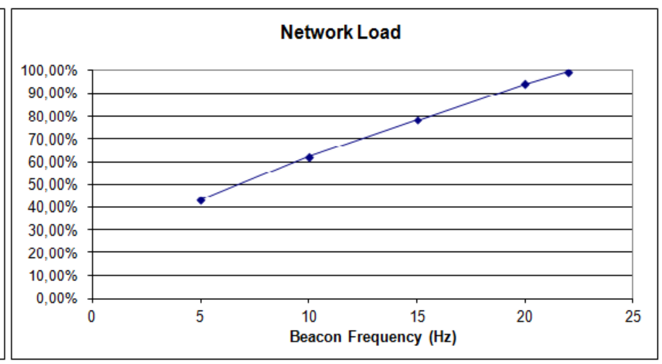
Parameter: Beacon Frequency

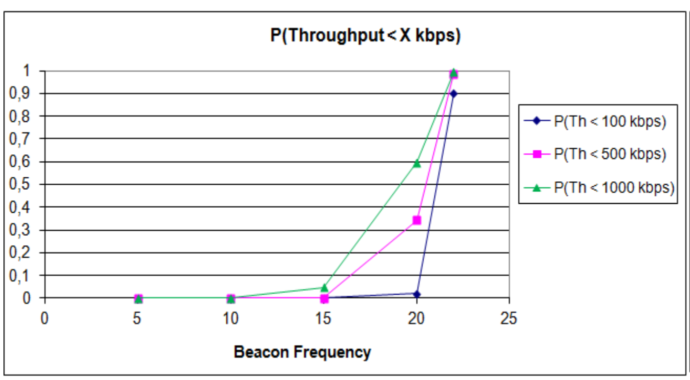
Beacon Frequency (Hz)	Total No of vehicles	Mean beacon delay (ms)	Percentage > 50 ms:	Percenage > 100 ms:	Load on the Network:	Calls Served/Arrived:	Throughput (kbps):	Percentage < 100 kbps:	Percentage < 500 kbps:	Percentage < 1000 kbps:
5	360	18,4152	0	0	43,37%	100,00%	4141	0	0	0,00015
10	360	18,4363	0	0	62,20%	99,98%	2560	0	0	0,00175
15	360	18,5049	0	0	78,15%	100,00%	1430	0	0,00175	0,0466
20	360	19,7652	0,00000077	0	94,04%	99,90%	503	0,02	0,3426	0,5978
22	360	10619	0,7	0,6625	99,21%	98,44%	28	0,9016	0,9874	0,9943

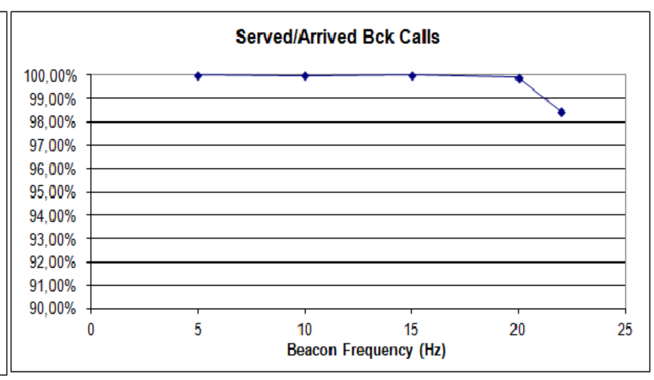






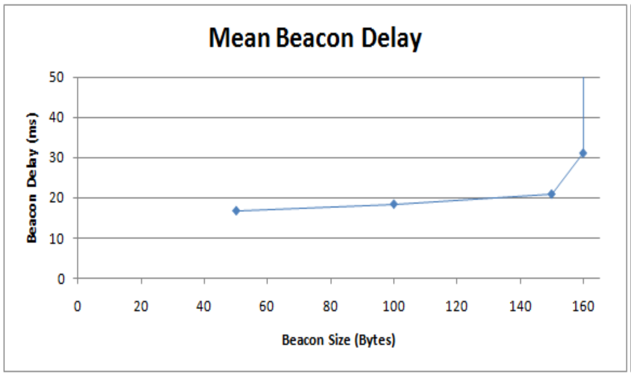


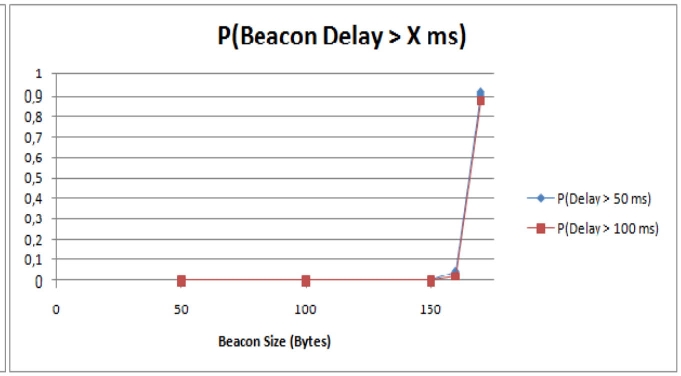


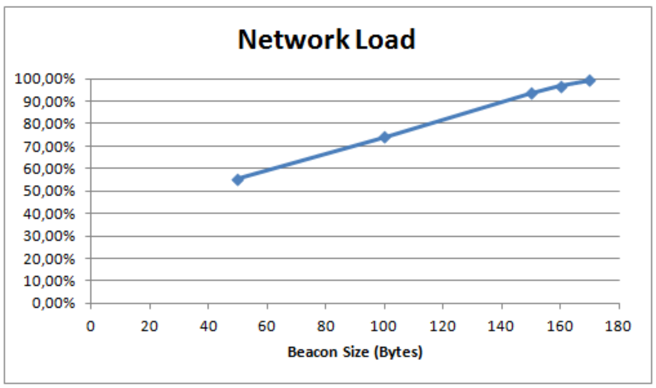


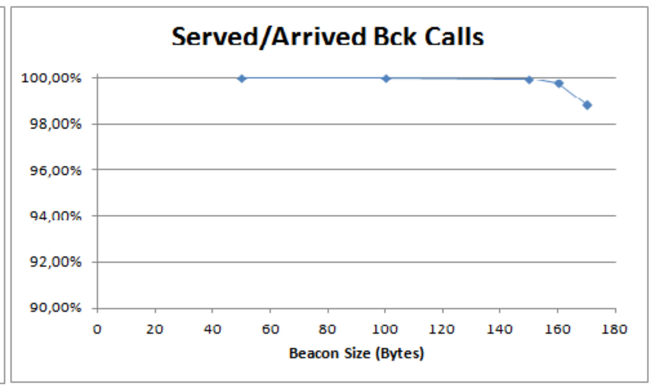
Parameter: Beacon Size

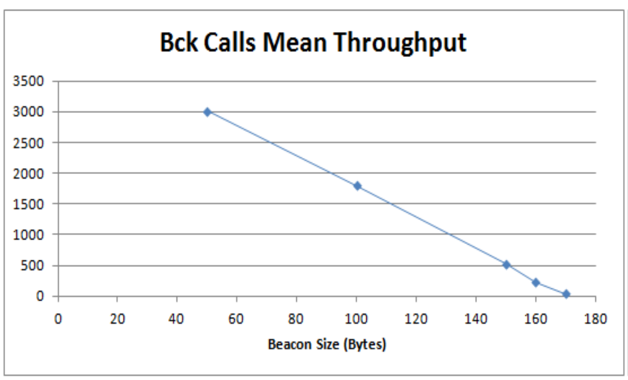
Beacon Size (Bytes)	Total No of vehicles	Mean beacon delay (ms)	Percentage > 50 ms:	Percenage > 100 ms:	Load on the Network:	Calls Served/Arrived:	Throughput (kbps):	Percentage < 100 kbps:	Percentage < 500 kbps:	Percentage < 1000 kbps:
50	240	16,7583	0	0	55,50%	100,00%	3012	0	0	0,0059
100	240	18,4031	0	0	73,95%	100,00%	1803	0	0,0077	0,135
150	240	20,9301	0,000005727	0	93,72%	99,97%	526	0,036	0,594	0,874
160	240	31,207	0,04313	0,0185	96,67%	99,77%	226	0,406	0,896	0,978
170	240	24884	0,911	0,8785	99,20%	98,86%	44	0,959	0,994	0,999

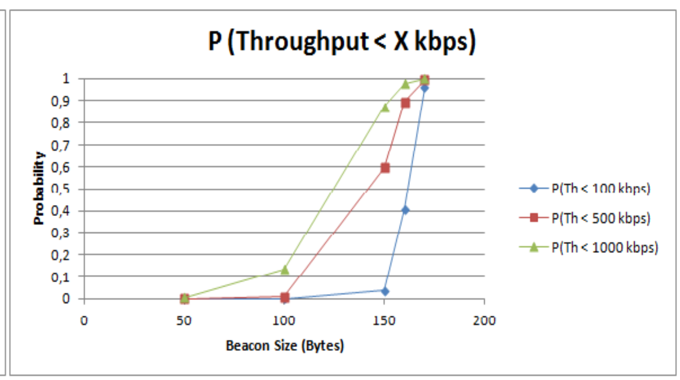






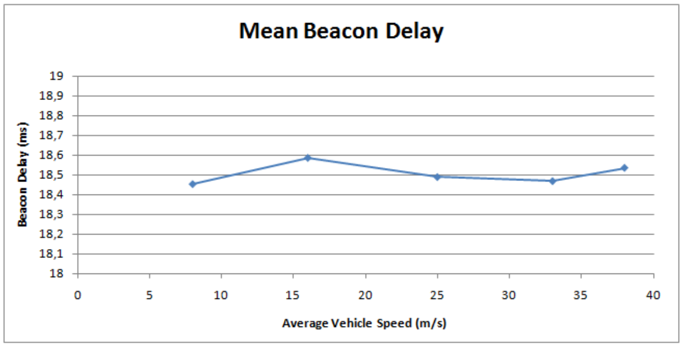


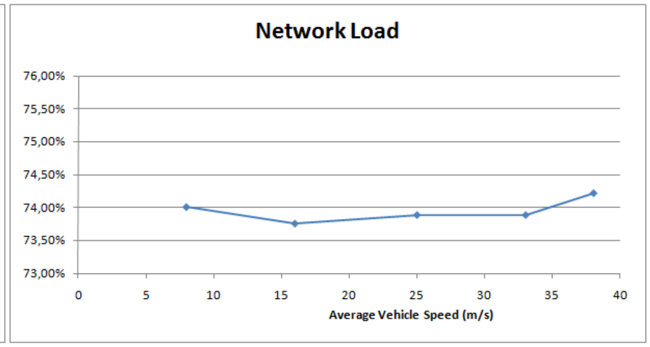


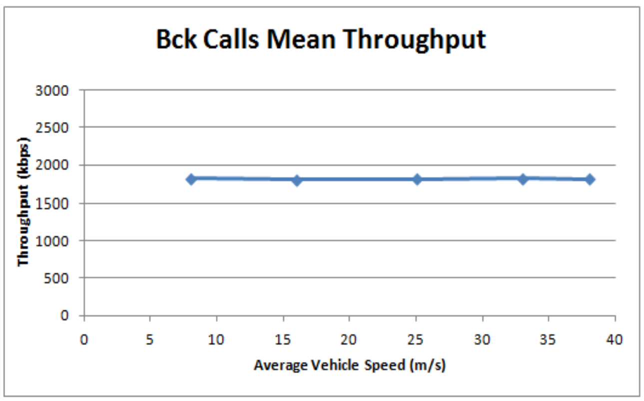


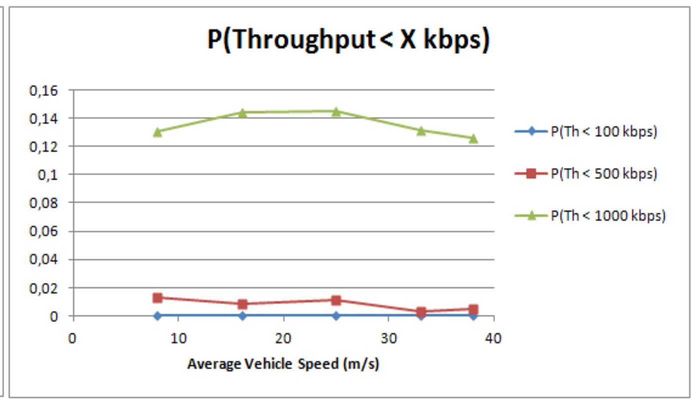
Parameter: Vehicle Speed

Vehicles Avg Speed (m/s)	Total No of vehicles	Mean beacon delay (ms)	Percentage > 50 ms:	Percenage > 100 ms:	Load on the Network:	Calls Served/Arrived:	Throughput (kbps):	Percentage < 100 kbps:	Percentage < 500 kbps:	Percentage < 1000 kbps:
8	240	18,4527	0	0	74,01%	100,00%	1819	0	0,0132	0,1303
16	240	18,5827	0	0	73,76%	99,95%	1801	0	0,0085	0,144
25	240	18,4874	0	0	73,89%	99,97%	1806	0	0,0109	0,145
33	240	18,4675	0	0	73,89%	100,00%	1821	0	0,0034	0,1314
38	240	18,5335	0	0	74,22%	99,99%	1813	0	0,0054	0,126



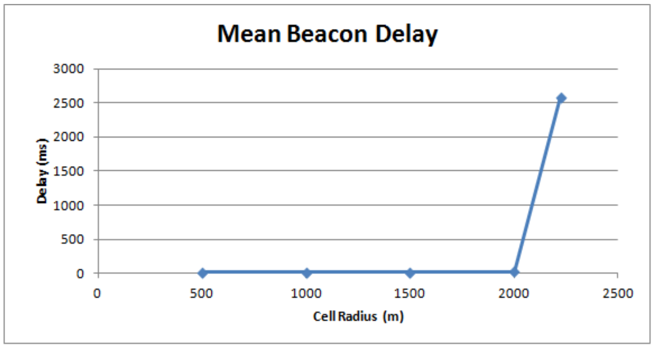


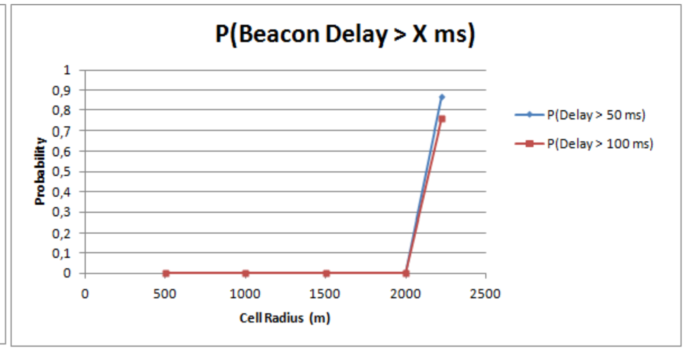


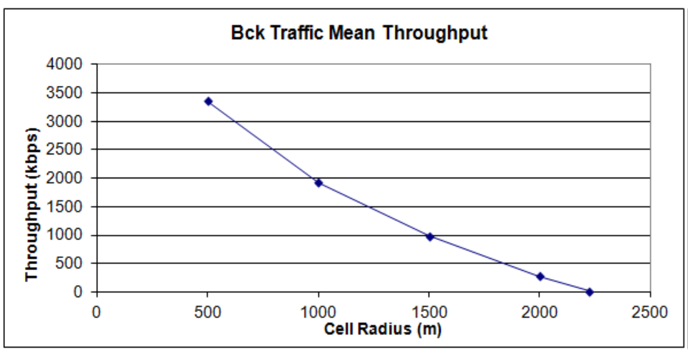


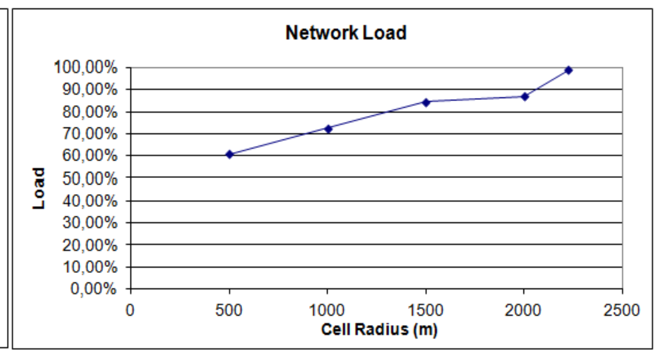
Parameter: Cell Radius

Cell Radius (m)	Total No of vehicles	Mean beacon delay (ms)	Percentage > 50 ms:	Percenage > 100 ms:	Load on the Network:	Calls Served/Arrived:	Throughput (kbps):	Percentage < 100 kbps:	Percentage < 500 kbps:	Percentage < 1000 kbps:
500	480	17,4788	0	0	60,73%	100,00%	3352	0	0	0,0027
1000	480	18,4594	0	0	72,54%	100,00%	1920	0	0,0048	0,107
1500	480	19,473	0	0	84,65%	100,00%	987	0	0,2029	0,575
2000	480	23,6284	0,003054	0	87,11%	99,78%	278	0,263	0,848	0,966
2225	480	2585	0,8709	0,7613	99,11%	96,59%	20	0,97	0,997	0,999









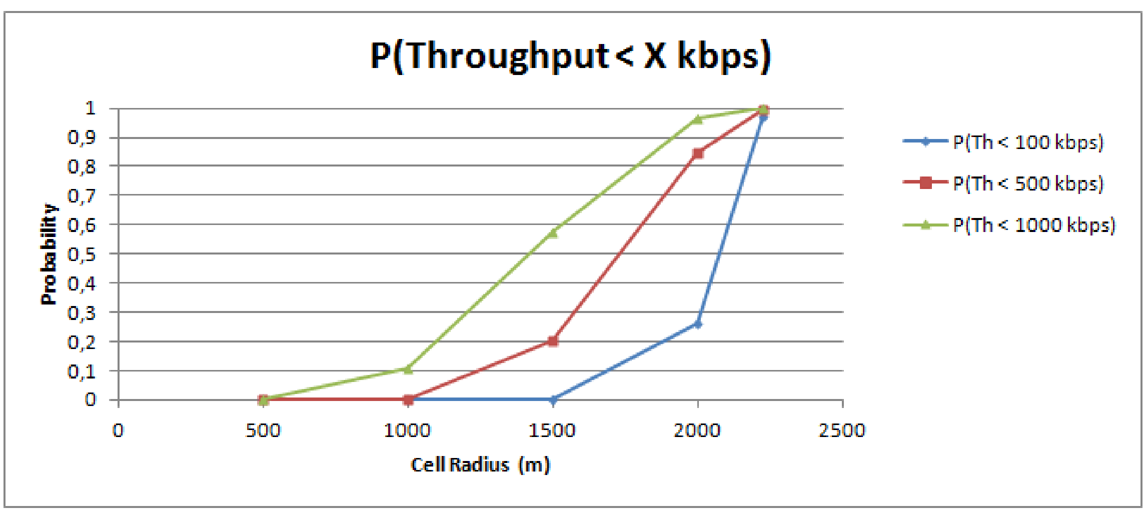


EXHIBIT 3

INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

High Accuracy Location Based Services Cost Benefit Study: Final Report

Adam Goodliss, Christian Manasseh, Venkatesan Ekambaram, Raja Sengupta, Adib Kanafani, Kannan Ramchandran

Research Report
UCB-ITS-RR-2011-1

May 2011

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Acknowledgment

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I. Executive Summary

This report presents a benefit and cost study of a Cooperative High-Accuracy LOcation (C-HALO) service. The Department of Defense operating the GPS constellation guarantees a location service accurate to 7 meters 97% of the time. Using this as a baseline, we define the High Accuracy Location service to be sub-meter (alternatively, decimeter) level accuracy. This report is about the costs and benefits of realizing a location service with sub-meter accuracy in the United States.

There are several GPS augmentation technologies aimed at enhanced accuracy. Some such as Inertial Navigation Units are on the rovers and entail no new infrastructure. Others such as DGPS, N-RTK or HAN-DGPS, build new infrastructure to assist new rover units. In our definition, these augmentations only constitute a high accuracy location service, if they entail a promise like the one provided by the DoD for the GPS constellation, e.g., Infrastructure X provides a location service accurate to 1 meter or better Y% of the time. A High Accuracy Location service should be ubiquitous and reliable, like its LALO[1] equivalent, the GPS constellation.

The business model of the Inertial Navigation Unit industry envisages no such guarantee. The ubiquity of any higher accuracy outcome of GPS/INS fusion is left entirely to the purchaser of the unit, if anybody at all. On the other hand, our literature and market survey suggests, the N-RTK market does entail guarantees or promises like the one from the DoD for GPS. The N-RTK service providers seek to assure customers that the ubiquity or reliability of their high accuracy location service will be adequate. HAN-DGPS is a public sector infrastructure build that could also provide assurances. Hence this report discusses the details and salient features of these infrastructures. We do not study the INS industry.

We have surveyed the literature on location services, and discovered a body of work on the benefits of a high accuracy location service. The literature establishes the benefits of high accuracy location to industries such as agriculture, construction, mining, and aerospace. Chapter III summarizes this literature. We focus on road travel and the findings suggest this focus is worthwhile. Chapter IV of this report quantifies the benefits of HALO services to road travel, and estimate benefits to be between $160 billion and $320 billion. This translates into 1.1 to 2.2 percent of the current US GDP. The estimated benefits are gross benefits over a time horizon of 22 years discounted to the present day value. They do not account for the costs of implementation. The range depends on whether one uses the low-level or mid-level efficacy assumptions. The benefits arise from smoother traffic flow on the roads leading to reduced travel delays, and fewer accidents leading to reduced injuries and saved lives. We expect HALO to also yield climate-change and public health benefits through its enabling of smoother traffic flow but have been unable to quantify these benefits for this report.

The assessment of the costs associated with these benefits has two challenges. One must assess where new infrastructure is required and how much each installation might cost. To understand where HALO

[1] Low Accuracy LOcation

services need new infrastructure it helps to think of places with "good" GPS coverage as distinct from "bad" GPS coverage. This is the subject of Chapter V. The chapter presents a way to process data from a county assessor's office and divide the county into good and bad GPS areas. The method is illustrated by application to San Francisco. When 6 or more satellites are visible and they are well spread out, GPS accuracy is good and enhancements such as N-RTK or HAN-DGPS make it even better, resulting in decimeter or even centimeter level accuracy. When the number of GPS satellites is lower, GPS errors can be over a meter and these augmentations are less effective. Some other kind of technology, perhaps pseudolites, is required. We call the area not well served by the GPS constellation, the "bad GPS" area or "dark area." We expect tall buildings in urban areas to reduce satellite visibility on streets. Likewise, tall trees can occlude satellites. Thus urban canyons or parkways in wooded area would be part of the dark area or bad GPS coverage areas.

The existence of the N-RTK market makes the distinction between good and bad GPS areas useful. Since N-RTK realizes HALO in good GPS areas, HALO services for good GPS areas are more advanced than HALO services for bad GPS areas. There are no significant location services sold in the US consumer market for bad GPS areas. Therefore the work in chapter V computing the percentage of the road area that is "good" and "bad" GPS coverage provides insight into how much of HALO needs fundamentally new location infrastructure that is not GPS augmentation, and how much could potentially be achieved by leveraging GPS augmentation methods such as HAN-DGPS or N-RTK market.

Finally, for good GPS areas, chapter V presents infrastructure cost numbers based on N-RTK. There are enough N-RTK deployments to collect and compare these numbers. We assess the current cost to be $560,000 to $1.6 million per base station over a time horizon of 22 years covering a 60x60 sq.km area. A simple linear scaling, puts this at 1.6 to 4.4 billion nationwide, of the order of 1% of the benefits of HALO estimated to accrue from road travel alone. We have been unable to do the same for bad GPS areas.

The good and bad GPS coverage classification method in chapter V is GIS based. It produces a map with good and bad areas marked on it. Other GIS data can be over-layed to visualize the value of enabling HALO services in a particular place. We overlay accident data. One can spot the bad GPS streets coincident with higher accident rates. The idea is to spot the streets where one gets a bigger bang for the buck. The other good news in our findings, is that out of the total 121 sq km. area of San Francisco (121 sq.km), only 0.3 to 4% of the San Francisco streets fall in the "dark" area. This range is the 95% confidence interval. Since the dark areas are few and we can spot them, one can target new investment to areas yielding safety or mobility benefits. If an area is estimated by us to be dark, we know new high accuracy location infrastructure beyond GPS augmentation methods is required with high confidence. Our model does not say the converse with high confidence, i.e, GPS augmentation technologies like N-RTK will work in the "light" areas. This is because even in the "good" GPS areas with sufficient satellite coverage the errors can be quite large due to multipath effects.

II. Motivation

The study is motivated by the possibility of the benefits of High Accuracy (sub-meter) Location being large, such a service being technologically feasible, and deployable at reasonable cost.

The high benefit argument rests on research showing vehicle-based collision avoidance systems can reduce accidents (8). The systems require location services accurate enough for a vehicle to discriminate its lane, which in turn requires sub-meter accuracy (30). Likewise high-speed tolling or intelligent traffic light control also requires lane discrimination and sub-meter accuracy. Since the economic cost of lives lost in accidents is high as is the economic cost of delays due to traffic congestion, the benefits of HALO as a critical enabler of services mitigating accidents or congestion should also be high.

The technological feasibility argument rests on the proliferation of GNSS[2] systems and services. GPS has become a stable component of global economic activity. Other GNSS such as GLONASS and Galileo, are becoming established. Technologies such as DGPS, GPS-WAAS, GPS+INS, GPS-RTK, and Network RTK(2,3) have been developed and partially deployed in recent years. Limited-coverage pseudolite-based systems are also available (61-63). Ultra Wide Band systems coupled with RTK (66,67) are being proposed to achieve high levels of accuracy in multipath rich environments. Wide-area multi-lateration systems (4) are being substantially deployed around airports for aircraft and ground vehicle tracking. Inertial Navigation Systems are rapidly dropping in cost even as the rise in accuracy. All of these suggest there may be many options in the market or near-to-market that might be leveraged to realize a ubiquitous and reliable HALO service.

Many of these new location options will rely on the ubiquitous availability of mobile communication services. HAN-DGPS requires ubiquitous broadcast communication from base station to mobile, and N-RTK ubiquitous unicast communication between infrastructure and mobiles. Here too the rise of 3G, 4G (65), Dedicated Short Range Communications (DSRC) (64), software defined radio (5), smart antenna systems (6), and other techniques, along with use of vehicles as excellent mobile communication platforms (7), may provide for advancements in positioning techniques and integrated systems.

The market analysis and literature review section indicates a lack of coverage of the benefits of C-HALO technology to the Transportation domain in general and ITS in particular. From the literature presented, efforts exist that attempt to quantitatively estimate the costs and benefits of high accuracy location data. These efforts are mostly market wide, or specific to an individual industry that is not transportation. In addition, plenty of literature exists to understand the costs and benefits of implementing certain ITS applications like curve speed warnings (8), or intelligent signal control systems (9). This later effort usually addresses the particular application under study and does not analyze the monetary benefits to the market; their results are presented in number of accidents reduced or total vehicle miles saved by the deployment of the application.

[2] Global Navigation Satellite System

This lack of coverage of the transportation industry motivates us to tackle the job of estimating the economic benefits that could be reaped from a C-HALO nationwide deployment to the ITS sector of the transportation domain. It is the objective of this analysis to develop an exhaustive list of ITS applications that require high accuracy location data to realize the costs of implementation and the expected economic benefits that accompany each application.

This study aims at providing a tool enabling government and private funding agencies to assess the benefits of investing in a new breed of positioning technologies and wide-scale deployments to meet the goals first noted above. It will shed light on the range of costs of the most promising technologies, their integration, and phases of deployments leading to a nationwide C-HALO infrastructure.

III. Literature Summary

We have reviewed existing GNSS related market analyses and cost benefit studies done by others on various sectors of the economy and in various parts of the globe. This section summarizes our findings.

A. Market Analysis

Rob Lorimer of Position One Consulting performed a three year projection on the GNSS global market in his report titled: GNSS Market Research and Analysis September 2008 (10). Based on this report and analysis, we created a table of global positioning companies, along with which industry(ies) each company is involved in. The complete table is included as Appendix A.

The table identifies the three most ubiquitous providers of GNSS-based services as Leica Geosystems, Trimble, and TopCon/Sokkia. Omnistar is also relevant in many industries, but they are mainly focused on precision augmentation services, while the other three are more vertically integrated, and typically incorporate numerous levels of the value chain. Interviews conducted by Lorimer with the CEO's of the companies listed in Appendix A (10) provided insight into the industries that are major consumers of location services. The biggest consumers are the Aerospace, Agriculture, Autonomous Vehicles, Construction, Defense, Maritime, Mining, and Surveying industries. Clearly void from this list is the transportation sector, which we choose to analyze as part of this CBA. Benefit estimates have been completed in some of these industries and are discussed in more detail in the subsequent section.

B. Published Benefit Analysis Reports of Various GNSS

The Allen Group (11) estimated the economic benefits of C-HALO type technology in three specific Australian industries: Agriculture, Mining, and Construction. The Allen Group determined the benefits to be between $100 and $200 billion, approximately 10 to 20 percent of Australian GDP. These three markets make up approximately 10 to 13 percent of GDP. Assuming that the U.S. transportation market makes up 5 percent of GDP, a simple linear scaling of the Allen Group's numbers suggests the HALO benefits derived from the transportation sector alone should be 4 to 9 percent of GDP, which would be approximately $560 to $1.2 billion in benefits. We find $160 to 300 billion. These benefit numbers appear conservative in relation to the Allen Group study.

We have incorporated a key piece of the Allen Group report in our method. The adoption rate for the C-HALO technology is represented by this studies' industry-wide national rollout adoption scenario.

A socio-economic benefit study was commissioned by US Department of Commerce (DoC) (12) to determine where there is value added by the CORS and GRAV-D systems. The study is focused on the benefits derived from the increased vertical accuracy of GPS. We do not consider this dimension at all. The study suggests the surveying and mapping industry will be the most significantly impacted, but goes on to list other possible industries like construction, agriculture, environmental science, and transportation. Again this reiterates the fact that researchers are continuing to view transportation as a realm for potential benefits from C-HALO technology. The US DoC study assesses benefits utilizing the productivity methodology, which is typical and similar to the methodology used in our study and many others contained in the literature review. One slight difference to our methodology is that their time horizon is 15 years while ours is 20 years.

Alcantarilla, et al. analyze the benefits of a multi-constellation system, versus a stand-alone GNSS system, and ultimately a SBAS approach (14). A piece that may be of importance to us when discussing the costs is the distribution of the number of satellites in view. They conduct a simulation of an urban environment and contend that with GPS & Galileo 65% of the area is covered by more than 3 satellites, while 20% is covered by 3, and 15% by less than 3. They then go on to qualitatively discuss the principal pieces of a future GPS system along with the envisioned benefits of multi-constellation GNSS SBAS augmentations. Similar analysis is carried out by Zabic et al. (68) but with actual data in Copenhagen. They estimate the average satellite availabity in Copenhagen through extensive data collection and use simulation tools to predict the improvement in satellite availability with the addition of Galileo.

Swann, et al. discuss the qualitative benefits of location-based services, the architectural issues involved in multi-constellation systems, and the market aspects that need to be addressed for deploying multi-constellation systems (15). They focus on the benefits of reliability of a combined GPS/Galileo signal where availability is at 99.7% in their Stuttgart analysis. In addition, they estimate the GNSS service provision market to be 135 billion Euros by 2015 with a significant portion of that residing in the transportation industry. This is significantly higher than what Lorimer's report quotes for the U.S. market by 2012, which is around $9 billion.

Vollath, et al. aimed to look at how NRTK and the third frequency to be offered by Galileo will interact (16). Vollath et al. present the value of the Galileo third frequency in allowing higher horizontal accuracy and increasing distances between base stations among other things. NRTK, however, still proves to be more accurate in the vertical direction. Ultimately, they do not assess the monetary benefits, but only the technical reliability. They conclude that NRTK will not be replaced by the Galileo new third frequency, but that the two could be used as complimentary technologies.

Arthur, et al. delve deeper into the impacts of Galileo by going beyond cost benefit analyses and conducting specific input-output models (17) which actually predict economic output rather than just analyzing costs and benefits. They even go as far to suggest that some 'market externality' impacts, like induced effects, could be twice as large as the direct impacts. They also suggest how to enhance a CBA by including innovation effects (through supply-push or demand-pull forces), or market and social externalities. These types of analyses could be worthwhile as future work. They are not included in this report.

Brennan, et al. wrote National PNT Architecture: Interim Results to facilitate the decision making process on a national PNT architecture for the United States by 2025(18). It does not focus on costs or benefits in quantitative terms. It does however evaluate many different technological options to achieve their stated goals. Ultimately, they want to put together a transition plan from an "as is" architecture to a "should be" architecture. Unfortunately, this is not directly related to our CBA.

C. Existing C-HALO Type Deployments

In order to understand the existing C-HALO deployments and technologies, we reviewed the initiatives undertaken by the government agencies. The material here is based on reports (56) and (59) provided by the Federal Highway Authority. The earliest deployments were the Differential GPS (DGPS) base stations by the US Coast Guard for maritime services. These base stations broadcast the actual and measured pseudo-range differences of the received code measurements from the different satellites. These error measurements are used by GPS receivers to calibrate their own measurements resulting in accuracies as high as 1m under good line-of-sight conditions. The corrections are broadcast typically in the longwave frequency range between 285kHz and 325kHz. The U.S. Army Corps of Engineers (USACOE) later realized the benefits of accurate localization and efforts were made to increase the coverage of the DGPS base stations (56). This resulted in the N-DGPS or nationwide DGPS program under which a total of around 137 base stations were to be installed nationwide to provide accurate localization services. The defense establishment also found need for decimeter and centimeter level accuracies. This could be obtained by sending corrections to the carrier phase received by the DGPS stations, as the carrier frequency of GPS is 1000 times higher than the frequency of the modulated code sequence. Hence one could obtain very high accuracies by measuring the carrier phase. This technology came to be known as RTK or Real Time Kinematic positioning and the proposed system implementation by government agencies has come to be known as HA-NDGPS – High Accuracy NDGPS (56).

One of the challenges of HA-NDGPS is that the allocated bandwidth does not suffice for broadcasting the carrier measurements for all the satellites (59). This requires compression of the phase measurements. This work is still in progress. Prototypes of this system were deployed and evaluated (56). During deployment it was found that, if a receiver obtained corrections from more than one base station, a combination of the measurements provided higher accuracies. More sophisticated combination could provide still higher accuracies, and this is the proprietary technology used in N-RTK or Network RTK, a service, provided by companies such as Leica, Trimble etc. The N-RTK service has two methods of operation (71). The Virtual Reference Station (VRS) method as adopted by agencies like Trimble is a unicast system where the GPS receiver contacts a central server, which in turn computes the corrections from the set of receiver stations in the vicinity of the receiver and gives an estimate of the receiver's location. The Master Auxiliary Concept (MAC) method allows for a broadcast system wherein a single master reference station amongst a cluster of reference stations in a cell, broadcasts the corrections. The rover in turn interpolates these corrections to estimate the corrections at its location. The MAC method also allows for a two-way mode where the reference station calculates the corrections for the rover as in the case of VRS. In our opinion, the question of whether one would want to adopt a unicast system or a broadcast system depends on the application. For a large-scale application like Intelligent Transportation Systems, it might be desirable to have a broadcast system and have all the intelligent processing done at the GPS receiver as compared to a central server. If every vehicle is required to know its location accurately, it is more efficient to broadcast the error measurements to all the vehicles in contrast to every vehicle contacting a centralized server to compute its location estimate since the error measurements would be common to all the vehicles in a particular region of interest.

HA-NDGPS is the technology that is being standardized by the federal DOT as the technology of choice for achieving high accuracy positioning for ITS applications. The federal DOT has commissioned a couple of pilot programs to improve on this technology to achieve cm level accuracies nationwide. The pilot sites are in Maryland and Pennsylvania and the research is being headed by the Turner Fairbanks Highway Research Center. The current and planned coverage areas are in the map below:

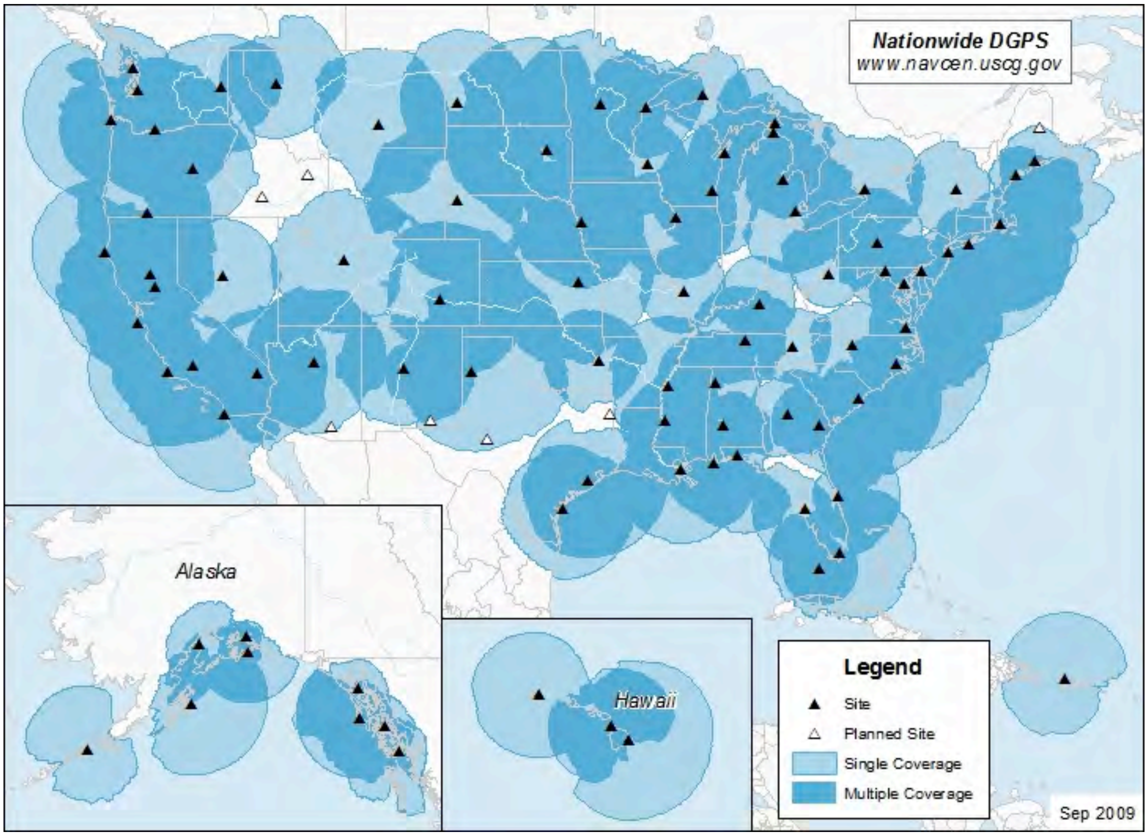

Figure 1 HA-NDGPS Coverage Area

Additionally, we have researched state run, cooperative and private run positioning and augmentation services. Most of these services are N-RTK corrections. Figure 2 shows the states with N-RTK deployments we have found as of December 2010.

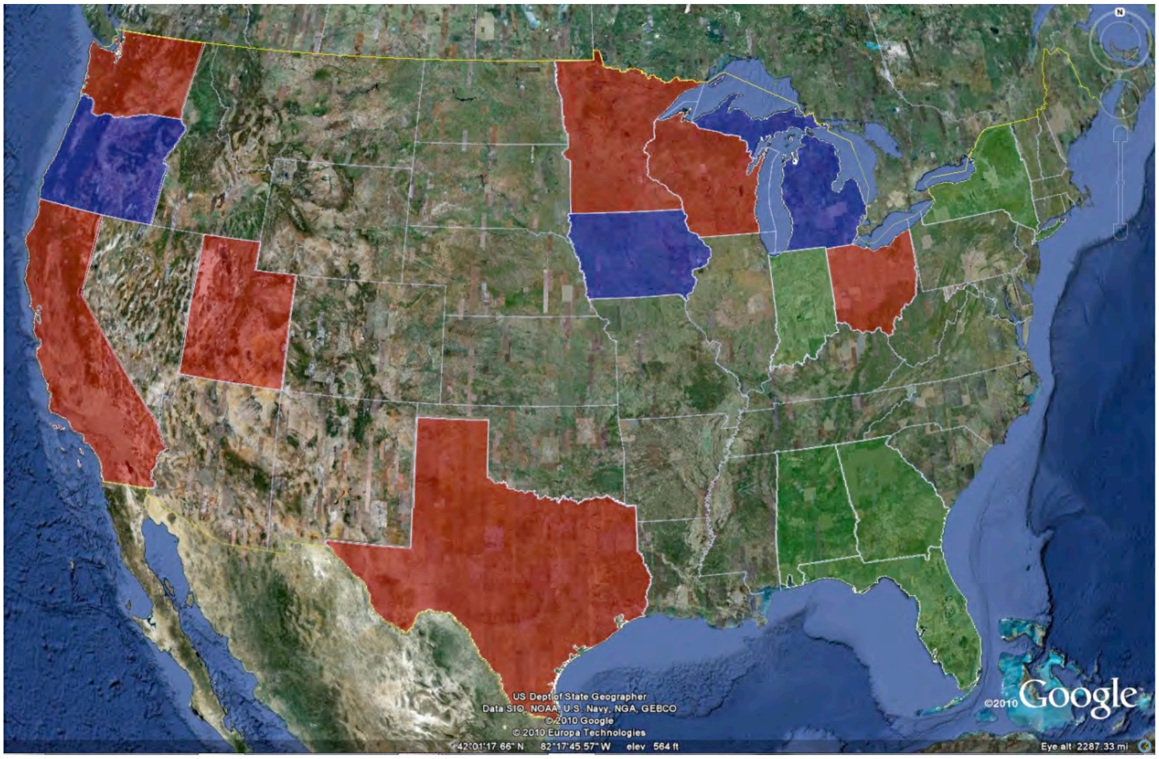

Figure 2 N-RTK Deployments Reviewed (36 – 46)

The red states denote N-RTK deployments partnered with Trimble, while the blue states denote N-RTK deployments partnered with Leica. The green states partners were either unidentifiable or only explored, but never actually deployed, an N-RTK the network. Within this group of states the State run programs and Private/Public Cooperatives are as follows:

Table 1 State N-RTK Deployments (36 – 46)

State DOTs	Public/Private Cooperatives
Utah	Texas
Ohio	Washington
Iowa	Midwest (Indiana)
Oregon	Alabama
California	
Michigan	
Minnesota	
Wisconsin	

Throughout these deployments there are many similarities in infrastructure. The first implementations were in the early 1990s and have continued through the 2000s. From an infrastructure standpoint the industry standard seems to place N-RTK base stations 60km to 70km apart. Most of the deployments have from 50 to 80 base stations. Some of the cooperative deployments continue to grow due to increasing membership, and in addition, some of the nascent state DOT's deployments also have expansion plans in place. All of the deployments offer centimeter level accuracy within their network. (36 – 46)

The networks differ in their access rules. Currently all state DOT networks charge no fee for usage, except for Utah, which just changed policies and began charging $400 annually. The cooperative networks typically charge between several hundred and several thousand dollars annually. On top of this, users must purchase a receiver and applicable cellular plan for the data flow. Cellular plans typically range in the order of $100 while receivers range from several hundred to several thousand depending on capability. (36 – 46)

These costs seem bearable by markets such as Agriculture, Surveying, and Construction services, due to their high use of these state-run and cooperative networks. Only one state, Minnesota, had implemented and deployed N-RTK for transportation purposes. They use the network for snowplows and inner city bus routes. (42)

Three states were questioned for cost information: Iowa, Ohio and Washington. These systems range between $50K and $115K in expenditures per base station to perpetuity. These costs are discussed in further detail in a separate chapter.

To gain further understanding of the availability of C-HALO services, we review private services offered by Omnistar and Leica. (47,48 & 49)

Leica has SmartNet, which is N-RTK coverage, in many states across the United States. Based on SmartNet's service agreement (54, 55), Leica offers 1-2 cm horizontal accuracy and 2-3 cm vertical accuracy under conditions of good satellite coverage, good geometry, and low multipath environments. However we have not been able to locate, from Leica, the percentage of time those conditions are satisfied within their areas of coverage. The map below documents many of the states in which Leica has some private coverage available. Typically this coverage is provided through private investment, and partnerships with other Leica network deployments. The service agreement (54) explicitly mentions that Leica geosystems disclaims warranty to the accuracy of the data created by or passing through the SMARTNET Reference Station Network. Omnistar currently claims 99% availability of C-HALO services in the United States. This is offered using DGPS technology and entails an annual subscription service as well as investment in a GPS receiver. The subscription services range from $800 for the least accurate (sub-meter) to $2500 for the most accurate (centimeter) per receiver. The receivers generally cost around $5000 and are available from Trimble, Novatel, Raven, Topcon and others (50).

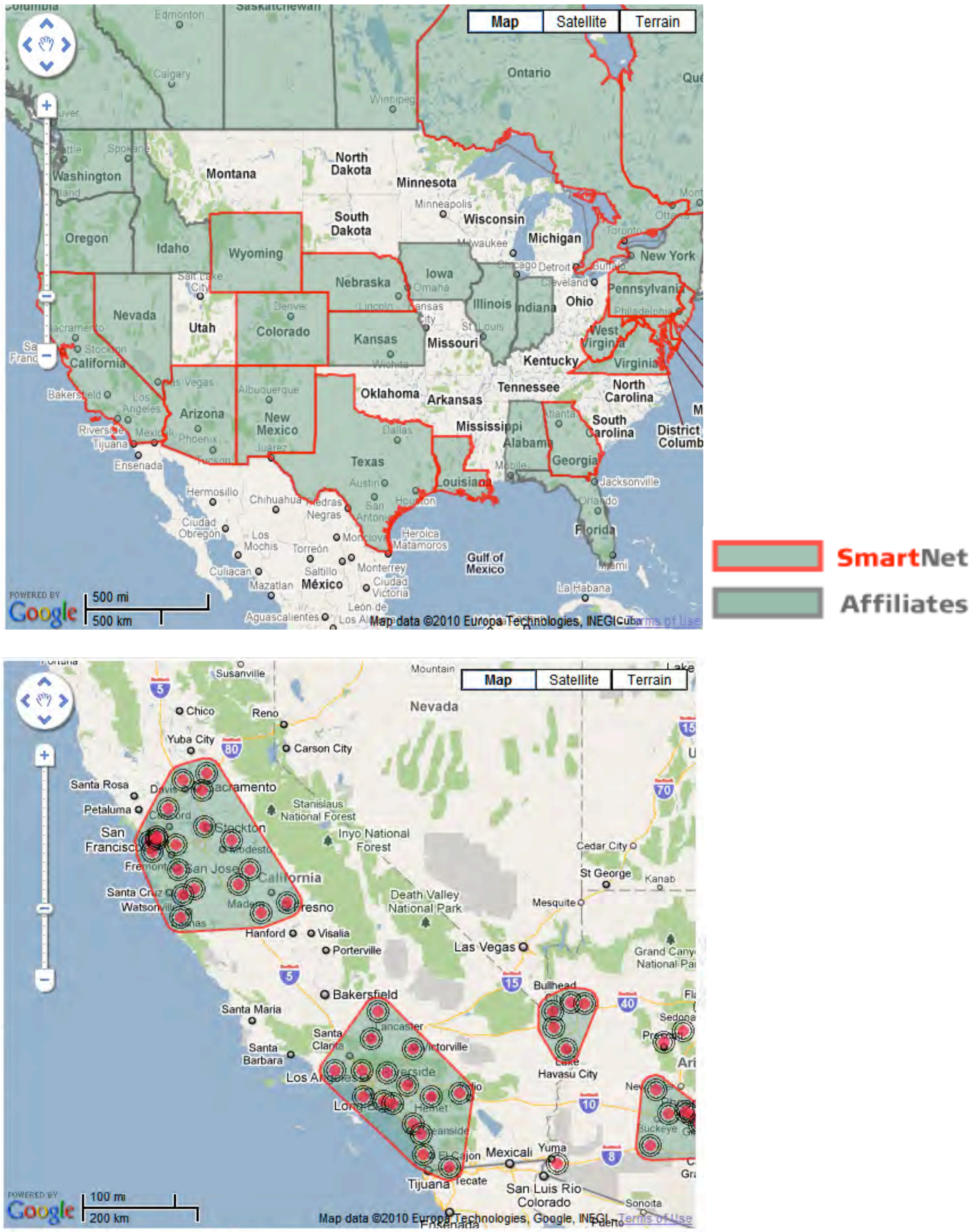

Figure 3 Leica N-RTK Service Area map (lower portion show covered spots in a three states: California, part of Nevada and part of Arizona).

IV. Benefit Assessment

Our approach is to determine a suite of ITS applications that require a high accuracy location service, find the benefits of these applications, and associate them to C-HALO. The ITS applications analyzed are those listed by the FHWA (19). A comprehensive list of these applications appears in appendix B. This list is analyzed for its location accuracy requirements. This filters down the application list to 8 groups of applications. If the applications require 1m or less accuracy, the applications and their benefits are analyzed, and associated to C-HALO.

Each application is explored independently to determine the efficacy rate, and the monetary benefit from reducing accidents (and in turn injuries and fatalities), VMT, travel times, emissions, and the like depending on the application. This type of methodology is similar to those used in other CBA's completed by the USDOT and other international governmental agencies. The method we use takes into account the cash flow estimates of the benefits over a 22 year period, and discounts those into "today's" worth via a discount rate that is proposed for this type of analysis by the congressional budgetary office. The analysis is similar to that adopted by the Allen Group (11).

The final list of applications can be seen in the Table 2 below:

Table 2 ITS Applications that Benefit from C-HALO Deployment

ITS Applications	Type	Included in Benefit Analysis
Curve Speed Warning	**Safety**	**Y**
Forward Collision/Braking Warning	**Safety**	**Y**
Emergency Electronic Brake Lights		
Cooperative Forward Collision Warning		
Merge/Lane Change Applications	**Safety**	**Y**
Highway Merge Assistant		
Lane Change Warning		
Blind Spot Warning		
Blind Merge Warning		
Left Turn Assistant	**Safety**	**Y**
Stop Sign Movement Assistant	**Safety**	**Y**
Highway/Rail Collision Warning	**Safety**	**Y**
Intersection Collision Warning	**Safety**	**Y**
Corridor Management	**Mobility**	**Y**
Intelligent Traffic Flow Control		
Free-Flow Tolling		

A. Assumptions

Some overall assumptions have to be made to estimate the benefits. Overall assumptions cover predictions we make about the national economy into the next 20 years, and general assumptions on how the new technology would be adopted by the ITS sector. We later on make application-based assumptions to estimate the particular efficacy of each application.

Technology Adoption Rate – The shape of this curve determines how quickly the fleet will adopt new technology, in this case C-HALO. The s-curve used in this analysis is leveraged from a report, by the Allen Group (11), which analyzes the benefits of high accuracy location data in non-ITS industries. The general shape of the curve is in Figure 4.

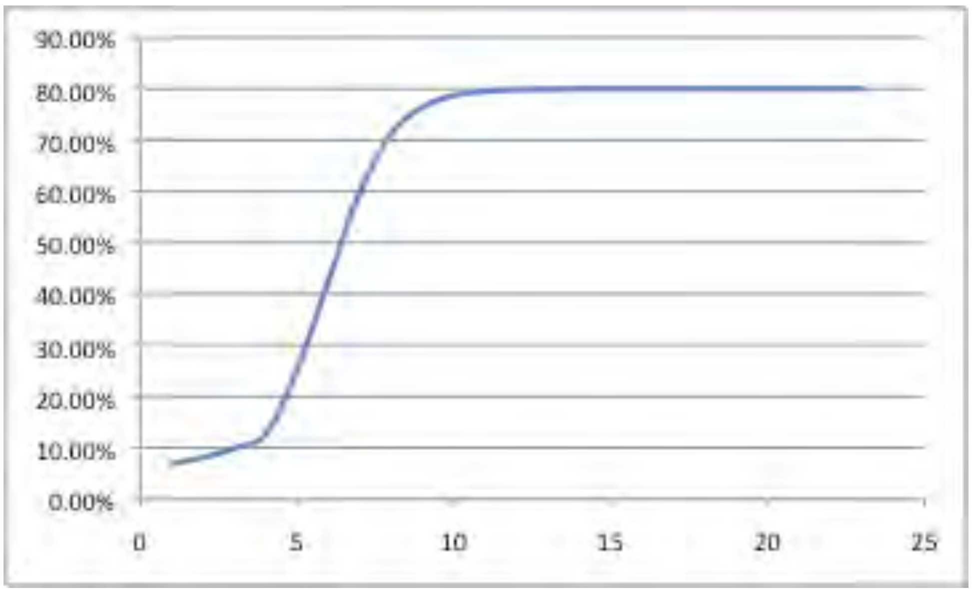

Figure 4 Technology adoption curve

This curve is applied over a project horizon of 22 years, 2008 – 2030. In calculating benefits, this adoption rate was typically used to determine the correct portion of benefits accumulated in a given year.

Discount Rate – This rate is used to discount future cash values to current day terms by taking into account inflation and a risk free rate of return, the higher the rate the more significant the discount to future cash values. For this analysis, a discount rate of 5 percent is used, and is taken from the Office of Budget and Management (20). They also suggest using a range from 3 to 7 percent.

Value of Time – The value of time is used in quantifying reductions in delay into monetary benefits. Again, the Volpe study quotes two figures, one for local travel, $11.20, and the other for intercity travel $15.60. These figures are from guidance from the office of the Secretary of Transportation (21). In our analysis, we take both figures and average them since in our data. The resulting figure is $13.40.

Delay Growth – The delay growth is calculated using figures from the Traffic Congestion and Reliability Report prepared by Cambridge Systematics for the FHWA in 2005 (22). Using twenty-year historical data (hours of delay per traveler) and trend analysis a growth rate of 6.5 percent is calculated.

B. Sources of Data

Accident Data – For the Safety applications, all accident data is culled from the GES database (35), which includes all types of accidents, not just accidents including fatalities. This database is then queried to ensure the appropriate accidents are being accounted for with regards to each individual application. Please see Appendix C for the querying methodology for each application class. We have also examined the FARS database (23) which includes fatal accidents.

Accident Growth Rate – The accident growth rate is used to project accident counts for years 2009 – 2030. The Volpe VII report projects accident rates based on VMT estimates and increased safety measures. These yearly accident rates are used to calculate the compound annual growth rate over the project horizon (21) This rate is calculated to be -0.2 percent.

Fatality Worth – This value is used in determining the benefit of reducing the count of fatal accidents. The Office of Management and Budgets put forth a memorandum in 2008 that suggests to the DOT that $5.8 million be used for the value of a life. It also suggests using a range of $3.2 million to $8.4 million (24).

Injury Worth – These values are based on percentages of the fatality worth. Again there is a standard, and that is the Maximum Abbreviated Injury Scale. Typically there are 5 injury levels not counting a fatality (24). In the FARS database only three levels of injuries are reported not counting fatalities. Therefore averages were taken first and second level and the third and fourth levels to determine the three percentages used in this analysis. The percentages used are in Table 3.

Table 3 Injury Worth Percentages

Injury Worth (% of Fatality Worth)	
Incapacitating	47.50%
Non-Incapacitating	5.80%
Possible/Light Injury	0.90%

C. Safety Applications

As part of the safety analysis, seven applications are analyzed: Curve Speed Warning, Forward Collision Warning, Merge/Lane Change Warning, Left Turn Assistants, Stop Sign Movement Assistant, Highway/Rail Collision Warning, and Intersection Collision Warning. All of these applications are focused on reducing accidents, and in turn fatalities and other injuries.

1. Curve Speed Warning

Curve speed warnings would aid drivers in negotiating curves at appropriate speeds. This is aimed at reducing single and multi-vehicle accidents in curves due to unsafe speeds.

To quantify the benefits of such a system we aimed to determine the number of accidents that could be reduced, then by using the assumptions laid out in previous sections, calculate a monetary benefit for reducing accidents.

To begin this process, the GES database was queried for specific accident data related to the application in question. For instance, all accidents that took place in curves, and were related to speed were included in this analysis.

In 2008, there were 1048 fatalities, and ~29000 other injuries where this type of application may be applicable. To determine the benefit of this system an efficacy rate must be determined to see how much of a reduction from these figures can be expected.

Through another literature review, several reports were found discussing how effective curve speed warnings could be. The three reports and results are summarized briefly below:

- Field Evaluation of the Myrtle Creek Advanced Curve Warning System (Oregon DOT 2006) – Empirical analysis of I-5 implementation near Myrtle Beach, over 75 percent of people reduced speeds entering the curves with dynamic message signage. The FHWA report (21) uses this value as a measure of efficacy of the curve speed warning applications when assessing the benefits of wireless communication to ITS.
- Rural ITS Toolbox (FHWA 2001) – Empirical study for trucks in Colorado. Speeds were reduced by 25 percent.
- An Evaluation of Dynamic Curve Warning Systems in the Sacramento River Canyon: Final Report (CA DOT 2000) - Empirical analysis of five locations on I-5 in California, over 70 percent of people reduced speeds entering the curves with dynamic message signage.

Using these sources as references, we chose to use 40% accident reduction as a mid-level efficacy rate. A low level would be 20% while a high efficacy level would be 70%. For a matrix of the efficacy rates please see Appendix D.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B = (EffRate_j * Adopt_n * \sum(InuryCount_{i,n} * Injury\%_i * FatalityWorth)) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, j is the application, and i is the injury level (fatal, serious, etc.).

Using this formula and the low efficacy rate, preliminary benefits of ~$54 Billion were estimated.

2. Forward Collision Warning

Forward collision warnings alert a driver when a forward vehicle brakes hard (deceleration is above a predetermined threshold). This is very similar to Cooperative Forward Collision Warning which is used to preemptively avoid rear-end collisions with vehicles in front of the subject vehicle.

To quantify the benefits of such a system we aimed to determine the number of accidents that could be reduced, then by using the assumptions laid out in previous sections, calculate a monetary benefit for reducing accidents.

To begin this process, the GES database was queried for specific accident data related to the application in question. For instance, all accidents that took place in curves, and were related to speed were included in this analysis.

In 2008, there were 241 fatalities, and ~109000 other injuries where this type of application may be applicable. To determine the benefit of this system an efficacy rate must be determined to see how much of a reduction from these figures can be expected.

Through another literature review, several reports were found discussing how effective forward collision warnings could be. The three reports and results are summarized briefly below:

- Evaluation of an Automotive Rear-End Collision Avoidance System (Volpe 2006) – A study that analyzed data from a field operation test and the results suggest that 10% of all rear-end collisions could be reduced.
- Integrated Vehicle Based Safety Systems: A Major ITS Initiative (FHWA 2005) – A study on IV systems that suggests these types of applications could reduce rear end, run off road, or lane change collisions by 48%.
- The Evaluation of Impact on Traffic Safety of Anti-Collision Assist Applications (Sala, Gianguido & Lorenzo Mussone, 1999) – A simulation study that suggests between 10 and 60% accident reduction could be attainable depending on the adoption rate of the technology. This is very interesting and one of the only studies that addresses changes in effectiveness due to technology adoption.

Using these sources as references, we chose to use 25% accident reduction as a mid-level efficacy rate. A low level would be 10% while a high efficacy level would be 50%.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B = (EffRate_j * Adopt_n * \sum (InuryCount_{i,n} * Injury\%_i * FatalityWorth)) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, j is the application, and i is the injury level (fatal, serious, etc.).

Using this formula and the low efficacy rate, preliminary benefits of ~$28 Billion were estimated.

3. Merge/Lane Change Warning

These warnings would alert vehicles on highway on-ramps if another vehicle is occupying its merging space (or in its blind spot). This is similar to Blind Merge Warning where warnings are used for vehicles attempting to merge with limited sight distance, and another vehicle is predicted to occupy the merging space. In addition, this system could warn the subject driver if a lane change is likely to cause a collision, triggered by turn signal activation.

To quantify the benefits of such a system we aimed to determine the number of accidents that could be reduced, then by using the assumptions laid out in previous sections, calculate a monetary benefit for reducing accidents.

To begin this process, the GES database was queried for specific accident data related to the application in question. For instance, all accidents that took place in curves, and were related to speed were included in this analysis.

In 2008, there were 13 fatalities, and ~3500 other injuries where this type of application may be applicable. To determine the benefit of this system an efficacy rate must be determined to see how much of a reduction from these figures can be expected.

Through another literature review, several reports were found discussing how effective merge or lane change warnings could be. The four reports and results are summarized briefly below:

- Integrated Vehicle Based Safety Systems: A Major ITS Initiative (FHWA 2005) – A study on IV systems that suggests these types of applications could reduce rear end, run off road, or lane change collisions by 48%.
- Freightliner to Offer Collision Warning on New Truck Line (Inside ITS 1995) – Empirical study of Transport Besner Trucking Co, which reduced its at-fault accidents by 34%.
- Dutch Field Operational Test Experience with "The Assisted Driver" (Alkim, Boostma, and Hoogendoorn 2007) – Empirical study of 20 vehicles in the Netherleands equipped with warning systems which were driven for five months. It found that unintentional lane changes were reduced by 35% on arterials, while it was reduced by 30% on highways.
- Run-Off Road Collision Avoidance Using IVHS Countermeasures: Final Report (NHTSA, 1999) – A simulation study that looked at lane departure warnings. Suggests passenger vehicle lane departures would decrease by 10%, while heavy trucks would decrease by 30%.

Using these sources as references, we chose to use 35% accident reduction as a mid-level efficacy rate. A low level would be 15% while a high efficacy level would be 60%.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B = (EffRate_j * Adopt_n * \sum (InuryCount_{i,n} * Injury\%_i * FatalityWorth)) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, j is the application, and i is the injury level (fatal, serious, etc.).

Using this formula and the low efficacy rate, preliminary benefits of ~$2.1 Billion were estimated.

4. Intersection Collision Warning

Intersection Collision Warning applications provide warnings to drivers that a collision is likely at the upcoming intersection either due to their own speed or inattention, or that of another driver.

To quantify the benefits of such a system we aimed to determine the number of accidents that could be reduced, then by using the assumptions laid out in previous sections, calculate a monetary benefit for reducing accidents.

To begin this process, the GES database was queried for specific accident data related to the application in question. For instance, all accidents that took place in curves, and were related to speed were included in this analysis.

In 2008, there were 88 fatalities, and ~37000 other injuries where this type of application may be applicable. To determine the benefit of this system an efficacy rate must be determined to see how much of a reduction from these figures can be expected.

Through another literature review, several reports were found discussing how effective intersection collision warnings could be. The two reports and results are summarized briefly below:

- Field & Driving Simulator Validations of System for Warning Potential Victims of Red-Light Violators (Inman, Vaughan TRB 2006) – A Field and Simulation study that tested participants in a driving simulator and on a closed track. In the simulator, 90% stopped or avoided the collision, while on the track, 64% stopped or avoided the collision.
- Intersection Collision Avoidance Study (FHWA Office of Safety 2003) – An in depth analysis of literature and operational concepts of specific ICAS systems, and they state that 100% reduction in accidents is not unrealistic, however a more conservative estimate would be a 50% reduction in accidents.

Using these sources as references, we chose to use 50% accident reduction as a mid-level efficacy rate. A low level would be 25% while a high efficacy level would be 75%.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B = (EffRate_j * Adopt_n * \sum (InuryCount_{i,n} * Injury\%_i * FatalityWorth)) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, j is the application, and i is the injury level (fatal, serious, etc.).

Using this formula and the low efficacy rate, preliminary benefits of ~$33 Billion were estimated.

5. Left Turn Assistant

Left Turn Assistants provide drivers information about oncoming traffic when trying to take a left-hand turn at an unprotected intersection.

To quantify the benefits of such a system we aimed to determine the number of accidents that could be reduced, then by using the assumptions laid out in previous sections, calculate a monetary benefit for reducing accidents.

To begin this process, the GES database was queried for specific accident data related to the application in question. For instance, all accidents that took place in curves, and were related to speed were included in this analysis.

In 2008, there were 26 fatalities, and ~24000 other injuries where this type of application may be applicable. To determine the benefit of this system an efficacy rate must be determined to see how much of a reduction from these figures can be expected.

Since the application is very similar to that of intersection collision warnings, the literature used to determine an efficacy rate for that application were leveraged for this application as well.

Using these sources as references, we chose to use 50% accident reduction as a mid-level efficacy rate. A low level would be 25% while a high efficacy level would be 75%.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B = (EffRate_j * Adopt_n * \sum(InuryCount_{i,n} * Injury\%_i * FatalityWorth)) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, j is the application, and i is the injury level (fatal, serious, etc.).

Using this formula and the low efficacy rate, preliminary benefits of ~$21 Billion were estimated.

6. Stop Sign Movement Assistant

Stop Sign Movement Assistants alert vehicles about to cross an intersection, after stopping, of cross traffic.

To quantify the benefits of such a system we aimed to determine the number of accidents that could be reduced, then by using the assumptions laid out in previous sections, calculate a monetary benefit for reducing accidents.

To begin this process, the GES database was queried for specific accident data related to the application in question. For instance, all accidents that took place in curves, and were related to speed were included in this analysis.

In 2008, there were 110 fatalities, and ~10000 other injuries where this type of application may be applicable. To determine the benefit of this system an efficacy rate must be determined to see how much of a reduction from these figures can be expected.

Since the application is very similar to that of intersection collision warnings, the literature used to determine an efficacy rate for that application were leveraged for this application as well.

Using these sources as references, we chose to use 50% accident reduction as a mid-level efficacy rate. A low level would be 25% while a high efficacy level would be 75%.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B = (EffRate_j * Adopt_n * \sum (InuryCount_{i,n} * Injury\%_i * FatalityWorth)) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, j is the application, and i is the injury level (fatal, serious, etc.).

Using this formula and the low efficacy rate, preliminary benefits of ~$10 Billion were estimated.

7. Highway/Rail Collision Warning

Highway/Rail Collision warnings provide alerts to reduce the likelihood of a collision between vehicles and trains on intersecting paths.

To quantify the benefits of such a system we aimed to determine the number of accidents that could be reduced, then by using the assumptions laid out in previous sections, calculate a monetary benefit for reducing accidents.

To begin this process, the GES database was queried for specific accident data related to the application in question. For instance, all accidents that took place in curves, and were related to speed were included in this analysis.

In 2008, there were 0 fatalities, and ~0 other injuries where this type of application may be applicable. To determine the benefit of this system an efficacy rate must be determined to see how much of a reduction from these figures can be expected.

Through another literature review, a report was found discussing how effective Highway/Rail Crossing Warnings could be. The report and results are summarized briefly below:

- Second Train Coming Warning Sign Demonstration Projects (TCRP Research Results Digest, 2002) – A demonstration study of two sites, one in Baltimore and the other in LA, where warnings were placed for approaching trains. 26% of drivers reduced the most risky behavior.

Using these sources as references, we chose to use 25% accident reduction as a mid-level efficacy rate. A low level would be 10% while a high efficacy level would be 50%.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B = (EffRate_j * Adopt_n * \sum (InuryCount_{i,n} * Injury\%_i * FatalityWorth)) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, j is the application, and i is the injury level (fatal, serious, etc.).

Using this formula and the low efficacy rate, preliminary benefits of ~$0 Billion were estimated.

D. Mobility Applications

As part of the mobility analysis, two applications are analyzed: Intelligent traffic flow control and free flow tolling. Both of these applications are focused on reducing delay. Both those applications require lane-level positioning accuracy to operate and therefore would benefit from a C-HALO nationwide deployment.

1. Intelligent Traffic Flow Controls (ITFC)

ITFC uses real-time data to adjust signal phases to an optimal level. These applications could also include Green Light Optimal Speed Advisory, which would provide the subject vehicle with the optimal speed given signal phase timing at upcoming intersections.

To quantify the benefits of such a system two additional pieces of information are needed to complete the calculation. The first is to determine how much delay is currently realized at signalized intersections. This was done through a literature review, and Temporary Losses of Highway Capacity and Impacts on Performance (Phase 2), written by Oak Ridge National Laboratory for the Department of Energy, discusses sub-optimal signal timing specifically. Through surveying and significant quantitative modeling they determine that there is, as of 1999, ~295 million hours of delay at signalized intersections.

Lastly, the efficacy of these new systems needs to be estimated. Through another literature review, several reports were found discussing how much more optimal signal timing assisted in reducing delay. The three reports and results are summarized briefly below:

- Preliminary Evaluation Study of Adaptive Traffic Control System (LA DOT 2001) – Empirical study in LA with 375 intersections, reduced delay by ~21%
- Realizing Benefits of Adaptive Signal Control at an Isolated Intersection (Park and Change 2002) – A simulation study on a hypothetical intersection of two one-way streets. Reductions in delay were between 18-20%
- ITS Benefits: The Case for Traffic Signal Control Systems (Skabardonis 2001) – Empirical study of multiple California implemented systems, reductions of delay close to 25%.

Using these sources as references, we chose to use 15% delay reduction as a conservative efficacy rate.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B_n = (EffRate * Adopt_n * TotDel_n * TVoM) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, and TVoM is the monetary value of time.

Using this formula, preliminary benefits of ~$10 Billion were estimated.

2. Free Flow Tolling

Toll collection without toll plazas reducing stop and go traffic surrounding current toll plazas, also beneficial, but not included in this analysis is the fact that in tolling situations, costs are actually saved by not having to build facilities. In this exercise we only look at reduced delay.

To calculate the delay reduced by free tolling systems, some metrics needed to be deciphered. Average delay at a toll facility, the total revenue of all tolling facilities, and the average toll for toll roads in the U.S is three metrics needed to calculate total delay due to toll facilities. Again, this was done through a literature review, and Temporary Losses of Highway Capacity and Impacts on Performance (Phase 2), written by Oak Ridge National Laboratory for the Department of Energy, discusses average toll delay. Through thorough quantitative analysis, they determine the average tolling delay to be 11.9 sec per vehicle.

With this figure, only the number of vehicles would be necessary to determine overall delay. To determine the number of vehicles using toll facilities, total tolling revenues and average toll were sought. In the Highway Statistics 2007 published by the FHWA, the total revenues of toll facilities was \$7.7 billion, while in the Toll Facilities in the U.S. August 2009, the average toll is calculated to be \$3.89 (25). Using these two figures, an annual vehicle count of ~2 billion was determined. This was grown on a year-to-year basis at a rate of 1.65% (26).

Lastly, the efficacy of these new systems needs to be estimated. Through another literature review, several reports were found discussing how much free tolling systems reducing delay. The two reports and results are summarized briefly below:

- Evaluation of Impacts from Deployment of an Open Road Tolling Concept for a Mainline Toll Plaza (Klodzinski 2007) – Twenty-month empirical study done around UCF which reduced delays by approximately 50 percent.
- Operational and Traffic Benefits of E-Zpass to the New Jersey Turnpike (NJ Turnpike Authority 2001) – EZ-pass empirical study that showed 85 percent reductions in delay.

Using these sources as references, we chose to use 70% delay reduction as a conservative efficacy rate.

With all of this data, a discounted yearly monetary benefit can be calculated. The equation would as follows:

$$B_n = (EffRate * Adopt_n * TotVeh_n * AvgDel * TVoM) / DiscountFactor_n$$

Where B is monetary benefits, n is the year, and TVoM is the monetary value of time.

Using this formula, preliminary benefits of ~\$0.6 Billion were estimated.

E. Efficacy Literature Caveat

The ITS application benefit numbers are from the RITA ITS Benefits database online. Since ITS funding is part of RITA's budget, we have found and checked benefit numbers from some of these applications in documents from m the GAO (27), RAND (28), and CBO (29). These do not challenge the assumptions made and published by RITA with respect to the analyzed applications. The RITA database is the most comprehensive.

F. Summary of Benefits

After completing all these individual analyses, the sum of these benefits ranges from $160 billion to $320 billion. This range depends on whether one uses the low-level safety application efficacy rates or the mid-level efficacy rates. This translates into 1.1 to 2.2 percent of GDP. The safety benefits in the analysis dominate, making up over 90 percent of the total benefits calculated.

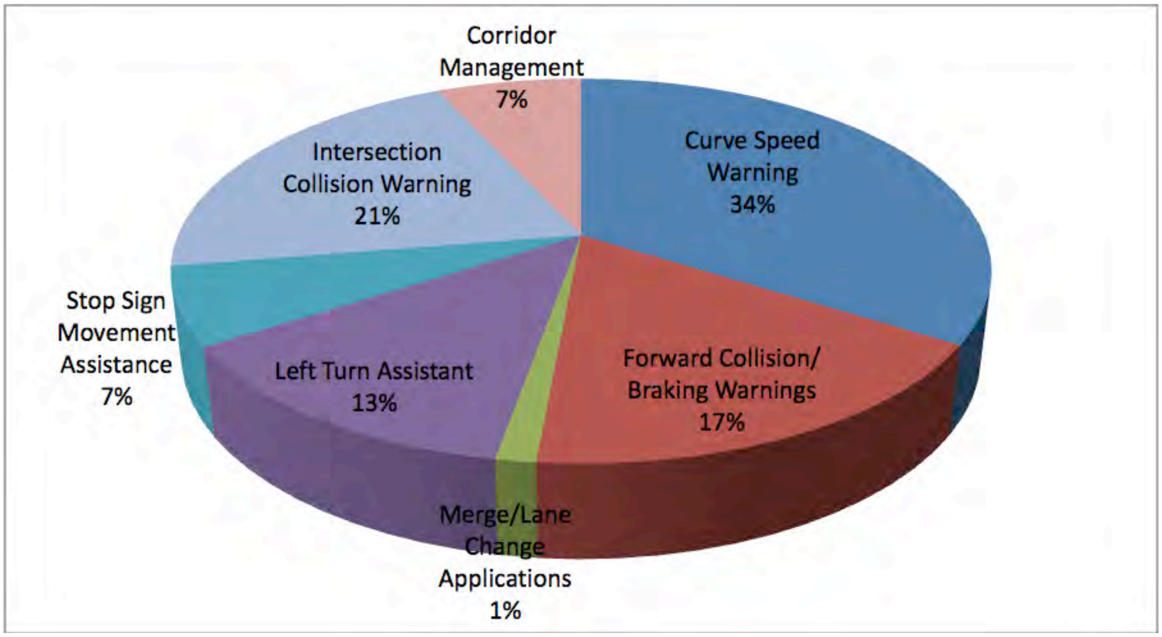

Figure 5 Benefits by Category

V. Separating HALO Costs into Good and Bad (Dark) GPS areas

In order to accurately estimate the cost of delivering C-HALO services in areas of need, we estimate the accuracy of existing location services on the ground and determine the area without good GPS coverage today We refer to this area as the “dark area” or the area, that may not realize HALO using N-RTK or HA-NDGPS, and to be targeted by a newer C-HALO infrastructure.

This chapter describes the methods and tools we have developed to estimate dark area. Emerging technologies such as the penetration of INS systems in vehicles could mitigate this gap. For example, we know from our prior work (30) that GPS augmented with INS can dead reckon to lane level precision for about 20 seconds if there are no sudden lane changes or turns at intersections (31,32).

Several reports exist on the causes of errors when measuring position on the ground using the GPS system (33). These reports address the theoretical values of the various types of errors. Table 4 below shows the possible values for the different errors attributed to locating objects on the ground using GPS.

Table 4 Sources of GPS Errors

Source	Effect (m)
Signal Arrival C/A	±3
Signal Arrival P(Y)	±0.3
Ionospheric effects	±5
Ephemeris errors	±2.5
Satellite clock errors	±2
Multipath distortion	±1
Tropospheric effects	±0.5
σ_R C/A	±6.7
σ_R P(Y)	±6.0

As part of this study, we set out to estimate the size of the “gap” using empirical and data modeling techniques to arrive at a more accurate assessment of GPS accuracy on the ground. Our method for doing this relies on understanding the satellite coverage and the visibility of satellites at a Point-of-Interest (POI) on the ground. When the POI is in an open space environment, the GPS receiver is capable of communicating with several satellites (6 or more) and is able to locate the POI with good accuracy (1-3m). When comparing this POI with another POI in an urban setting with several high-rise buildings, the number of satellites viewed drops significantly resulting in lower location accuracy.

Our effort rests on modeling the relation between position accuracy and number of satellites-in-view by incorporating the PDOP values, the height of buildings near the POI, and the open-space area - as represented by street widths - into the model. The method is tested on data from the city of San Francisco. We collected validation data in the San Francisco Downtown blocks highlighted in Figure 6.

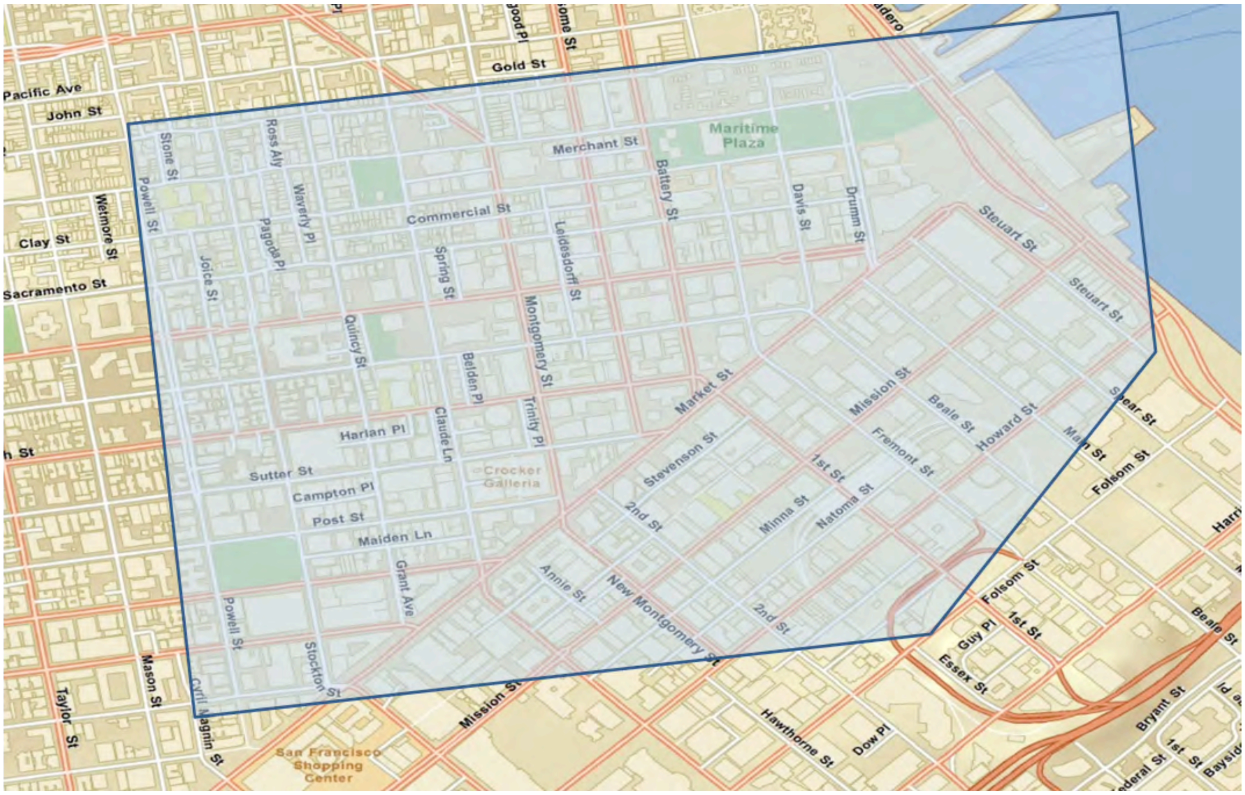

Figure 6 Shaded area represents study area

This area encompasses 2 sq.km of buildings of various heights providing us with a variety of satellite counts. Figure 7 is a Google Earth 3D rendering showing the structures in this area as of 2009.

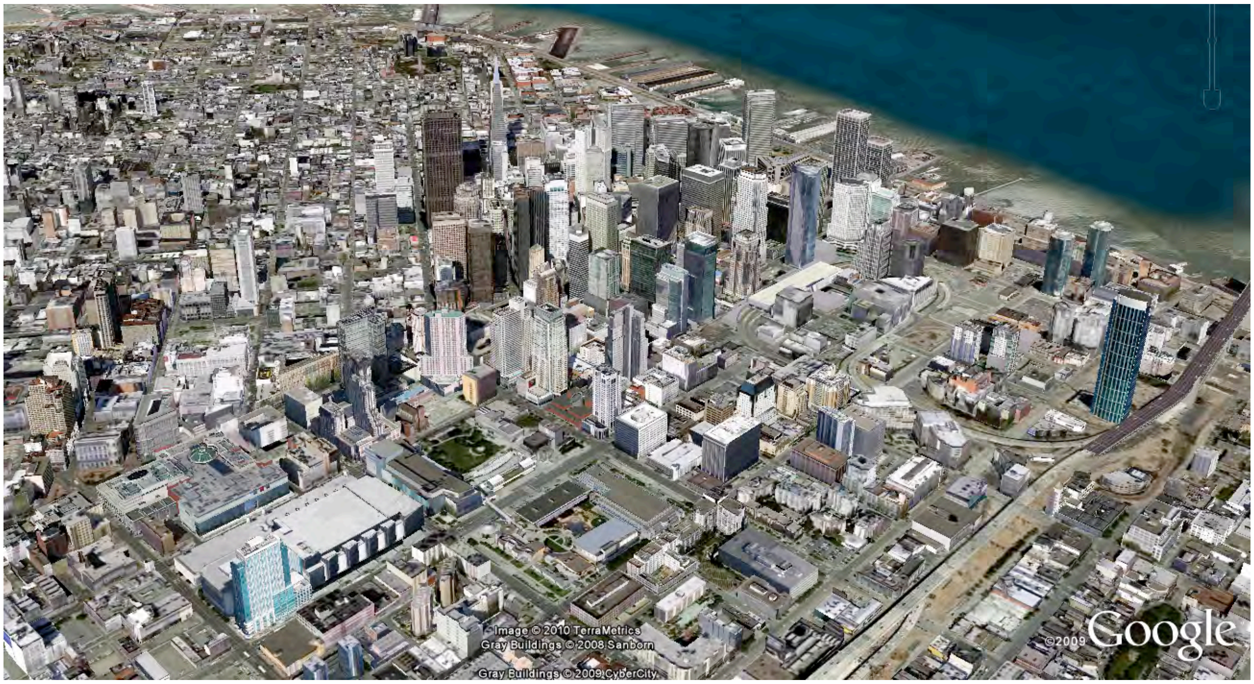

Figure 7 3D rendering showing building coverage in validation area

A. Data for Modeling Satellite Count

In order for us to systematically replicate the modeling of the gap across various cities, we rely on data that is easily accessible in the public domain. The International Association of Assessing Officers (IAAO) in collaboration with the Urban and Regional Information Systems Association (URISA) have been among the leading efforts in enabling GIS use by cities all over the world. As a result almost all major cities in the US have implemented GIS[3] and are affiliated with either of those two organizations. In San Francisco, the assessor office manages the SFParcel GIS system which holds information on close to 198,000 parcels . Of those we were able to obtain clean data on 160,000 parcels covering approximately 86% of the built area of San Francisco. In the remaining 14%, the height data could not be verified. These are dropped from the model (visualized as grey points in the plots below). The 86% that is used covers only the parts of San Francisco that are registered with the assessor's office. This does not include open spaces, public gardens, etc. Those areas (aka Park Acres) are estimated by the San Francisco County's office to be 0.19% of the total 121sq.km area of the City of San Francisco. So for the purposes of this model, we will be assume them negligible, and the clean data we have on San Francisco from the assessor's office will be assumed to cover all the 121sq.km.

The model is constructed using the ESRI GIS software ArcMap. Data for the model includes:

- Building heights as reported by the SFParcel GIS system controlled by the County of San Francisco
- Street width as measured using the ArcMap GIS software

[3] According to a 2003 survey by Public Technology Inc (a national not-for-profit that works with local governments) 97% of cities with a population greater than 100,000 have a GIS system in place. (Public Technology Inc., "2003 Survey on the Use of GIS Technology in Local Governments," December 2003.)

Thus building heights and street width at a Point Of Interest (POI) are “known” variables in the model and could be obtained from the GIS system of most city assessor’s office. The “unknown” variable is the satellite count. To calibrate the model we measure satellite count on the ground in the proposed area. This is done by driving around with a GPS equipped Smartphone. We developed an application on the Windows Mobile 6.5 operating system and deployed it on two HTC phones, namely, the HTC Diamond and HTC Touch Pro 2. The application logs the following values:

- GPS Longitude and Latitude
- Number of Satellites Visible
- Number of Satellites Connected
- Vertical Dilution of Position (VDOP)
- Horizontal Dilution of Position (HDOP)

The preliminary data collected is visualized in Figure 8.

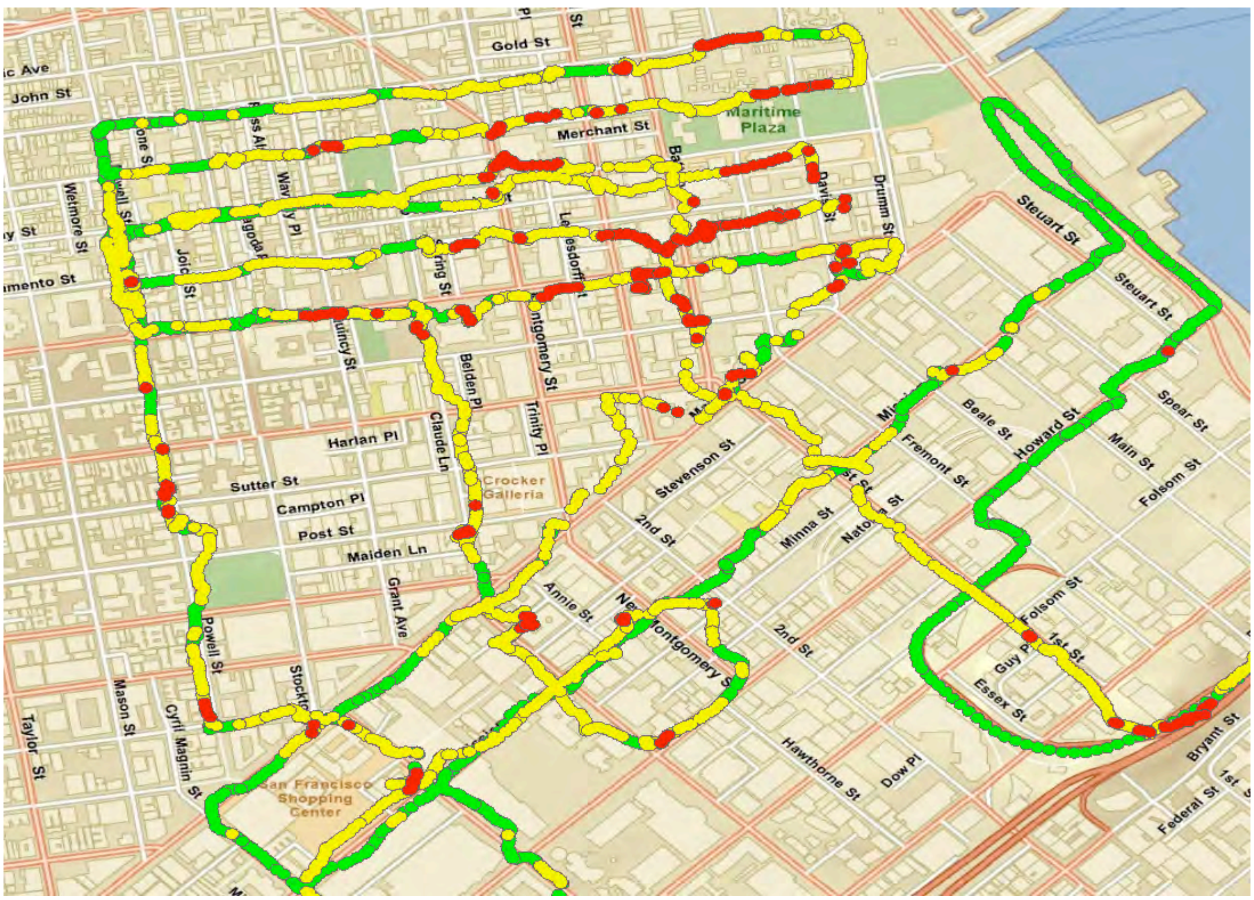

Figure 8 GPS data collection depicting satellite counts: >6 are shown in green, between 4 and 6 are shown in yellow, <4 are shown in red

The number of satellites at a POI can be taken as an indicator of the GPS accuracy. However the Horizontal Dilution of Precision (HDOP) is a better indicator of the localization accuracy of the GPS. For example, given a fixed number of satellites, the accuracy is better at a POI where the satellites are seen well spread out as compared to a place where the satellites are more clustered together. The HDOP captures this. Given the total number of operational satellites (N = 30 (57)) and the predicted number of satellites (s) at a POI, the HDOP can be theoretically calculated as follows

$$\text{HDOP} = \frac{4}{s\left(1 - \frac{\sin(2\cos^{-1}(1-\frac{2s}{N}))}{2\cos^{-1}(1-\frac{2s}{N})}\right)}$$

Figure 9 shows the theoretical and the empirical HDOP values obtained from the data set along with the 95% confidence intervals for the empirical HDOP. The empirical HDOP values were obtained from the data set collected in the city of San Francisco. The theoretical HDOP is obtained from the equation above.

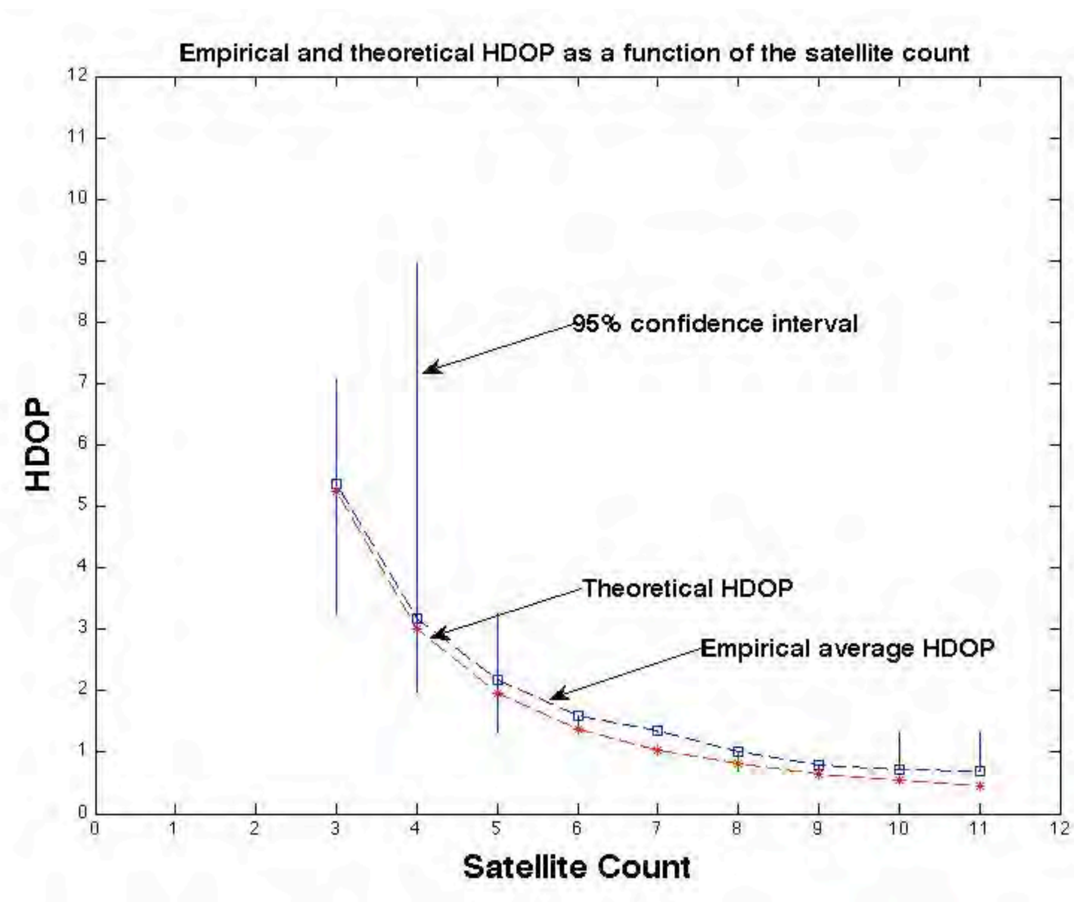

Figure 9 Empirical and predicted HDOP values with 95% confidence intervals.

The question of what values of HDOP is good for high-accuracy localization would depend on the receiver, ionospheric conditions etc. Typically, under normal conditions, HDOP values below 4 are considered to be good (52). However, for high accuracy applications, we would require the HDOP values to be lesser than 2 or 1. Using this as a rule of thumb, based on Figure 9, we roughly categorized the satellite counts as < 4, 4 to 6 and > 6 and the model predictions were carried out for these three categories. The use of 6 as a threshold for good GPS coverage is empirically supported by a 100 miles of driving data (30). In the next section we will describe the models used to predict the satellite counts and evaluate the performance based on the collected data.

B. Hidden Markov Model to Predict Satellite Counts

This section describes the method used to predict the number of satellites at a POI given the GIS data i.e. building heights and street widths. The quantity being predicted is illustrated by Figure 10.

The estimate of the satellite count at the point of interest is obtained as follows. We think of the satellites as being placed on the surface of a hemisphere with a radius R centered at the POI. We assume the POI is occluded from the satellites only by buildings at the sides of the street and there is visibility in the forward and backward directions as in Figure 10. The mask angle alpha (shown in Figure 10) is calculated based on the heights of the buildings and street width as follows.

$$\begin{aligned} \alpha &= \tan^{-1}\left(\frac{h_1}{w}\right) + \tan^{-1}\left(\frac{h_2}{w}\right) \\ \alpha &= \text{mask angle} \\ h_1, h_2 &= \text{height of building} \\ w &= \text{street width} \end{aligned}$$

Figure 10 Mask-Angle Representation using street width and building heights

The satellites visible at this point, are essentially the ones lying on a strip of the hemisphere with angular width alpha. The fraction of these satellites is given by

$$\text{Satellite Count} = \text{N} \times \alpha$$

where N is the total number of satellites in orbit. The satellite count data collected in downtown San Francisco is compared against the predicted count computed as described above. The data set consisted of 1657 data points. These were a subset of the 13822 data points collected overall. The subset was chosen by excluding data points that were not part of downtown San Francisco as in Figure 8 and data points that did not have corresponding meaningful building heights in the SFParcel GIS system. Out of these 1657 data points, 34 data points had satellite counts < 4, 568 points had satellite counts 4 to 6 and the rest had satellite counts > 6.

Table 5 shows the prediction accuracy of the model. Each column in this table is the prediction accuracy for the corresponding category of satellites. For example column 1 shows the percentage of data points having < 4 satellites being predicted as < 4, 4 to 6 and > 6 number of satellites.

Table 5 Model Prediction Accuracy

Satellites	**True < 4**	**True 4 to 6**	**True >6**
Predicted < 4	0.74	0.16	0.02
Predicted 4 to 6	0.24	0.25	0.07
Predicted > 6	0.02	0.59	0.91

The overall prediction accuracy is around 69%. The prediction accuracy is calculated by adding the fraction of data points in each of the categories multiplied with the corresponding diagonal entry. We next add a Hidden Markov Model (HMM) (51) to improve the prediction accuracies. The HMM captures the statistical dependence of the satellite count at a POI on the building heights at neighboring points as well.

The idea of the HMM modeling is as follows. Depending on the time of day, climatic conditions, or scatter in the environment, the number of satellites visible at a point could vary significantly. These random parameters lead to a stochastic dependence between the building heights and the number of satellites at a given point. Furthermore, the number of satellites at a particular point would be dependent on the number of satellites in nearby points. These dependencies could be captured by a HMM as shown in the figure below.

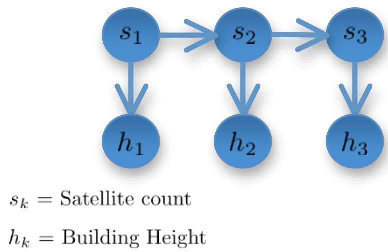

Figure 11 HMM for predicting satellite count

The nodes corresponding to the heights are values that are known. The nodes corresponding to the satellite count are the hidden nodes that need to be estimated. The hidden nodes are connected to their neighbors to model the dependency between satellite counts in adjacent regions. The transition probabilities between the satellite count variables are modeled using a sticky Markov chain (51). This is validated using the empirical data collected. The distribution of the building height given the satellite count is modeled as a Gaussian random variable with mean and variance empirically determined from the collected data. The mean height and variance for the Gaussian model and the transition probabilities between the states were obtained empirically from the collected data. 95% confidence intervals were calculated for the estimated parameters of the model. The satellite counts were predicted by taking the mean of the estimated parameters and the corresponding prediction accuracies for this model are as shown in Table 6.

Table 6 HMM Satellite Count Accuracies

Satellites	True < 4	True 4 to 6	True >6
Predicted < 4	0.70	0.01	0
Predicted 4 to 6	0.08	0.41	0.11
Predicted > 6	0.22	0.58	0.89

The results of this model are 87% accurate. Experimental results [53] have shown that with less than 7 satellites, GPS estimates have errors of the order of 1 meter. Therefore we focus on a 7 satellite threshold. Our model predicts that 0.3 to 4 % of the streets of San Francisco has satellite coverage of less than 7 satellites with 95% confidence. The prediction is made for all the streets of San Francisco where we have the building height data from the assessor's office. Figure 12 shows the results of the model. The figure is drawn by aggregating and averaging the values of the model into 10m x 10m grids that lie on roads. Each grid is given a color based on the average satellite count in that grid: red if <4, yellow if between 4 and 6 and green if >6. The 14% of San Francisco for which we do not have height data is not modeled. It appears as grey areas in the figure. We would also like to note that the effects of multipath are not taken into account in this modeling. Thus the green areas do not

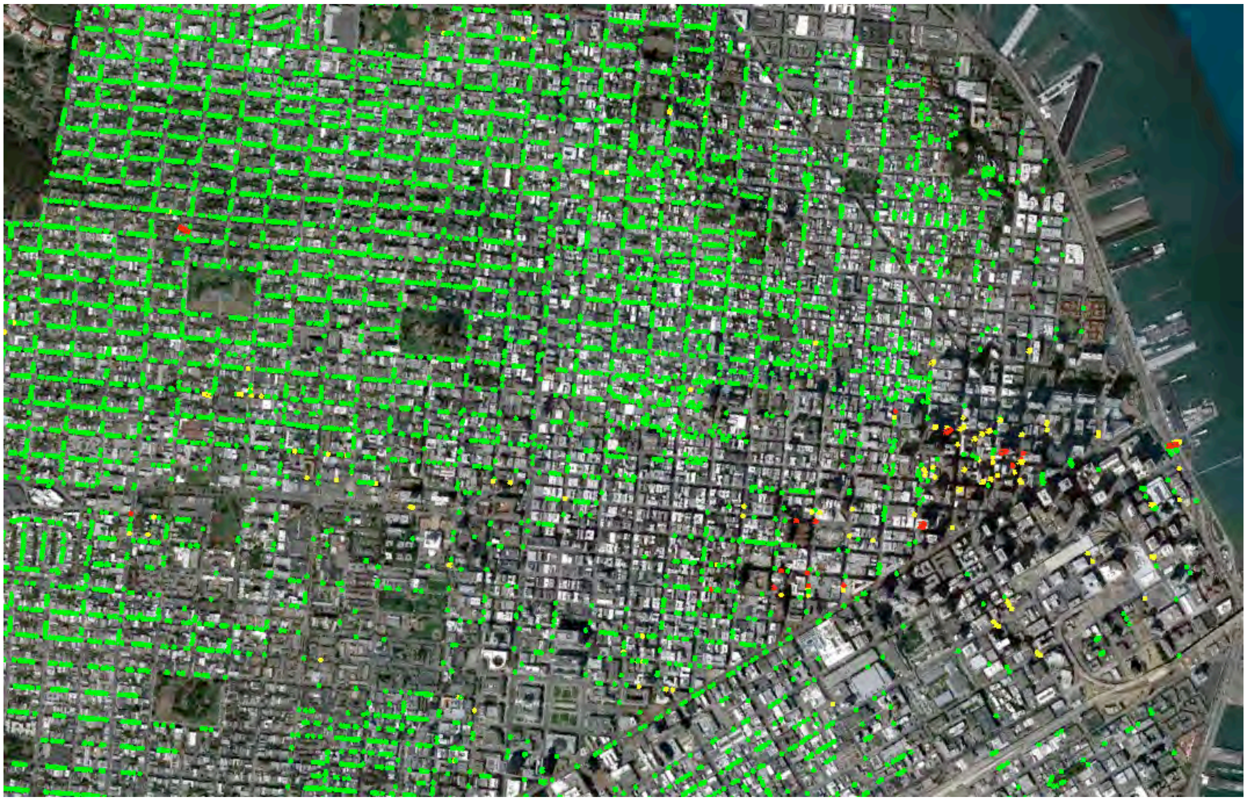

Figure 12 GPS data estimating satellite counts: >6 or more are shown in green, between 4 and 6 are shown in yellow, <4 are shown in red

necessarily reflect regions of high accuracy. Even though there is a satellite visibility of >6, multipath can cause significant errors. However, we can say with high confidence that the dark areas are regions of bad location accuracies. Table 6 can be related to some numbers in the literature. The methods in the literature use precise LiDAR data to yield good prediction accuracies [58]. The authors of [58] evaluated their method by two test cases. With a 5m RADAR digital surface map, the mean error in the predicted number of satellites using their model is 2.7 and 4.85 satellites with the corresponding error percentages being 46% and 82% in the two test cases. This improves with a more precise digital surface map. However it would be very expensive to obtain precise LiDAR data for an entire city and all the cities in the US. Under the same error metric, the mean error in the predicted number of satellites using our model is 1.85 satellites and the error percentage is 29.14%, which seems good. We use only building height data that can be obtained from the city planning department or a similar agency. However the comparison of the models is to be taken with caution given that the test data under consideration is vastly different for the two approaches. Our accuracies could be improved by having more data points. Extensive data collection during different times of the day and in different regions can help build and evaluate better models.

C. Use of the Model

The approach we adopted to obtain the satellite count on the surface in San Francisco can be repeated to any city in the US. The method is based on a GIS model constructed from the building heights and street width of the whole city – information easily accessible for all urban centers in the US via the local assessor's office. This would quantify the area where decimeter level accuracy cannot be achieved today with the current GPS and DGPS technology in many cities nationwide.

Our method produces a figure such as figure 12. Such a figure can guide the phased deployment of C-HALO infrastructure and provide insight into the full extent of new infrastructure required. The red areas are candidates for a first phase C-HALO deployment. Fortunately, they are also few in number, suggesting one might reap considerable improvements in location accuracies for moderate initial investment.

The benefits of deploying in red or yellow areas can be better understood by using GIS tools to overlay other statistics such as the distribution of accidents on figure 12. We have done this for San Francisco. Figure 13 shows a quadrant of San Francisco which include 1000m x 1000m grids of 2008 accident data as reported by NHTSA where red are areas of high accident counts, yellow those of medium counts and green of low or no accidents. This type of plot could be repeated by overlaying emissions data, or congestion data or other types of data relevant to the benefit measures guiding C-HALO pilot deployments or initial infrastructure investments.

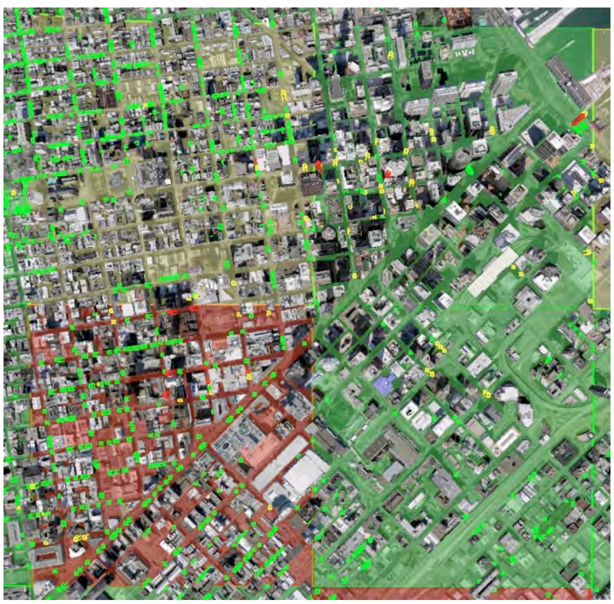

Figure 13 Overlay of accident data on satellite count projection data

VI. Cost Assessment in Good GPS Areas

This chapter quantifies the new infrastructure investment required to realize a C-HALO service in areas with good GPS coverage based on N-RTK technology. This cost does not include the wireless communication technology between vehicles, but just the cost of deploying the infrastructure to provide the service. For the purposes of this analysis we explored the cost of implementing N-RTK infrastructure. This of course, is an upper bound on the cost estimate of the infrastructure since in reality some areas of the U.S. are already covered by N-RTK service, while others areas may not need it (i.e. some areas may already have C-HALO capability without N-RTK).

The present N-RTK system consists of a set of references stations and servers installed and maintained by companies/governmental agencies offering the service. Customers use the service by paying a subscription fee. The NRTK servers provide the rovers with the RTCM corrections as and when requested by the rover. A typical N-RTK system as implemented by companies like Trimble and adopted by the present DoT's, consists of the following components[4]:

1. N-RTK base stations with geodetic and communication capabilities
2. Server(s) that handle incoming NRTK requests and RTK corrections, process the data and transmits the correction data to the rovers.
3. Communication links between reference stations and server(s) and the rovers and the server(s).

The capital costs involved in setting up such a system would include

a) Hardware - NRTK reference stations (*) and the servers.
b) Software on the servers and reference stations. This should also have the ability to handle secure communication.
c) Design (hardware, site selection etc), testing and installation of the reference stations (*).
d) Predicted hardware and software upgrades (*).

Variable costs include

a) Hardware and software maintenance costs for the server and reference stations (*)
b) Rent/value of facility for the reference stations (*) and servers
c) Link costs for the communication from reference stations to server (*) and from server to rovers
d) Power supply to reference stations (*) and servers.
e) Customer support

The cost estimates in Table 7 are for the installation and maintenance of a single base station and include the costs marked (*) in the NRTK system components.

[4] The OSI National NRTK solution, http://www.fig.net/pub/athens/papers/ts11/TS11_5_Bray_Greenway.pdf

A. N-RTK Base Station Cost Estimation

To begin estimating the infrastructure cost of deploying N-RTK infrastructure, discussions, via email and phone, were held with employees of three current N-RTK deployments, 2 state DOT's (Iowa [Steve Milligan] and Ohio [Dave Beiter) and one Cooperative (Washington [Gavin Schrock]). During these emails and conversations the costs associated with infrastructure cost requirements, as well as maintenance and operating costs were focused on (47,48,49,60). We also obtained concrete documents on invoices and cost reports for the hardware, servers, services etc (69,70) from these DOT's. These costs are summed and determined over the 22-year horizon using a 5% discount rate. The calculations are as follows.

Table 7 N-RTK Cost Estimation (No Other (Contingency) Costs) (47,48,49.60)

	Cost Estimate (Per Base Station)
Hardware	**$20,000**
Software	$400
R&D	$300
IT	$120
Misc Hardware	$120
Servers	$90
Support/Maint	$1,000
Comm/Power	$1,000
Rent	$24,000
Other	$0
TOTAL per Tower	**$47,030**
PV of Horizon Cost	**$413,402**

This is the representative cost given average levels of all the above costs. There are low and high estimates for each cost category, including the useful life of the hardware, which ranges from 7 to 15 years. This useful life changes the 22-year horizon cost of the hardware.

The range of infrastructure costs is from $220K to $615K per base station for the life of the system. Using a range of annual contingency expenses from $25K to $70K the range of infrastructure costs increases to $570K to $1.6M per base station for the life of the system. If one were to provide N-RTK coverage over the entire US land mass for the horizon of this project, approximately 2,730 base stations would be needed. Using this figure, nationwide N-RTK coverage would cost between $1.6B to $4.4B. This may be compared to benefits ranging between $160 and $300 billion from the Intelligent Transportation Systems Sector alone.

VII. Further Research

While accomplishing many things during this process, there are still many areas of research that could improve the analysis and enhance scope to incorporate more levels of detail. Areas of further explorations are briefly discussed below:

- **Further model refinement:**
  Continue to update the model with more empirical data and expand use to other cities and use nationwide to determine nationwide 'dark area.' Different models than the HMM could be investigated for better accuracy. Obtaining real data that spans across weather conditions and time would enable the model to provide time-based projection of satellite coverage, yielding a statement such as satellite count less than 6 for x % of the time. The use of variations on the satellite count, such as number of satellites used to calculate position could offer a better understanding of multi-path errors in the region.
- **Cost of infrastructure adjustment:**
  Utilizing the new 'dark area' estimation a more accurate infrastructure cost estimate can be made based on average coverage area of a base station.
- **Communication Technology Research:**
  Further research needs to be done on how the actual augmentation services will be communicated to the vehicles and between vehicles. This analysis has not been included in this report, but is integral in realizing the benefits of the new ITS applications.
- **Benefit Refinement:**
  Ultimately, the benefits calculations could be expanded to include environmental benefits.
- **Technology Assessment:**
  To achieve a more thorough understanding of where N-RTK stands in terms of cost effectiveness a more complete technology assessment needs to be completed. As part of this, the cost of infrastructure for each technological alternative needs to be completed, as well as analyzing the capabilities of each technology. Once this analysis is complete, the technologies can be compared and a prudent decision going forward could be made.
- **Other Economic Stimulus:**
  Analysis could be completed on what type of economic development may be induced due to these applications, specifically the mobility applications since the main component of the benefits is saved time. Typically if users are saving time, they are using that time to create benefits in another industry or realm. These effects need to be explored more fully to get a better estimate of the full benefits of implementing C-HALO services.

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Appendix A – Market Presence (X-Major; O-Minor)

	Aero.	Agri.	AV	Constr.	Def.	Mari.	Mine	Survey
Automated Positioning Systems							X	
Atair Aerospace					X			
Axio-Net GmbH	O	O		O		O		O
Biscarosse BV					X			
C&C Technologies						X		
Credent Technologies	X							
Crossbow Technology	O	O		O	O	O	O	O
DataGrid Inc.	O	O		O		O	O	X
Fugro/Omnistar	X	O	O	X		X	X	X
GeoKosmos	X							
GPS Ag		X						
Grumman			X		X			
Hemisphere GPS		X				O	O	O
Honeywell					X			
Javad GNSS				X				X
John Deere/Navcom Technology	X			O				
Leica Geosystems/ Novatel/Hexagon	O	X		X			O	X
Locata Corporation		O		X			X	
Magellan								X
MMIST Inc.					X			
NavSys Corportation	X	O	X	O			O	
Novariant	O	X		O	O		X	
New Zealand Aerial Mapping	X							
Septentrio BV	X					X		
Stara Technologies, Inc.					X			
Subsea 7/Veripos						X	X	X
Suzhou FOIF				X				X
TopCon/Sokkia	O	X		X		O	X	X
Trimble	O	X	O	X	O	X	X	X

Appendix B – Process of Selecting ITS Application that Stand to Benefit from C-HALO

A. Initial Application Selection Matrix (1,2)

ITS Applications	Safety	Location Services Necessary	Accuracy Requirements	Transmission	Min Frequency	Allowable Latency	Required Range
Units	**(Y/N)**	**(Y/N)**	**(m)**	**(Event/Periodic)**	**(Hz)**	**(msec)**	**(m)**
Traffic Signal Violation Warning*	Y	Y	1	P	10	100	250
Stop Sign Violation Warning	Y	Y	1	P	10	100	250
Curve Speed Warning*	Y	Y	1	P	1	1000	200
Emergency Electronic Brake Lights*	Y	Y	1	E	10	100	300
Adv. Warning Info/Weather & Road Conditions							
Approaching Emergency Vehicle Warning	Y	Y	5	E	1	1000	1000
Emergency Vehicle Signal Preemption	Y	Y	5	E	N/A	1000	1000
SOS Services	Y	Y	25	E	1	1000	400
Post-Crash Warning	Y	Y	1	E	1	500	300
In-Vehicle Signage	Y	Y	5	P	1	1000	200
Work Zone Warning	Y	N	N/A	P	1	1000	300
In-Vehicle Amber Alert	Y	N	N/A	E	1	1000	250
Safety Recall Notice	Y	N	N/A	E	N/A	5000	400
JIT Repair Notification	N	N	N/A	E	N/A	N/A	400
Low Parking Structure Warning	Y	Y	5	P	1	1000	100

ITS Applications	Safety	Location Services Necessary	Accuracy Requirements	Transmission	Min Frequency	Allowable Latency	Required Range
Units	**(Y/N)**	**(Y/N)**	**(m)**	**(Event/Periodic)**	**(Hz)**	**(msec)**	**(m)**
Wrong Way Driver Warning	Y	Y	1	P	10	100	500
Low Bridge Warning	Y	Y	5	P	1	1000	300
V2V Road Feature Notification	Y	Y	5	E	2	500	400
Cooperative Glare Reducation	N	Y	1	P	1	1000	400
Instant Messanging	N	N	N/A	E	N/A	1000	50
Vehicle-Based Road Condition Warning	Y	Y	25	E	2	500	400
Visibility Enhancer	Y	Y	1	P	2	100	300
Road Condition Warning	Y	N	N/A	E	1	1000	200
Highway Merge Applications							
Highway Merge Assistant	Y	N	N/A	P	10	100	250
Intelligent On-Ramp Metering	N	N	N/A	E	1	1000	100
Blind Merge Warning	Y	N	N/A	P	10	100	200
Left Turn Assistant*	Y	Y	1	P	10	100	300
Stop Sign Movement Assistance*	Y	Y	1	P	10	100	300
Pedestrian Crossing Information	Y	Y	1	P	10	100	200
Collision Warning Applications							
Pre-Crash Sensing*	Y	Y	1	E	50	20	50
Cooperative Forward Collision Warning*	Y	Y	1	P	10	100	150

ITS Applications	Safety	Location Services Necessary	Accuracy Requirements	Transmission	Min Frequency	Allowable Latency	Required Range
Units	**(Y/N)**	**(Y/N)**	**(m)**	**(Event/Periodic)**	**(Hz)**	**(msec)**	**(m)**
Cooperative Collision Warning	Y	Y	1	P	10	100	150
Highway/Rail Collision Warning	Y	Y	1	E/P	1	1000	300
Intersection Collision Warning	Y	Y	1	P	10	100	300
Adapative Headlight Aiming	Y	Y	1	P	1	1000	200
Adaptive Drivetrain Management	N	Y	5	P	1	1000	200
Lane Change Warning*	Y	Y	1	P	10	100	150
Blind Spot Warning	Y	Y	1	P	10	100	150
Corridor Management							
Cooperative Vehicle-Highway Automation System	Y	Y	5	P	50	20	100
Cooperative Adaptive Cruise Control	Y	Y	5	P	10	100	250
Intelligent Traffic Flow Control	N	Y	5	E	1	1000	250
Free-Flow Tolling	N	Y	1	E	N/A	50	50
Private Applications							
Enhanced Route Guidance & Navigation	N	Y	1	E	N/A	1000	200
Point of Interest Notification	N	Y	5	P	1	1000	400
Map Downloads & Updates	N	N	N/A	E/P	1	1000	400
GPS Correction	N	N	N/A	P	1	1000	400

B. Applications that stand to benefit from C-HALO

1. Safety

a) Curve Speed Warning

Aid drivers in negotiating curves at appropriate speeds.

b) Emergency Electronic Brake Light

Warns a driver when forward vehicle brakes hard (deceleration is above a predetermined threshold). This is very similar to Cooperative Forward Collision Warning which is used to preemptively avoid rear-end collisions with vehicles in front of the subject vehicle.

c) Highway Merge Assistant

Warns vehicles on highway on-ramps if another vehicle is occupying its merging space (or in its blind spot). This is similar to Blind Merge Warning where warnings are used for vehicles attempting to merge with limited sight distance, and another vehicles is predicted to occupy the merging space.

d) Blind Spot Warning

Warns subject driver if another vehicle is occupying his/her blind spot during an intended lane change maneuver.

e) Lane Change Warning

Warns subject driver if a lane change is likely to cause a collision. Triggered by turn signal activation.

f) Intersection Collision Warning

Provides warnings to drivers that a collision is likely at the upcoming intersection

g) Cooperative Collision Warning

Warns vehicles when a collision is likely with surrounding vehicles.

h) Left Turn Assistant

Provides drivers information about oncoming traffic when trying to take a left-hand turn at an unprotected intersection.

i) Stop Sign Movement Assistance

Warns vehicles about to cross an intersection, after stopping, of cross traffic.

j) Highway/Rail Collision Warning

Provides warnings to reduce the likelihood of a collision between vehicles and trains on intersecting paths.

k) Pedestrian Crossing Information

Alerts vehicles if there is danger of a collision with a pedestrian in a crosswalk.

2. Mobility

a) Free Flow Tolling

Toll collection without toll plazas reducing stop and go traffic surrounding current toll plazas.

3. Emissions

a) Adaptive Drivetrain Management

Allows vehicles to anticipate shift change patterns, and assist engine management systems to stabilize the transmission. Effects should be seen in increased gas mileage, reduced emissions, and improved shifting performance.

4. Mobility & Emissions

a) Intelligent On-ramp Metering

Uses real-time data to adjust ramp metering signal phases

b) Intelligent Traffic Flow Control

Use real-time data to adjust signal phases to an optimal level. Could also include Green Light Optimal Speed Advisory, which would provide the subject vehicle with the optimal speed given signal phase timing at upcoming intersections.

c) Private Applications (Etc.)

Enhanced Route Guidance & Navigation
Drive-thru Payments
Parking Lot Payment/Spot Locator

C. References

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Appendix C – Querying Methodology Matrix

	Driver Related Factors							Manner of Collision			Relation to Junction								Roadway Alignment		Traffic Control Device				Vehicle Manuever				
	Drowsy, Sleepy, Asleep, Fatigued	Operating in Careless or Inattentive Manner	Improper of Erratic Lane Changing	Failure to Keep in Proper Lane	Failure to Yield Right of Way	Driving Too Fast for Conditions	Driving in Excess of Posted Maximum	Front-to-Rear	All	Other	Intersection (Non-Interchange)	Intersection Related (Non-Interchange)	Rail Grade Crossing (Non-Interchange)	Crossover Related (Non-Interchange)	Intersection (Interchange Area)	Intersection Related (Interchange Area)	Crossover Related (Interchange Area)	All	Curve	All	Stop Sign	Stop Sign	Other	All	Turning Left	Changing Lanes or Merging	Negotiating a Curve	Other	All
Curve Speed Warning						X	X		X									X	X					X			X		
Electrtonic Brake Warning	X	X						X										X		X				X					X
Merge Warning (1)	X	X								X								X		X				X		X			
Merge Warning (2)			X	X					X									X		X				X		X			
Left Turn Assistant (1)					X					X	X	X		X	X	X	X			X				X	X				
Left Turn Assistant (2)	X	X							X		X	X		X	X	X	X			X				X	X				
Stop Sign Assistant	X	X								X	X	X		X	X	X	X			X	X	X						X	
Intersection Collision Warning	X	X								X	X	X		X	X	X	X			X			X					X	
Highway/Rail Collision Warning	X	X								X			X							X				X	X			X	

Appendix D – Efficacy Rate Matrix

	Low	Mid	High
Curve Speed Warning	20.00%	40.00%	70.00%
Emergency Electronic Brake Lights	10.00%	25.00%	50.00%
Highway/Rail Collision Warning	10.00%	25.00%	50.00%
Intersection Collision Warning	25.00%	50.00%	75.00%
Left Turn Assistant	25.00%	50.00%	75.00%
Merge/Lane Change Applications	15.00%	35.00%	60.00%
Stop Sign Movement Assistance	25.00%	50.00%	75.00%
Free Flow Tolling		70.00%	
Intelligent Traffic Control		15.00%	

Appendix E – Cost Estimation Emails

Email from David Beiter to Adam Goodliss:

Adam, my answers to your questions below are in Red

David J. Beiter, PE /SIT, Transportation Engineer 2
ODOT Office of Aerial Engineering and Surveying
1602 West Broad St, Columbus, Ohio 43223
Voice: (614)-275-1372 FAX: (614)-275-1673
e-mail: dave.beiter@dot.state.oh.us

Adam Goodliss <agoodliss@gmail.com>	To	<Dave.Beiter@dot.state.oh.us>
10/20/2010 11:59 AM	cc	
	Subject	Re: RTK/CORS Network Cost Information UC Berkeley Research

Dave,

Thanks so much for getting back to me. I just want to clarify what you wrote to make sure I understand you correctly, and then ask a couple questions to follow up.

From your summary, I understand the base towers cost ~$2K fully loaded (installation, crew, fixed cost, etc.) and the mount cost fully loaded, if put on a building, cost $500. This does not include the receiver or antenna.
The $2k and $500.00 cost detailed was for materials only, labor costs are not figured in

Follow up questions:

Are there any estimated maintenance costs of such a system? Are the on a per tower basis? Maintenance is a fairly low cost, the only "normal" maint items are the battery back-ups that are replaced every 2 yrs approx $150.00 / station.

Am I correct in assuming that the receiver is what is used by the end user? The end user is therefore responsible for the cost of this equipment and any data plan necessary. For the rovers, yes. Each base (CORS) has a GPS receiver and antenna, and yes the end users are required to pay for their own data plan.

What is the antenna's purpose? Are those the responsibility of the end user or the DOT? The antenna is the device that collects the GPS signal, each CORS has one. These are the responsibility of the DOT

Do you have any range of costs for receivers and antennas? I am assuming the range may be significant depending on what brand and function it is meant to serve. A high end GNSS receiver and antenna (Geodetic Grade) (Like what we have on our stations) will run around $18k

How many users are on your system currently? How long has it been operational? Is there an industry (agriculture, construction, etc.) that dominates the network? We currently have 964 users on our system. It has been operational since 2004. Our users are, in order of prevalence : Surveyors, Agricultural, GIS users, Construction machine control. Surveyors are, right now our biggest users but the Ag market has come on strong in that last few years and I expect it to be our biggest user in the near future.

Adam, if you have any further questions, or need clarification, just let me know or give me a call

Thanks
DJB

Again, thanks for the timely response. Look forward to hearing from you soon.

Cheers,
Adam

On 10/18/10 5:29 AM, "Dave.Beiter@dot.state.oh.us" <Dave.Beiter@dot.state.oh.us> wrote:

We built our Trimble VRS network completely in house, the Concrete monuments with foundations extending down at least 10' at 3' diameter cost us approximately $2000.00 each in materials, with a three man crew for 3 partial days. Our building mount stations cost about $500.00 in materials and only took us 1 day to complete with the 3 man crew. Please note that these costs do not include the receiver or antenna.

If you need anything else, let me know

Thanks
DJB

David J. Beiter, PE /SIT, VRS/CORS system Manager
ODOT Office of Aerial Engineering and Surveying
1602 West Broad St, Columbus, Ohio 43223
Voice: (614)-275-1372 FAX: (614)-275-1673
e-mail: dave.beiter@dot.state.oh.us

Adam Goodliss <agoodliss@gmail.com> 10/14/2010 07:29 PM
To Adam Goodliss <agoodliss@gmail.com>

Subject: RTK/CORS Network Cost Information - UC Berkeley Research

Hello, My name is Adam Goodliss and I am currently a graduate student, in transportation engineering, at the University of California, Berkeley. I have been working on a research project revolving around analyzing the costs and benefits of high accuracy location data with regards to intelligent transportation systems. You can find more information at this website, http://ucbchalo.wordpress.com/ <http://ucbchalo.wordpress.com/> . I have contacted you specifically due to your involvement with CORS/RTK networks. As part of our research we are looking into N-RTK solutions among others. I was wondering if you had additional cost details (most not available on your website) from an infrastructure/maintenance point of view, ie. the cost of a tower, installation cost, etc. Ultimately, I want to estimate the cost of implementing N-RTK networks of differing sizes and possibly on a national scale.

I also realize that you could have possibly worked with Trimble or Leica Geosystems so if they would be more suited to deal with this type of question please advise accordingly. If you do not have this information, but know someone within your organization that does I would greatly appreciate being put in touch with them.

Thanks in advance, and if you have additional questions please do not hesitate to be in touch via email or at 781.888.8033. -Adam

Email from Steve Milligan to Adam Goodliss:

Adam,

The Iowa network cost approximately $1.70 million, and it consists of 80 reference stations. Each reference station cost approximately $21,250 which included installation.

In the first 1.75 years of operation it cost approximately $60,000 for equipment repairs and replacements due to lightning/power surges. Software and firmware upgrades run approximately $80,000/year.

Let me know if you need any additional information.

Regards,

Steve Milligan
Statewide RTN Coordinator
515-239-1981
515-290-2831 cell

From: Adam Goodliss <agoodliss@gmail.com>
To: Milligan, Steven [DOT]
Sent: Fri Oct 15 12:21:08 2010
Subject: Re: RTK/CORS Network Cost Information - UC Berkeley Research

Steve,

Thanks for the timely response. I appreciate any information you are able to share with me.

-Adam

On 10/15/10 6:47 AM, "Milligan, Steven [DOT]" <Steven.Milligan@dot.iowa.gov> wrote:

Adam,

I'm not in the office today, but I will get this information together and send it to you.

Steve Milligan
Statewide RTN Coordinator
515-239-1981
515-290-2831 cell

From: Adam Goodliss <agoodliss@gmail.com>
To: Adam Goodliss <agoodliss@gmail.com>
Sent: Thu Oct 14 18:19:09 2010
Subject: RTK/CORS Network Cost Information - UC Berkeley Research

Hello,

My name is Adam Goodliss and I am currently a graduate student, in transportation engineering, at the University of California, Berkeley. I have been working on a research project revolving around analyzing the costs and benefits of high accuracy location data with regards to intelligent transportation systems. You can find more information at this website, http://ucbchalo.wordpress.com/.

I have contacted you specifically due to your involvement with CORS/RTK networks. As part of our research we are looking into N-RTK solutions among others. I was wondering if you had additional cost details (most not available on your website) from an infrastructure/maintenance point of view, ie. the cost of a tower, installation cost, etc. Ultimately, I want to estimate the cost of implementing N-RTK networks of differing sizes and possibly on a national scale.

I also realize that you could have possibly worked with Trimble or Leica Geosystems so if they would be more suited to deal with this type of question please advise accordingly. If you do not have this information, but know someone within your organization that does I would greatly appreciate being put in touch with them.

Thanks in advance, and if you have additional questions please do not hesitate to be in touch via email or at 781.888.8033.

-Adam