EXHIBIT

BEFORE THE
FEDERAL COMMUNICATIONS COMMISSION
Washington, D.C. 20554

In the Matter of	)	
	)	**WT Docket No. 11-18**
Applications of	)	**DA 11-252**
AT&T Mobility Spectrum LLC and	)	
Qualcomm Incorporated	)	
	)	
for Consent to the Assignment of	)	**File No. 0004566825**
Licenses and Authorizations	)	

JOINT DECLARATION OF JEFFREY H. REED AND NISHITH D. TRIPATHI

1. I am Professor Jeffrey H. Reed. I am the Director of Wireless @ Virginia Tech and the Willis G. Worcester Professor of Electrical and Computer Engineering at Virginia Tech University. Wireless @ Virginia Tech is one of the largest and most comprehensive academic wireless research groups in the US. I am an author or co-author of over 150 peer-reviewed journal and conference papers and the co-author of three books. Early in 2011 my fourth book will be published by Wiley and IEEE, Cellular Communications: A Comprehensive and Practical Guide, with Dr. Nishith Tripathi. This book is based on the classes we teach at our respective organizations. I am also the President of Reed Engineering, a wireless engineering consulting firm with which Dr. Tripathi is also affiliated. I am a Fellow of the IEEE and past recipient of the College of Engineering Research Award. I have served on the technical advisory boards of many companies and have approximately 30 years of industrial and academic experience.

2. I am Dr. Nishith Tripathi. I am a principal consultant at Award Solutions, a provider of technical consulting and specialized technical training for wireless communications. My students include senior personnel from companies throughout the wireless industry and other wireless engineering instructors. I specialize in a variety of technologies, including as IS-95,

CDMA2000, 1xEV-DO, GSM, GPRS, EDGE, UMTS, HSDPA, HSUPA, HSPA+, WiMAX, and LTE. I received my doctorate in Electrical and Computer Engineering from Virginia Tech, and I have held several strategic positions in the wireless arena. As Senior Engineer for Nortel Networks, I gained 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, I worked on the infrastructure design and optimization of CDMA2000, 1xEV-DO, and UMTS radio networks. I am the co-author of Radio Resource Management (2001) and Cellular Communications: A Comprehensive and Practical Guide (forthcoming) with Professor Reed.

3. We have been asked by AT&T to review, from a technical/engineering viewpoint, claims that lower-frequency wireless spectrum bands (below 1 GHz) are categorically more effective than, and superior to, higher-frequency bands (above 1 GHz) for the delivery of mobile wireless broadband services. We conclude that, from a technical/engineering viewpoint, it is invalid to extrapolate from observations that, all else being equal, lower-frequency signals carry farther and, in some cases, penetrate buildings more readily than higher frequency signals, to a conclusion that lower-frequency spectrum is therefore necessarily "better" for broadband wireless deployments.

4. Our analyses and conclusions on these issues are set forth in the White Paper entitled "Comparative Analysis of Suitability of Lower and Higher Frequency Bands for Cellular Network Deployments," which is attached hereto as Exhibit 1. We hereby incorporate this White Paper into this declaration.

VERIFICATION PAGE

I hereby declare under penalty of perjury that the foregoing (including all referenced Exhibits) is true and accurate to the best of my knowledge and belief.

Jeffrey H. Reed

Nishith D. Tripathi

Executed on March 17, 2011

VERIFICATION PAGE

I hereby declare under penalty of perjury that the foregoing (including all referenced Exhibits) is true and accurate to the best of my knowledge and belief.

Jeffrey H. Reed

ndtripathi

Nishith D. Tripathi

Executed on March 17, 2011

EXHIBIT 1

COMPARATIVE ANALYSIS OF SUITABILITY OF LOWER AND HIGHER FREQUENCY BANDS FOR CELLULAR NETWORK DEPLOYMENTS

BY

PROF. JEFFREY H. REED AND DR. NISHITH D. TRIPATHI

Comparative Analysis of Suitability of Lower and Higher Frequency Bands for Cellular Network Deployments

Jeffrey H. Reed and Nishith D. Tripathi

Abstract

Spectrum ranging in frequency from 300 MHz to 3.5 GHz is generally suitable for mobile cellular networks. Each frequency band within this range has its own unique characteristics, advantages, and challenges, and a variety of technology advances and techniques have been developed to address coverage, capacity or other challenges that may be associated with a particular spectrum choice. The paper shows that when the entire cellular technology lifecycle and various real-world constraints on network deployments are considered, no one frequency band within this range is inherently "superior" to others at all times and under all circumstances. In particular, we show that it would be a mistake to extrapolate from the observation that, all else being equal, lower-frequency (less than 1 GHz) signals carry farther and sometimes penetrate buildings more readily than higher frequency (greater than 1 GHz) signals to a conclusion that lower-frequency spectrum is therefore necessarily "better" for broadband wireless deployments. We conclude that regulatory policies that would skew carriers' spectrum choices and portfolios based upon arbitrary line-drawing (at 1 GHz or elsewhere) would harm wireless consumers by diverting spectrum from its highest value uses and forcing "second best" engineering solutions and that a consumer-friendly spectrum policy would instead focus on making more spectrum available for mobile broadband wireless use (both above and below 1 GHz and preferably in larger, contiguous blocks), encouraging secondary market spectrum transactions, and leaving spectrum choices in the hands of network planners and engineers.

Professor Jeffrey H. Reed is the Director of Wireless @ Virginia Tech and the Willis G. Worcester Professor of Electrical and Computer Engineering at Virginia Tech University. Wireless @ Virginia Tech is one of the largest and most comprehensive academic wireless research groups in the US. Professor Reed is an author or co-author of over 200 peer-reviewed journal and conference papers and the co-author of three books. Late in 2011 his fourth book will be published by Wiley and IEEE, *Cellular Communications: A Comprehensive and Practical Guide*, with his co-author here, Dr. Nishith Tripathi. This book is based on the classes Professor Reed and Dr. Tripathi teach at their respective organizations. Professor Reed is also the President of Reed Engineering, a wireless engineering consulting firm with which Dr. Tripathi is also affiliated. Professor Reed is a Fellow of the IEEE and past recipient of the College of Engineering Research Award. He has served on the technical advisory boards of many companies and has approximately 30 years of industrial and academic experience. Professor Reed's complete vita is attached.

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 as 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 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's complete vita is attached.

1. Executive Summary

We have been asked by AT&T to review, from a technical/engineering viewpoint, claims that lower-frequency wireless spectrum bands (below 1 GHz) are categorically more effective than, and superior to, higher-frequency bands (above 1 GHz) for the delivery of mobile wireless broadband services. As we explain below, simply extrapolating from observations that, all else being equal, lower-frequency signals carry farther and may penetrate buildings more readily than higher frequency signals to a conclusion that lower-frequency spectrum is therefore necessarily "better" for broadband wireless deployments is misguided.

It is widely accepted in the wireless network engineering community that frequency bands between roughly 300 MHz and 3.5 GHz exhibit propagation characteristics that make them suitable for mobile broadband services. Each band within that range has its own unique characteristics, advantages and challenges, and there is no one frequency band that is the "best" or that is ideal for every mobile broadband deployment scenario. Which band within this range is the best fit for any given situation will depend upon many factors that interact in complex and dynamic ways, and factors other than intrinsic propagation characteristics often dominate wireless network design (and costs), particularly in the capacity-constrained wireless environments that exist today and are expected to persist for the foreseeable future.

Moreover, as we explain below, any given provider's spectrum preferences are likely to be heavily influenced by that provider's existing spectrum portfolio and mix of technologies and services. That is why any given provider tends to place more value on (and accumulate) spectrum in particular bands (which may be either below or above 1 GHz), why each provider's spectrum portfolio tends to be concentrated in a limited number of bands, and why one provider can truthfully claim that its above-1 GHz spectrum is better at the same time that another provider can truthfully claim that its below-1 GHz spectrum is better. Within the broad range of broadband wireless-suitable spectrum, obtaining *contiguous* large blocks of spectrum can be much more important – because of peak cell capacity advantages and enhanced user throughput – than obtaining spectrum with more desirable propagation characteristics, especially when service-provider-specific circumstances are considered.

For these and other reasons that we discuss below, including the engineering challenges that drive real world cell size/base station placement decisions (and that are largely ignored in simplistic propagation-based spectrum comparisons), innovative new technologies that address both propagation and capacity issues (including technologies that work better at higher frequencies), and the scalability benefits associated with international harmonization in a world in which higher-frequency deployments are commonplace, it is simply not true that lower-band spectrum is inherently "superior" at all times and under all circumstances. And it makes no sense at all to consider the question of relative spectrum "superiority" in the abstract.

These technical realities can have important policy implications. In a dynamic wireless environment with rapidly evolving usage patterns and technologies, the engineers and operators responsible for designing and operating a broadband wireless network to provide the highest quality services most efficiently are best positioned to make spectrum choices. Any regulatory policy that attempted to skew carriers' spectrum choices and portfolios based upon arbitrary line-drawing – at 1 GHz or anywhere else within the range of broadband-suitable spectrum – would harm wireless consumers by diverting spectrum from its highest value uses and services and forcing "second best" engineering solutions.

Moreover, relative spectrum "value" is a moving target. The balance of coverage, capacity and other trade-offs may change over time as technologies and uses of the network evolve. Thus, even if regulators could be confident that they have identified some magic frequency line below which the spectrum is inherently "better" today, any such decision would be quickly outdated.

Arguments to the contrary generally proceed as follows: At a given power level, lower-band signals can typically travel farther than higher-band signals. To provide equivalent coverage, a wireless provider with higher-frequency spectrum must therefore construct more base stations than a provider with lower-frequency spectrum. Networks that employ higher-frequency spectrum therefore cost more than networks that employ lower-frequency spectrum. Because the network build costs are higher, higher-frequency spectrum is less desirable. Although the first statement is true as a description of basic wireless physics, the extrapolation to inherent superiority for lower frequencies is not.

First, the number of cells/base stations deployed in a wireless broadband network is influenced by many factors in addition to the intrinsic propagation characteristics of the spectrum used. The goal of the wireless network designer is not simply to provide *some* signal coverage of all relevant areas, but to provide *high quality service to users in those areas* – even at times of peak demand. In a wireless broadband network that means having enough *capacity* in each cell to meet expected demand at target performance levels, and ensuring sufficient capacity in each cell is an important, and often the controlling consideration in deciding how many base stations must be deployed. In other words, no network owner designs, operates or expands a cellular network based upon considerations of coverage alone. Both coverage *and* quality of service (QoS) (quantified by metrics such as capacity and throughput) must be considered at each stage of the technology lifecycle, from initial network design through network optimization and expansion.

Ironically, it is the very coverage advantages of lower-frequency spectrum that generate the capacity disadvantages that are likely to affect the real-world network design in ways that diminish or eliminate propagation-related cost advantages. Cell capacity is a function of channel bandwidth, not frequency. 10 MHz at 2.5 GHz spectrum will support the same throughput – *e.g.*, the same number of users in the cell simultaneously downloading data – as 10 MHz at 700 MHz spectrum. Consider a suburban development covered by four 2.5 GHz cell-sites that a 700 MHz provider could "cover" with a single cell site. The 2.5 GHz provider has *four times* as much capacity in this area, and when throughput demands exceed the capacity, the 700 MHz provider must typically take one or both of two (costly) actions: split/add cells or add more spectrum. Moreover, because the largest available spectrum bands are at the higher frequencies, the lower frequency network operator's ability to assemble larger chunks of spectrum is likely to be more limited. In short, any notion that a real-world lower-frequency operator will enjoy the full theoretical propagation benefits of a coverage-driven network design is misguided.

The impact of deployments that use multiple carrier frequencies must also be considered. If an operator uses both lower- and higher-frequency spectrum for its 4G deployments to meet the target throughput requirements, this could eliminate the lower-frequency propagation advantage, because effective network planning and seamless mobility typically require contiguous coverage of multiple carrier frequencies across a given geographic area. Hence, in a multi-carrier deployment the higher frequency band (and not the lower frequency band) would likely dictate how many base stations are needed to cover a given geographic area.

Obstructions (both natural and manmade), zoning restrictions, land use, antenna height, and other restrictions on base station placement, as well as efficient provider practices such as re-using existing base station sites for new technology deployments (to reduce expenditures) limit the achievable coverage performance (and associated cell size benefits) in real-world lower-frequency networks. Furthermore, additional base stations (and/or customized and expensive filtering or other solutions) may be needed to address interference from adjacent spectrum users (particularly broadcast and other high power sources of the types that may be adjacent to 700 MHz spectrum, for example).

It is also a mistake to conclude that reduced building penetration of higher frequency signals means that higher frequency networks must necessarily deploy more base stations. Although across a wide electromagnetic spectrum (*e.g.*, few MHz to hundreds of GHz) lower frequencies tend to penetrate better in buildings, this performance differential is very little in the range from 700 MHz to 2.5 GHz (and in some circumstances favor the high frequency signals). Moreover, in situations where signal-blocking building materials and customer demand for deep in-building penetration are an issue, they often impact in-building performance of both lower- and higher-band networks. That is why operators of both lower- and higher-band networks deploy a variety of engineering solutions other than altering cell size, such as WiFi, distributed antenna systems ("DAS"), relays, and femtocells or picocells.

At the same time, advanced antenna techniques, such as Multiple Input Multiple Output (MIMO) (that provides throughput gains due to spatial multiplexing) and beamforming (that enhances cell-edge throughput due to focusing of signal energy) may perform better at higher frequencies. For example, spatial multiplexing and beamforming gains are easier to achieve on the small form factors of handsets at higher frequencies where antenna sizes and spacing can be reduced.

In short, the claim that a higher-frequency network must have significantly more cell sites than a lower-frequency network is unlikely to be true in a variety of real-world scenarios, particularly in situations where capacity, and not coverage, is a critical network design factor. Indeed, by some estimates, a 2.5 GHz network could require *fewer* base stations in capacity-limited dense urban, urban and suburban areas than a 700 MHz network in real world scenarios where, for example, a larger spectrum block is available at 2.5 GHz [WiMAX_Forum_Study].

Although propagation-related advantages of lower-band spectrum are likely to be more pronounced in rural and open space areas where there are currently no capacity constraints these advantages do not prevent providers that hold primarily higher-frequency spectrum from serving these areas effectively. For example, Sprint has near nationwide coverage with higher-frequency spectrum, and AT&T provides near complete coverage of the Carolinas and other areas where it holds only higher-frequency spectrum. It would also be a mistake to assume that rural areas – where wireless may be the most economically feasible broadband solution – will remain free of capacity constraints. Indeed, even in open space deployments, such as along interstate highways, capacity-based designs that diminish coverage benefits of lower-frequency spectrum could well become prevalent as carriers work to keep up with burgeoning broadband demand from drivers, passengers and even the vehicles themselves.

Nor does it follow that a higher-frequency network operator would necessarily have materially higher costs even if more base stations were required to obtain equivalent coverage. While the number of base stations deployed is certainly one important driver of wireless costs, there are many others. The cost per base station is also important and, here, high-frequency deployments may have some cost advantages. Antennas for higher-frequency spectrum tend to be shorter and smaller and can be placed closer together. And, to the extent a provider is able to amass large (contiguous) blocks of a single (higher) frequency rather than relying upon multiple smaller blocks across multiple frequency bands, less equipment may be needed – both in base stations and in end user equipment. In addition, although efficiency and cost control are certainly important, the service quality that a larger high-frequency spectrum block will enable and its potential future uses can be equally important.

And, as noted, the engineering challenges and costs that any given provider will face when using various spectrum bands are likely to be heavily influenced by that provider's existing spectrum portfolio and business strategy. Augmenting capabilities with the addition of new spectrum bands can raise a host of complex technical issues as compared to adding more spectrum in bands already in (or adjacent to) the provider's portfolio. Each additional band increases the complexity (and cost) of both base stations (*e.g.*, the need for separate antennas) and user equipment (*e.g.*, frequency synchronization and monitoring of different carrier frequencies) as well as the complexity of network tuning. There are chipset and other limitations on how many bands can be incorporated in a single network, and even within those limits, spectral efficiency, interference losses, handset form factor and power capabilities – and, of course, costs – can all be affected negatively by decisions to increase the number of frequencies in use, especially across multiple bands. These concerns will only grow over time as the need for larger spectrum blocks to meet growing demand most efficiently rises. Moreover, to the extent that higher frequency spectrum is really expected to impose materially higher overall network costs (accounting for the entire technology lifecycle of design, optimization and expansion), one would expect those higher costs to be reflected in the prices operators are willing to pay for that spectrum. In other words, purchasers of high-band spectrum may pay a lower price for spectrum that reflects the potentially higher deployment costs.

For all of these reasons, the categorical suggestion that spectrum above 1 GHz is inherently inferior to, and should be treated differently than, spectrum below that arbitrary line is an obsolete, voice-centric view that fails to account for real-world issues faced by wireless radio network engineers. The key to meeting real-world challenges efficiently is a fluid spectrum market that allows service providers rapidly to adjust their network configurations as capacity demands and new technologies dictate. A consumer-friendly spectrum policy would thus focus not on attempts to define through regulation which spectrum is "better," but instead on: (i) identifying and distributing through unrestricted auction much more spectrum for wireless broadband (both below and above 1 GHz), (2) allocating that spectrum in large blocks and with proper attention to international harmonization; (3) encouraging and facilitating secondary market transactions that will allow already allocated spectrum to be put to its highest-valued uses; and (4) strictly enforcing interference rules and reducing zoning and other obstacles to efficient base station placement to ensure that all licensees can get the most out of the inherent characteristics of their spectrum.

The remainder of this white paper is organized as follows:

In **Section 2**, we provide an overview of the cellular technology lifecycle that includes network planning and design, network optimization, and network expansion for capacity and coverage. We explain why a meaningful assessment of the cost of a commercial wireless network must include not only the initial deployment costs, but also the substantial costs of network optimization and expansion. We show that at each stage, network engineers and planners must account for multiple competing considerations beyond coverage, including capacity and throughput and the operator's existing technologies, services, devices, infrastructure, and carrier frequencies, in determining how a network should be constructed and operated.

In **Section 3**, we focus on coverage aspects of network deployments. We provide a brief primer on RF propagation in cellular networks. We explain how propagation models are used to compare coverage for various frequency bands in theoretical urban, suburban and rural environments where there are no real-world constraints and coverage is the only metric of interest. We discuss the design impacts of real-world constraints, including land use and use restrictions, re-use of existing cell sites, capacity and multi-carrier deployments. We show how these constraints (as well as operator-specific circumstances) can shrink and even eliminate the coverage benefits of lower-frequency deployments.

In **Section 4**, we describe the capacity and quality-of-service aspects of wireless network deployments. Exponential growth in wireless Internet access, the expected rise in the use of broadband wireless access in rural environments, and the widespread success of multimedia devices push capacity and quality-of-service considerations to the forefront during all phases of the cellular network technology lifecycle.

In **Section 5**, we outline some of the more widely discussed theoretical distinctions – both advantages and challenges – between lower- and higher-frequency spectrum in the 300 MHz to 3.5 GHz range. We then discuss some of the technological innovations and advances that have developed to address both coverage and capacity challenges and how these technologies may further reduce perceived advantages of lower-band spectrum.

Finally, in **Section 6**, we explain that when network planning, optimization, and expansion are properly executed in the absence of any obstacles presented by performance-constraining regulatory policies, the end user should not perceive any quality difference between lower- and higher-band network deployments. We explain why large spectrum chunks are, and will remain, important to successful network deployment at a given frequency band (lower or higher). And we identify key spectrum allocation policies – focused on allocating more unrestricted spectrum in large, contiguous blocks and ensuring fluid secondary markets – that will allow competing wireless networks to continue to deliver innovative wireless services most efficiently, and maximize benefits for wireless consumers.

2. The Cellular Network Technology "Lifecycle"

When a new cellular technology is commercially launched, it passes through various phases during its lifecycle as depicted in Figure 2.1. The three main lifecycle phases are (i) network planning and design, (ii) network optimization, and (iii) network expansion.[1] Each phase plays an important role in network design and costs, and during each phase the network operator makes numerous decisions that affect cell size, the numbers and locations of base stations, and the frequency bands and bandwidths of spectrum utilized in the network. To understand the true impact of spectrum frequency on network design and costs, it is critical to account for all three phases of the technology lifecycle, and not just the initial design at commercial launch.

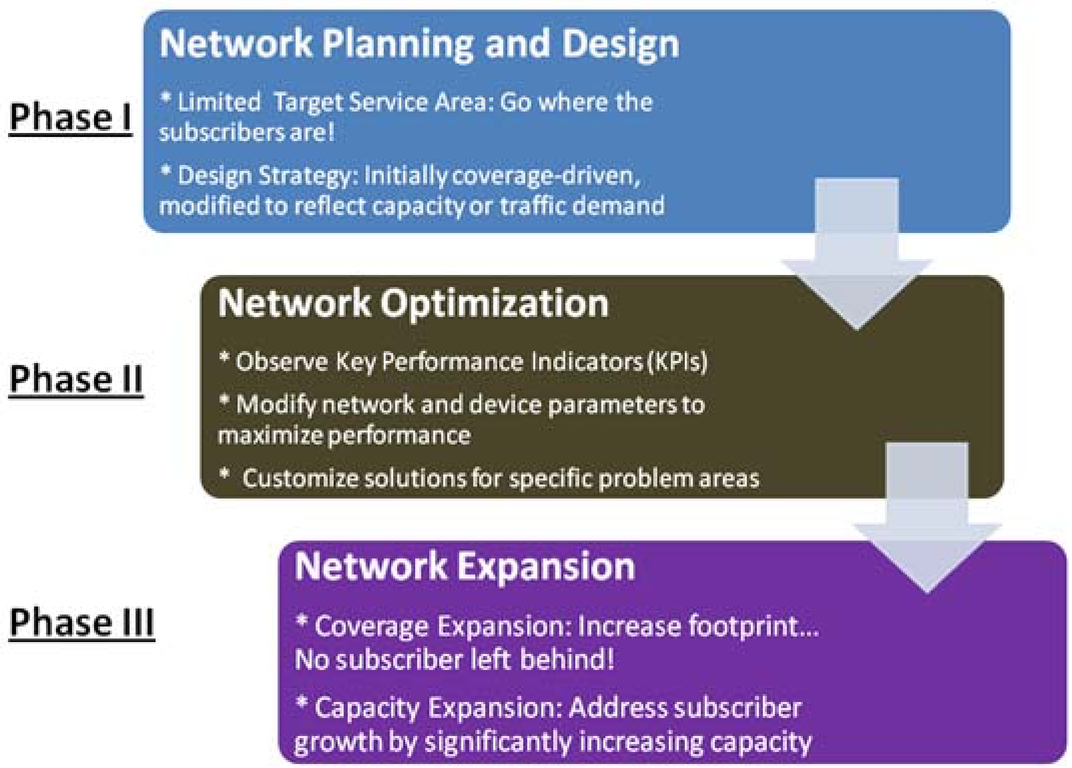

Figure 2.1. Phases During the Lifecycle of a Cellular Technology

2.1 Network Planning and Design

We provide a brief overview of the overall network planning and design process in Section 2.1.1. Three generic types of network deployments are discussed in Section 2.1.2. Finally, real-world complexities of the initial network planning and design process are summarized in Section 2.1.3.

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[1] In this paper, we use the word "capacity" to refer to both total cell throughput and number of simultaneous users. Where needed, distinctions between the two are explicitly mentioned.

2.1.1 An Overview of Network Planning and Design

Figure 2.2 shows the main inputs and outputs of the process of network planning and design.

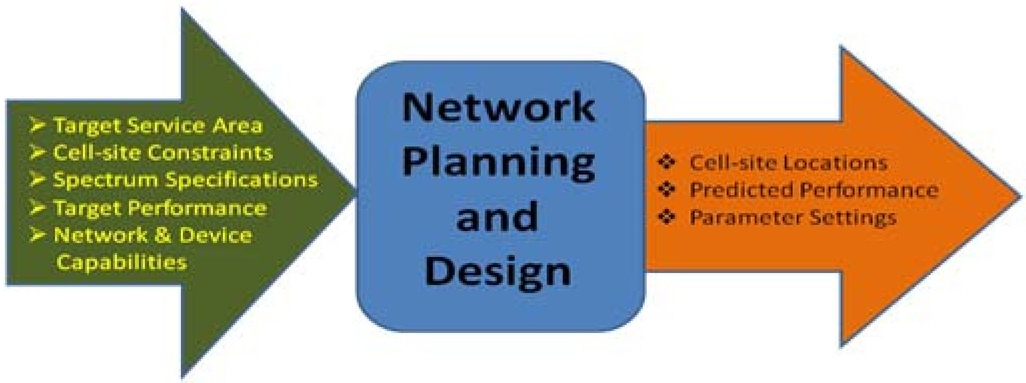

Figure 2.2. Network Planning and Design

Once the target service area where the new technology would be offered initially is identified, the network planner must consider constraints on cell-site locations, including constraints imposed by the reality that the operator is typically not deploying a new technology on a "blank slate." Thus, the operator may need to maximize the use of existing cell-sites deployed for legacy technologies, often using different frequency bands than are being used in the new technology deployment. Spectrum specifications such as available frequency bands (*e.g.*, Cellular, PCS, or AWS band), possible carrier frequencies within a band or bands, and channel bandwidth (*e.g.*, 5 MHz, 10 MHz, or 20 MHz) are also defined.

Target performance is specified in the form of capacity and throughput requirements (*e.g.*, expected average user throughput, cell-edge throughput and peak throughput) and coverage requirements (*e.g.*, 90% cell-edge reliability). Base station capabilities, such as the number and type of antennas, maximum power of the high power amplifier and equipment capabilities, including the maximum supportable data rate and the number of antennas, are also considered in the initial planning and design process.

The network planning and design process is an iterative process. Propagation models and traffic simulations are used in a network planning tool to meet coverage and capacity requirements while satisfying the constraints specified as inputs to the process. Main outcomes of the process include: (i) selected cell-site locations for the new technology; (ii) predicted performance maps, such as maps showing estimated throughput at given locations; and (iii) settings of various network parameters such as the "identities" of cells (*e.g.*, the Primary Scrambling Code for UMTS or the Physical Layer Cell Identity for LTE) and user mobility-related parameters.

It is important to recognize that even after the most meticulous planning, the predicted performance is just that – predictions that reflect the many unavoidable assumptions and abstractions from real-world complexities. Real-world performance can – and will – differ.

2.1.2 Generic Network Deployment Scenarios

Network deployment in a target service area may be coverage-driven, capacity-driven, or hybrid coverage- and capacity-driven. The first pass in the network planning process is typically to check if coverage-driven deployment is adequate. Figure 2.3 shows an "ideal" (unrealizable in practice) example network layout for a coverage-driven deployment.[2]

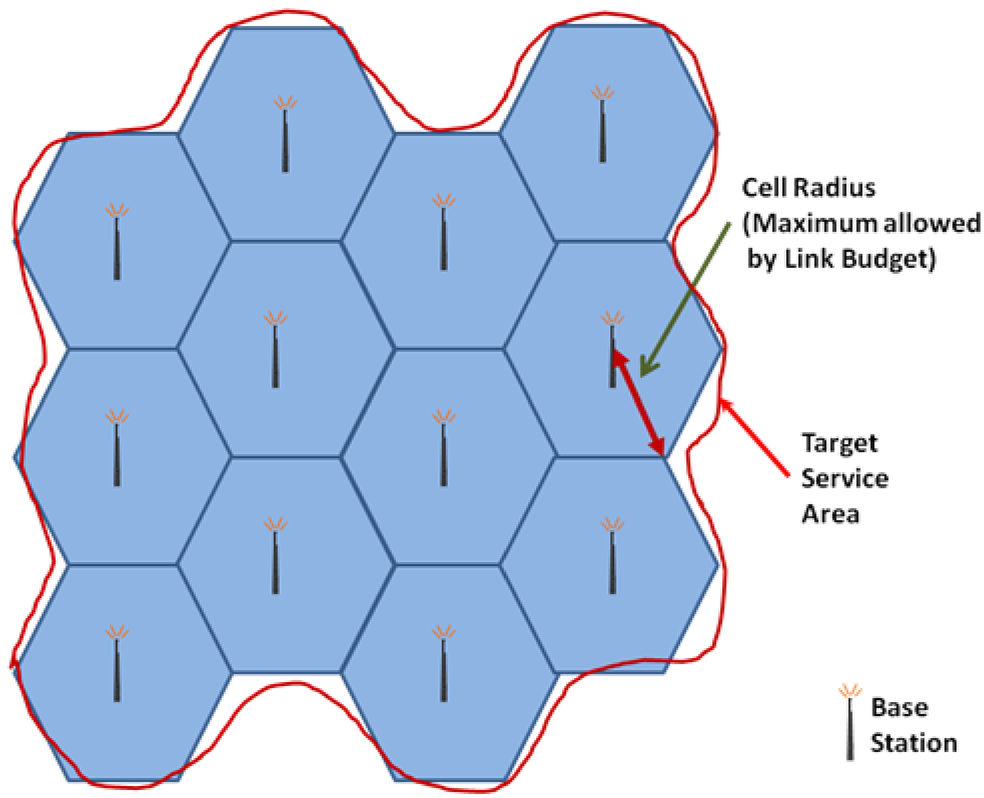

Figure 2.3. Coverage-driven Network Design

Assuming that coverage, not capacity, is the design constraint, the design process will yield the largest possible cell sizes that can be used to cover the target service area – and hence the fewest possible base stations. For example, if a propagation model estimates that the maximum cell

[2] For the sake of simplicity, Figure 2.3 shows a base station covering one hexagon-shaped cell. One base station covering three hexagon-shaped cells (120° sectorization) is the most-commonly deployed configuration.

radius to provide adequate cell edge coverage is 5 km, this cell radius of 5 km is used to choose cell-site locations. If the environment assumed by the propagation model is a close approximation of the real-world environment (often it will not be), coverage-driven deployment may be adequate – but only when the traffic demand generated by subscribers in the cell does not exceed the throughput supported by the cell.

For example, if the average supportable cell throughput is 25 Mbps but the subscriber demand is only 15 Mbps in the cell in Figure 2.3, coverage-driven deployment is sufficient. In practice, network deployments in rural environments have traditionally been coverage-driven. However, some recent studies indicate that even rural environments may now have capacity constraints [WiMAX_700MHz].[3]

Figure 2.4 illustrates the capacity- or throughput-driven deployment scenario. Observe that the cell size in Figure 2.4 is much smaller than that in Figure 2.3 and that more cells and base stations are present in Figure 2.4 compared to Figure 2.3.

At the risk of oversimplification, assume that the voice capacity of a cell (based upon the channel bandwidth) is 60 voice calls.[4] A coverage-driven cell radius estimate of 5 km implies a cell area ($=2.6r^2$, where r is the cell radius) of approximately 65 square kilometers. What happens if our target performance metrics require support for 120 simultaneous voice calls? Placing base stations using a 5 km cell radius will result in subscriber demand exceeding the cell capacity and network performance falling well below the target performance metrics. If we deploy just one base station to cover the 65 square kilometer area, a subscriber can make a call anywhere in the cell. However, when the total number of voice calls in the cell exceeds the cell capacity, new call attempts are blocked. Two cells are thus required to meet the traffic demand of 120 voice calls with each cell taking care of 60 voice calls. Planning for a capacity-driven voice deployment involves (i) estimation of the number of voice calls that future subscribers would generate and (ii) provisioning of a suitable number of base stations to meet the voice traffic demand.

Now, consider a throughput-driven deployment scenario. Assume that a cell has a maximum throughput of 25 Mbps (again based upon the channel bandwidth) but that our single cell with 65 km^2 area has expected subscriber traffic demand of 50 Mbps (based upon the expected number of simultaneous data users in that large area). If we deploy just one cell in this area, we can provide coverage to a subscriber anywhere in the cell, but subscribers would perceive the service

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[3] For example, where a 3G or 4G cellular network is the most economically viable Internet access solution in rural areas, cellular network deployment may well be capacity-driven.

[4] For the sake of simplicity, we are not differentiating between the maximum number of users "capacity" and the average number of simultaneous users ("Erlang" capacity), which are related to each other via a performance metric called Call Blocking Probability.

experience to be poor, because the subscribers are using data applications that require 50 Mbps total throughput to perform well and the cell can handle only 25 Mbps. Two cells would be required to meet the traffic demand of 50 Mbps, because each cell can handle only 25 Mbps. In practice, when the maximum cell throughput is below the subscriber-generated traffic, subscribers' packets experience long delays and the service experience (*e.g.*, video viewing experience) degrades for subscribers. Some users may be blocked from accessing the network altogether because the network runs out of resources. Planning and design for a throughput-driven deployment requires estimation of the amount of traffic that subscribers would generate and provisioning a suitable number of base stations to meet the traffic demand.

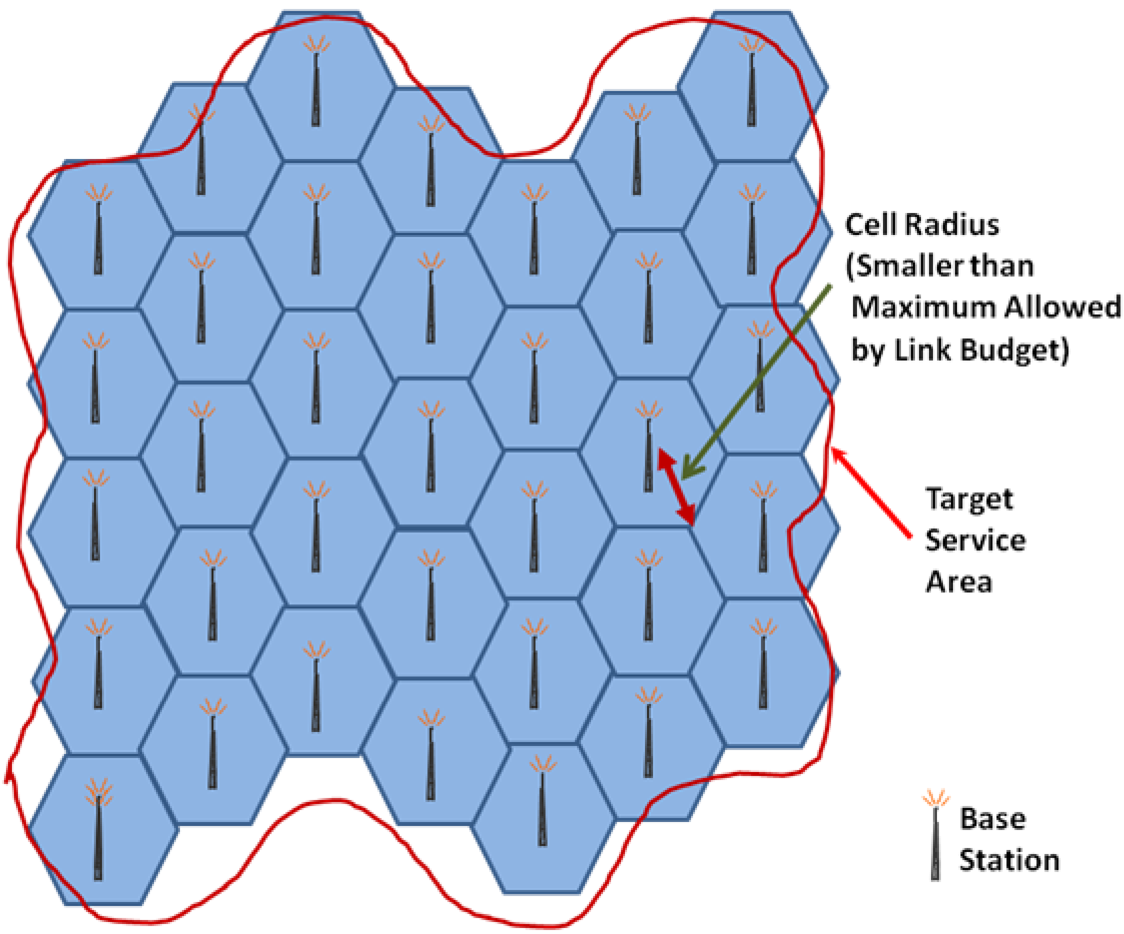

Figure 2.4. Capacity- or Throughput-driven Network Design

Figure 2.4 shows one way of increasing throughput per geographic area, *i.e.*, by using smaller cell sizes and hence more base stations. Another way to increase throughput in the same geographic area is to deploy multiple carrier frequencies.[5] (The term "carrier" in this context refers to a spectrum frequency, not to a company or provider.) Multicarrier deployment can double the available throughput when two carrier frequencies of the same channel bandwidth are deployed. However, care must be taken to match the coverage area of two carrier frequencies, which can be a difficult task when these carrier frequencies are from different frequency bands that are quite far apart from each other (*e.g.*, one carrier frequency at the cellular (850 MHz) band and the other at the PCS (1900 MHz) band). In this scenario, for all practical purposes the propagation characteristics and base station footprint of the *higher* frequency band will determine cell size and base station placement.

When the target service area is large, a hybrid coverage-driven and capacity-driven deployment can be a common scenario. Figure 2.5 illustrates an example scenario of hybrid deployment.

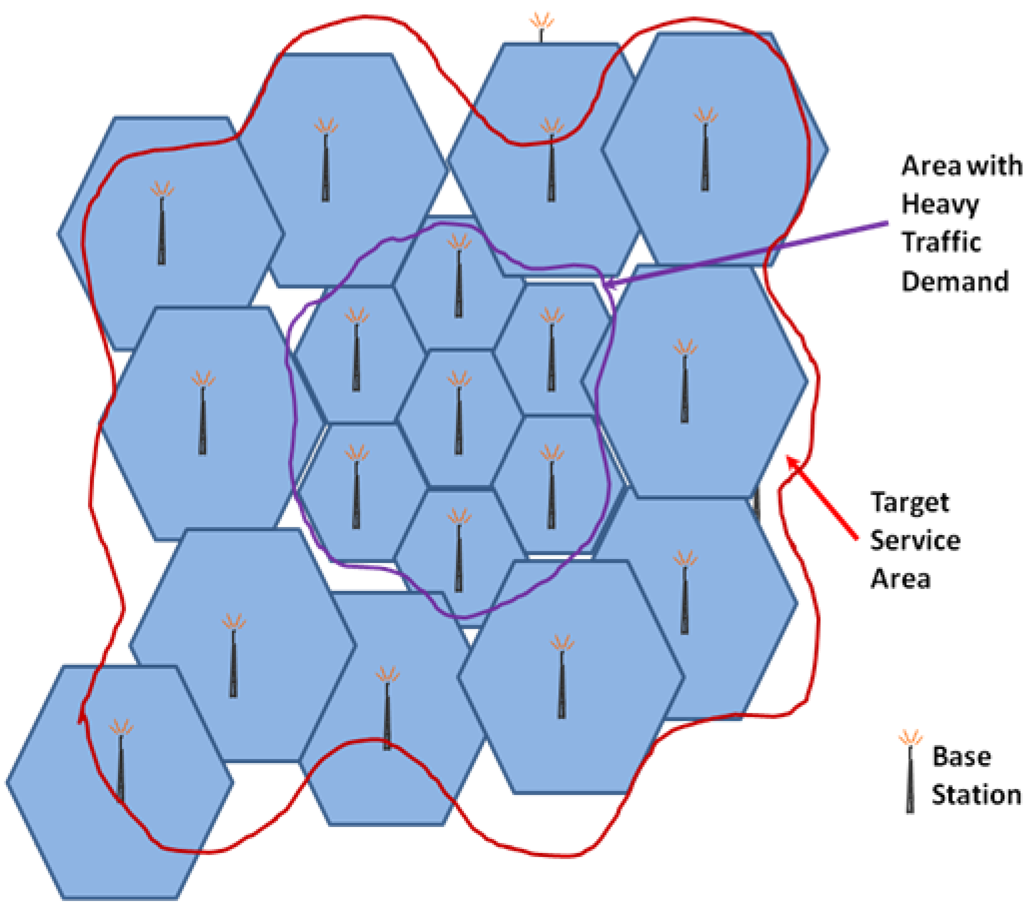

Figure 2.5. Hybrid Coverage-driven and Capacity-driven Network Design

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[5] Yet another way of increasing capacity and throughput is to use finer sectorization (e.g., 60° sectorization instead of more prevalent 120° sectorization).

In the parts of the target service area where the traffic demand is light, large cells are used to reduce infrastructure cost. In contrast, the parts of the service area that have heavy traffic demand necessitate more base stations. As mentioned earlier, either smaller cells or large cells with multicarrier base stations would generally be required to meet the traffic demand.

2.1.3 Factors Complicating the Network Planning and Design

Each service provider operates under constraints that may be different in important respects. Operator-specific circumstances complicate the network planning and design process and may introduce significant variability into the cost of initial network deployment.

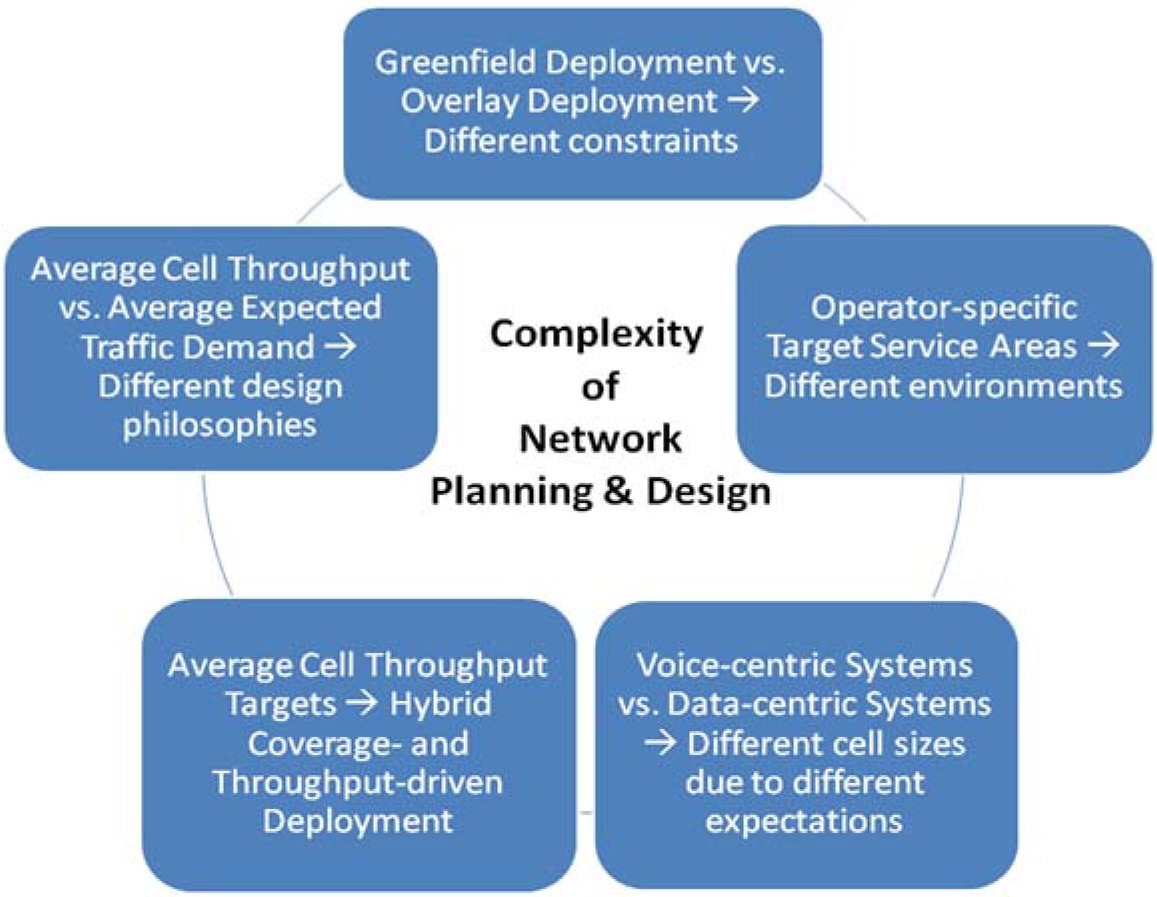

Figure 2.6. Real-world Complexities of Network Planning & Design

A new operator that is just entering the cellular network business may have the luxury of a so-called "greenfield" or "blank slate" deployment. Such an operator does not own any legacy technology networks, and its new technology deployment is not constrained by past decisions, the locations of existing infrastructure, and the characteristics of an existing spectrum inventory.

A more typical deployment, however, is an overlay network, where a new technology network is installed on the top of a pre-existing legacy technology network. An overlay network is more complex and usually has more constraints compared to a greenfield deployment. For example, interworking with legacy networks needs to be carefully managed and numerous interworking-specific parameters need to be optimized. Furthermore, the re-use of existing cell-site locations can be a very significant constraint.

Different service operators may also have a different cell throughput and cell-edge data rate as design targets. This is particularly important in current and future deployments. Earlier cellular technology deployments focused on voice-centric coverage (even systems that can support both voice and data services). However, significant growth in wireless data traffic has fundamentally changed the design process. Today's link budgets (described in more detail below) aim at providing much higher cell-edge data rates than legacy link budgets. Link budgeting now reflects a combination of coverage, QoS, and cell-edge throughput. Thus, cell-edge throughput now influences even the initial coverage-oriented design, which was not the case in earlier cellular systems focused on voice services.

In short, the network planning and design process is heavily influenced by each operator's philosophy and business strategy. For example, if data traffic demand is completely ignored and only coverage-driven deployment is pursued, there could be significant benefits of a lower-band deployment during the initial network roll-out. However, network expansion for capacity may be required much sooner in such a case, offsetting the cost advantage obtained at an earlier stage of the technology life. In contrast, when data traffic demand is considered properly and a hybrid coverage- and throughput-driven (or, pure throughput-driven) deployment is carried out, that network design would be able to satisfy the subscriber traffic requirements for a longer time, delaying the time when network expansion for capacity would be carried out. In yet another example of design philosophy, the service operator may forgo the propagation advantage of a lower-band and deploy a new technology on almost every legacy cell-site to delay the future capacity expansion and to avoid design complexities and potential network performance issues of hybrid coverage- and throughput-driven deployment. The possibilities are endless, but it should be clear that in all real-world lower frequency deployment scenarios, the number of base stations required will be significantly greater than the minimum number of base stations estimated by pure coverage-driven modeling.

2.2 Network Optimization

After the network is commercially launched with a new technology, subscribers start using the newly deployed technology. Although extensive testing is carried out prior to commercial launch, there is no test more severe than the actual use of the network. As the network gets loaded with subscribers, often using new devices and possibly unpredicted applications, issues emerge and network optimization begins. Figure 2.7 highlights major inputs and outputs of network optimization.

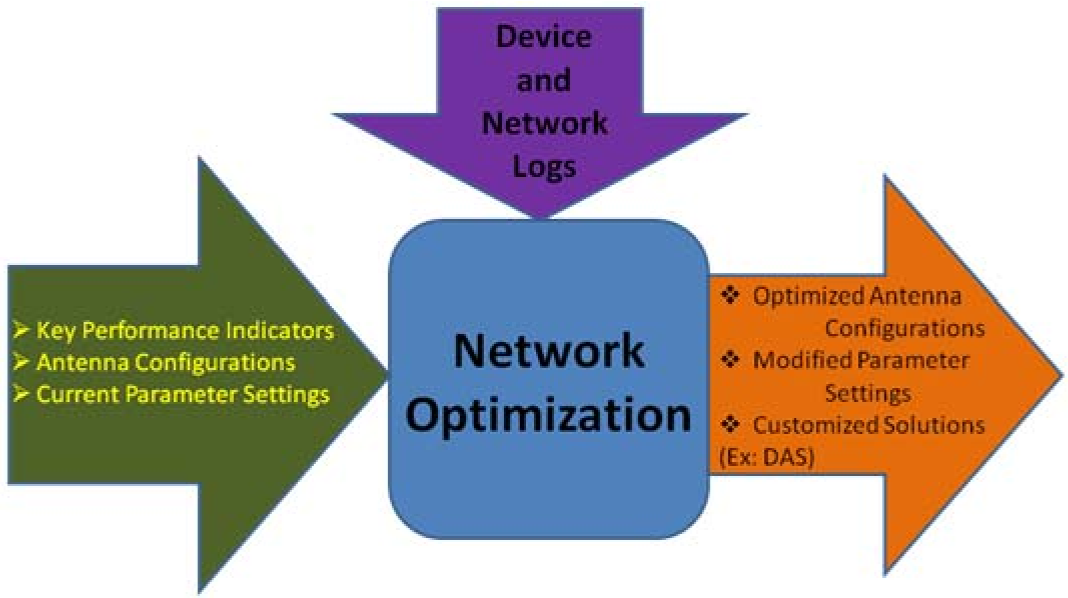

Figure 2.7. Real-World Complexities of Network Planning & Design

Network optimization considers inputs such as target and measured Key Performance Indicators (KPIs), existing antenna configurations, and current settings of network parameters. KPIs, for example, quantify the network performance and user experience (*e.g.*, call blocking probability and supported throughput). Network optimization is a resource-intensive iterative process of tuning and retuning numerous antenna configurations and network parameters. Network optimization often involves drive testing the coverage region to assess network performance. When strategies exploited by network optimization are not adequate to meet the target KPIs in a given area, the next phase of network expansion for capacity (and coverage) becomes necessary.

2.3 Network Expansion

When the footprint of the recently deployed technology is to be extended to cover new geographic areas, network expansion for coverage is carried out. When network optimization strategies fail to achieve capacity- and throughput-related KPIs, network expansion for capacity is warranted. Figure 2.8 summarizes the main inputs and outputs of network expansion.

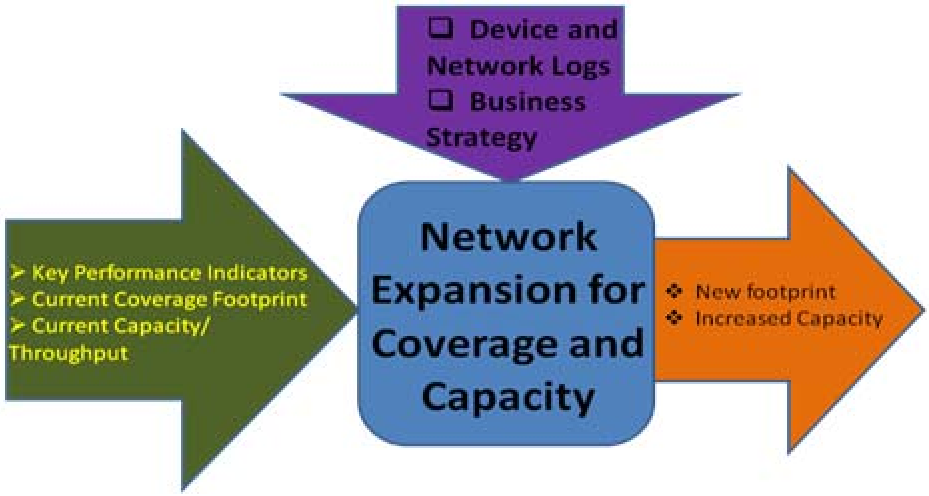

Figure 2.8. Network Expansion to Address Coverage and Capacity

Measured KPIs are continually compared against the target KPIs to identify the need to increase capacity and throughput in specific geographic areas. Example techniques to increase capacity and throughput in a given area include the addition of a carrier frequency (more spectrum), the use of smaller cells (cell splitting), increased sectorization, and smart antennas. Operators such as AT&T and Verizon, for example, have employed all of these mechanisms as subscriber growth and growth in data traffic have strained their networks.

Again, although an initial deployment at a lower-band can have advantages, an initial deployment at a higher-band yields benefits during the network expansion phase with regard to capacity and throughput. Major network expansion for capacity in a higher-band deployment can typically be delayed much longer compared to a lower-band scenario. In other words, higher-band spectrum deployment can yield substantial cost savings during the network expansion phase where capacity is the main driver for expansion. Moreover, if an operator has only narrow bandwidth available at a lower band and has to rely upon higher frequency bands for additional capacity and throughput, the cost and complexity of the network and end user devices may be much higher than a higher-frequency deployment that utilizes a single carrier frequency or band.

3. Coverage Aspects of Network Deployments

In this section, we provide a high-level summary of an extraordinarily complex set of issues: radio wave signal propagation theory; dynamic factors that influence the signal strength experienced by a radio receiver at any particular location and time; the theories, simplifying assumptions, and modeling that cellular network engineers use to determine an appropriate cell size and how many base stations should be employed (and where) to ensure basic coverage; and the many ways in which real-world constraints tend to reduce actual coverage below theoretical or modeled coverage. We first explain the basics of radio wave transmission and identify the key external factors and mechanisms that may influence signal degradation between the transmitter and receiver (Section 3.1). In Section 3.2, we discuss mathematical propagation models and the concept of a "link budget," which in combination can be used by network planners to estimate the *maximum* acceptable separation between the transmitter and the receiver – and hence the *maximum* cell radius – for a cellular network deployment for a given frequency in a defined environment. In Section 3.3, we move from theory to practice and explain why the relative superiority of lower frequency bands in terms of RF propagation characteristics may not lead to significantly fewer cell-sites in practice when various real-world factors are considered.

3.1 Propagation of RF Signals in Cellular Networks

Cellular communications employ electromagnetic radio waves called Radio Frequency (RF) signals. The RF signal in a cellular communication system travels at the speed of light regardless of frequency. However, the wavelength of the RF signal, which influences propagation (and, as we shall explain later, also impacts antenna design and the effectiveness of advanced antenna techniques designed to provide both coverage and capacity benefits) varies with frequency. As the carrier frequency increases, wavelength decreases. As a general theoretical matter, the longer the RF signal wavelength the greater the maximum separation distance between the radio transmitter and the radio receiver – all else being equal – although, as we explain below, all else may not be equal, and there are many other factors that influence cell size in real world cellular network deployments.

Radio wave propagation in real world environments is extraordinarily complex. Among other things, the propagation of RF signals may be influenced by numerous interactive factors, including terrain, weather, foliage, the presence, types and density of buildings and other manmade structures, and ambient "noise" and interference levels attributable to both environmental and other manmade radio wave emissions. Of course, all of these external factors may be constantly changing across both time and location. And where, as in modern cellular networks, mobility is introduced, the difficulty of predicting propagation – *e.g.*, the expected "attenuation" or signal loss (typically measured in decibels or dB) between the radio transmitter and a radio receiver at any particular location and time – only increases.

In order to deal with this complexity, cellular network engineers typically employ what is called "ray" theory to model four basic mechanisms that influence the overall attenuation or path loss experienced by the radio signal as it proceeds from the transmitter to the receiver: *reflection*, *diffraction*, *scattering*, and *absorption or penetration* [TripathiReedCellularBook].

When an electromagnetic wave encounters an object that has large dimensions compared to its wavelength, *reflection* occurs. Reflection allows signal propagation in the absence of a line-of-sight between the transmitter and receiver. Receivers can receive direct line-of-sight paths, or reflected paths, or both from the transmitter. Buildings in an urban environment, mountains in an open environment, and the earth's surface are examples of the objects that cause reflections of the RF wave.

When an electromagnetic wave encounters an object with sharp irregularities such as edges, it bends around the object and continues its journey forward. This propagation effect is called *diffraction*. Diffraction allows signal propagation in the absence of line-of-sight between the transmitter and the receiver. Higher frequency signals are typically better able to "bend" around corners than lower frequency signals.

When the electromagnetic wave comes across objects that are smaller than its wavelength, these objects scatter energy in numerous directions. This propagation effect is referred to as *scattering*, and it also contributes to signal propagation in the absence of line-of-sight between the transmitter and receiver. Scattering results in a strong signal relative to the combined propagation phenomena of diffraction and reflection; however, it also tends to produce a more distorted signal. Objects such as tree leaves and street signs cause scattering. Scattering tends to be less prevalent with lower frequency signals due to the larger wavelength relative to objects in the environment.

Atmospheric effects such as rain can cause *absorption*, but typically only at very high frequencies that are well above the range of frequencies used in cellular systems. Seasonal changes, however, may cause significant changes in vegetation, and, such effects may be considered during network planning and deployment (*e.g.*, provisioning of a 5 dB loss in case of wet forests [COST231_Report]). Certain types of building materials can also absorb RF energy. The relative absorption impacts of lower- and higher-frequency spectrum are highly material specific.

Because cellular networks are, for obvious reasons, concentrated where people are most likely to be, building *penetration* loss typically is a consideration in cellular network planning. The building penetration loss depends on factors such as the construction material, type of windows, frequency, and the floor. For example, a concrete wall might cause 8 to 15 dB attenuation, while a metal wall might cause attenuation of 40 to 50 dB. A tinted window may have an increased loss relative to a non-tinted window. The impact of frequency on penetration loss is particularly complex. Although in general there tends to be more loss at higher frequencies for materials that might have some conductivity, a number of studies have found that within the frequency ranges typical of cellular networks, building penetration losses actually *decrease* as frequency increases.[6]

Building penetration losses typically increase the further the receiver is from the exterior wall of the building. Building penetration losses can often be so significant that cellular network

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6 [TurkmaniToledo], [TanisPilato], [TurkmaniParsonsLewis], [DavidsonHill], [MirWhite], [Smith].

planners rely upon in-building solutions, including WiFi, and pico and femto cells. Losses due to building materials are an advantage when one deploys such indoor cellular systems, because building attenuation losses help prevent interference to the macro cellular network.

In some propagation models used in commercial network planning tools, attenuation caused by the building penetration loss is often considered only implicitly through consideration of urban, dense-urban, open space and other "clutter classes" [Atoll]. Obviously, propagation modeling using clutter classes can provide only average or rough estimates of expected attenuation over a given geographic area that may vary considerably from what is actually experienced at particular locations within that geographic area.

As the signal travels from the transmitter to the receiver, all of the phenomena discussed in Section 3.1 influence the signal propagation. The total attenuation experienced by the signal can be calculated as a sum of three components: distance-based path loss, large-scale fading loss, and small-scale fading loss. The distance-based path loss considers the factors such as distance between the transmitter and the receiver, frequency of the RF signal, antenna heights, and the type of the environment. The distance-based path loss (as the name suggests) increases as the signal travels farther from the transmitter. The large-scale fading loss accounts for the differences in the average signal strength at different locations with the same transmitter-receiver separation. The small-scale fading loss reflects sudden changes in the signal strength as the receiver moves by a small distance (*e.g.*, on the order of the wavelength or even a fraction of the wavelength).

3.2 Propagation Models and Simplified Coverage Analysis

Cellular service providers carry out the process of network planning and design to determine the locations and placement of base stations needed to meet the target coverage and capacity requirements. The first step in that process is typically to estimate the maximum possible separation between the transmitter and the receiver – and thus the maximum cell radius. This "coverage"-focused exercise is typically quantified by use of a link budget. As noted, the link budget specifies the maximum attenuation that a signal can tolerate during its journey from a transmitter to a receiver. For example, a link budget of 130 dB implies that the signal can tolerate a maximum path loss of 130 dB between the transmitter and the receiver.[7] When the link budget is used in conjunction with a suitable propagation model, we can estimate the maximum separation between the transmitter and the receiver. This "cell radius" dictates the minimum number of cell-sites that would be needed to provide coverage over a given geographic area.

[7] The link budget is separately calculated for the uplink and the downlink. Since the mobile device has a limited power available compared to the base station, the uplink is usually the limiting link from the perspective of link budget.

It is important to recognize that this modeled cell radius is a best-case exercise that focuses only on basic coverage and that both complexities in the real-world radio environment (from buildings and other obstructions to zoning and other restrictions that affect tower placement) and expected and experienced customer usage patterns may require many more actual cell-sites than estimated by the link budget/propagation model exercise. And, as we shall see, the latter capacity effects on the number of cell-sites required may be particularly pronounced in networks that employ lower-frequency spectrum.

To calculate the cell radius from the link budget, a mathematical formulation that relates the distance and the path loss is needed. A number of propagation models that reduce the propagation complexities to simplified mathematical formulations that focus on the distance-based path loss have been developed.[8] Different propagation models are applicable to different situations. For example, one popular model, the Okumura-Hata model, is often used for the frequency range 150 MHz-1500 MHz and distances of 1 km- 20 km. The COST231-Hata model is used for the frequency range 1500 MHz- 2000 MHz and the distance range of 1 km- 20 km. Another model, ITU-R M.1225, is used for the frequency range of 800 MHz-2000 MHz and distances between of 20 meters and 5 km.

From the pure coverage perspective – without any consideration of capacity and throughput needs, complexities in the real-world deployment that are not accounted for in the simplified propagation model, and advanced antenna and other technologies that may enhance both coverage and capacity and that may perform better at higher frequencies – lower frequencies support larger cells. Our analysis shows that the (theoretical) maximum cell size estimated by propagation models is smaller for higher frequency bands, provided that the coverage is the only consideration and that there are no constraints on cell-site locations. It is important to recognize, however, that such coverage differences reflect the *maximum gain* that lower bands can provide relative to higher bands. The *actual gain* – and the actual impact on network deployment and the number of cell sites required – can be a quite different story altogether.

[8] The large-scale fading loss and the small-scale fading loss are accounted for in the calculation of the link budget itself. The large-scale fading is modeled by a log-normal distribution and the link budget assumes a certain standard deviation (*e.g.*, 8 dB). The small-scale fading is reflected in the value of the signal-to-noise ratio (SNR) used in the link budget. In other words, the signal power in the SNR is an average power estimate after taking into account small-scale fading.

3.3 Propagation Benefits of Lower Bands: From Theory to Practice

Figure 3.1 summarizes the factors that prevent an operator from realizing the full potential of the propagation advantage of lower frequency bands.[9]

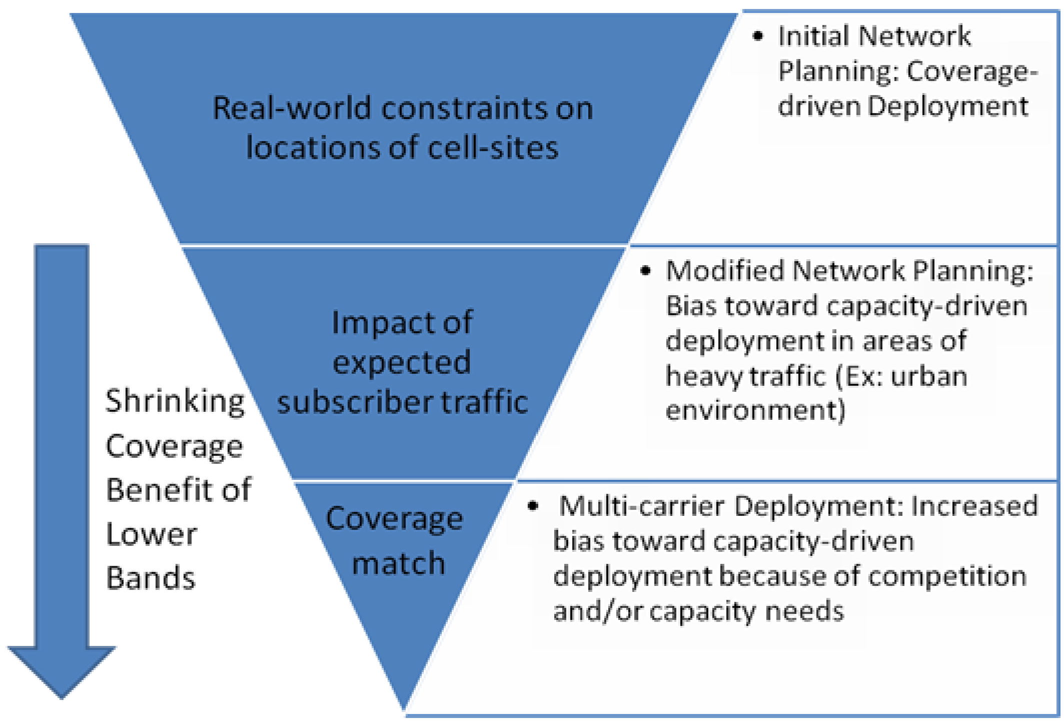

Figure 3.1. Obstacles Preventing Full Realization of Propagation Benefits of Lower Bands

As described in Section 2, coverage-driven network design that assumes that we can put a cell-site at the ideal location determined according to propagation analysis is carried out first during the initial network planning and design process. However, in the real-world, we often have to settle for sub-optimal cell-site locations for reasons such as unavailability of the location (*e.g.*, building owner's refusal to allow a cell-site and zoning restrictions on cell-site locations and/or antenna placements or heights) or the service provider's need to re-use pre-existing cell-sites to reduce cost. Sub-optimal cell-site locations introduce inefficiencies to the network design and create coverage holes, where the signal strength is inadequate for reliable communications. New cell-sites are added when other solutions such as changes in antenna parameters are not

[9] We assume in this section some numerical values of various parameters for low-band and high-band network deployments. Absolute values of these parameters are not critical; we are interested only in a relative comparison.

sufficient. Depending upon how often we cannot construct a cell-site at an "ideal" location, there may be a reduction in the comparative advantage of a lower band with respect to a higher band.

Coverage-driven initial network design must also be modified to consider capacity and throughput requirements growth as discussed earlier in Section 2. Although per-cell throughput is the same for a low-band or high-band cell, smaller cells at a high band imply more throughput potential per square kilometer area. This principle is explained in the example below.

Assume that we have 50 sites at the 700 MHz band and 100 sites at the AWS band to "cover" a given geographic area. Further assume that one cell-site supports a throughput of 50 Mbps in a 10 MHz channel bandwidth. If users in this area generate traffic of 5000 Mbps, we need 5000 Mbps/50 Mbps = 100 cell-sites to meet the traffic demand. Since we already have 100 sites at the AWS band to provide coverage, there is no need add any new cell-sites to meet the traffic demand.

In contrast, we have only 50 sites in the same geographic area at the 700 MHz band, and they can support throughput of 50 Mbps x 50 cell-sites = 2500 Mbps. Since the traffic demand is twice that amount, we need to add 50 more cell-sites (for a total of 100) at the 700 MHz band.

In summary, depending upon the capacity and traffic requirements in a given geographic area, the propagation advantage of lower bands could be reduced significantly and even eliminated. The numbers of cell-sites required for lower-band and higher-band deployment are unlikely to be much different when the network deployment becomes capacity-driven instead of coverage-driven, and especially if the cell-site locations already exist.

In a typical network deployment, there is a mixture of coverage-driven deployment and capacity-driven deployment. Hence, while lower-frequency bands could provide propagation advantages in some areas, they would provide much lower or no gain in other areas (and because cell site density is so much higher in the urban and suburban areas where capacity-driven deployment is most likely, overall network deployment cost advantages of lower frequency networks are likely to be modest).

Moreover, with the explosive growth in wireless data traffic, capacity-driven deployment would be more prevalent in newer network deployments compared to legacy network deployments. We discuss capacity and throughput aspects of deployments in more detail in Section 4.

Another real-world constraint that may dissipate or eliminate lower-frequency advantages in the number of required cell-sites is a multi-carrier (the term "multi-carrier" here refers to the use of multiple frequency bands) deployment for a new technology. Assume that Operator X has 10 MHz channel bandwidth at 700 MHz but has determined that 20 MHz of channel bandwidth is required to meet capacity and throughput needs (even after decreasing cell sizes through the deployment of additional cell sites). Assume also that Operator X's other spectrum holdings are in higher frequency bands such as AWS. The operator would deploy a multicarrier base station that supports both the 700 MHz band and the AWS band. Each cell would need suitable pieces of equipment (*e.g.*, power amplifiers, filters, and antennas) to support two carrier frequencies, one at the 700 MHz band and one at the AWS band. Multi-carrier deployments typically necessitate the same coverage footprint for each carrier, which means the smaller cell sizes of the highest frequency band in the mix, eliminating the propagation advantage of a lower band altogether.[10]

4. The Increasing Importance of Capacity and QoS in Cellular Network Design and Deployment

As explained above, network planning and design must consider not only coverage, but also network performance targets that are linked to capacity. And, as cellular systems have evolved from early voice-centric technologies and network deployments to modern data-centric technologies and deployments, capacity and throughput are increasingly eclipsing coverage as the dominant network design drivers. In this section, we explain both why and how the process of cellular network planning and design has undergone tremendous changes due to changing wireless usage patterns and, in particular, exponentially rising data traffic.

We provide a brief overview of the evolution of cellular standards and cellular services in Section 4.1. Section 4.2 highlights the very different network performance metrics for voice and data services. Section 4.3 illustrates the heavy influence of data service performance metrics on network planning and design and shows, once again, why real-world cellular network deployments at lower frequencies are unlikely to exhibit the coverage benefits over higher frequency deployments that simplistic propagation modeling might predict.

4.1 Evolving Cellular Standards and Evolving Usage of Cellular Networks

Subscribers of early cellular systems were primarily interested in making and receiving telephone calls while on the move, and first-generation cellular systems such as Advanced Mobile Phone System (AMPS) supported only circuit-switched mobile voice services. Second-generation cellular systems such as GSM and IS-95 added support for low rate (*e.g.*, on the order of tens of kbps) circuit-switched data services and also Short Message Service (SMS) capabilities. Third-generation cellular systems such as UMTS support significantly higher data rates and utilize a more efficient packet-switched approach. Fourth-generation cellular systems such as LTE and WiMAX are capable of providing much higher data rates (*e.g.*, peak theoretical rates greater than 100 Mbps).

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[10] A multi-carrier base station is typically more expensive than a single-carrier base station due to the need for additional components such as high power amplifiers, RF filters, and duplexers. Inadequate bandwidth at a low band essentially leads to a higher overall cost of deployment.

These technology transformations reflect consumers' expanding and changing uses of rapidly evolving mobile devices. As basic telephones have given way to wireless smart phones, laptops, and tablets and emerging devices that communicate "machine to machine," cellular networks are being used for an enormous range of new and evolving data-centric applications. This evolution has made demands on the network more variable and less predictable.

Rapidly rising data traffic has spurred cellular network operators to invest billions of dollars in their wireless networks to increase capacity/throughput [BusinessWeek_WirelessUpgrades]. This investment has taken the form of adding base stations and reducing cell sizes, adding carrier frequencies and deploying advanced technologies in existing cellular networks. And, as we explain below, the transformational shift to data-centric networks has prompted cellular network operators fundamentally to alter their network planning and design philosophies.

4.2 Quantifying Network Performance

A basic understanding of the different performance metrics for voice and data services provides the foundation for an explanation of how the rise of data relative to voice has affected cellular network planning and design. Figure 4.1 lists some of the key performance metrics that may be relevant to the provision of voice services only, data services only, or both voice and data services. Commercial cellular networks use these (and many other, more specific) performance metrics in the design, optimization and expansion processes [TripathiReed_CellularBook].

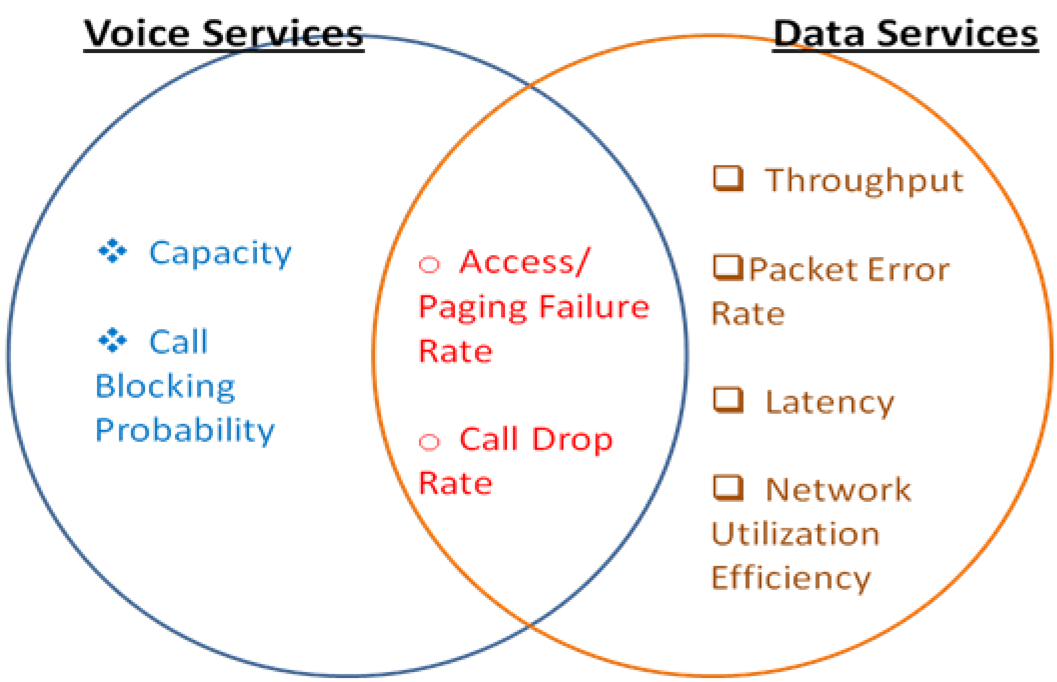

Figure 4.1. Performance Metrics for Voice and Data Services

As Figure 4.1 indicates, there are a few performance metrics that apply to both voice and data. The "access failure rate" measures how frequently a user is unable to establish a contact with the network. Paging refers to the process whereby the network sends out a "broadcast" message to the group of cells within which a particular user is thought to be located in order to pinpoint the cell in which the user is actually located so that a connection with the network may be established. The "paging failure rate" specifies how often paging is unsuccessful. And the "call drop rate" is the ratio of the number of call (or data connection) drops to total calls (or data connections) observed during a given time interval. Beyond these common performance metrics, the performance metrics used for voice and data differ considerably.

The major performance metrics applicable to voice services are voice capacity (and quality) and call blocking probability. Voice capacity is the maximum number of voice users that can be supported at a target QoS such as a 1% frame error rate.[11] Call blocking probability is the probability that a new call is blocked because of the unavailability of network resources. Commercial networks aim for a call blocking probability of 1% to 2%. If the observed call blocking probability in a given area consistently stays much above the target level of 1% to 2%, it is an indication of inadequate capacity. Voice calls use relatively low bandwidth (on the order of 12 kbps), and voice traffic tends to be more predictable than data traffic.

Data service performance is typically quantified using other metrics such as throughput and latency. Average throughput supported by a cell is the ratio of the average number of bits transmitted in a cell to the time period (using expected demand in the design phase or actual demand in the optimization or expansion phases), such as megabits per second (Mbps). The packet error rate for data services is like the frame error rate for voice services – it is the ratio of the number of packets in error to the total number of packets during a given observation period. Latency is the average delay experienced by packets moving through a network. Network utilization efficiency quantifies the extent to which the network resources are being used. Consistently high network utilization efficiency and increasing latency over an observation period indicate the need for capacity/throughput expansion.

Data traffic growth and variability, both on a total network basis and with respect to individual cells within the network, have proven frustratingly difficult to predict. The one constant to date seems to be that actual demand growth and variability have exceeded expectations, triggering the need for performance enhancements to existing data networks and changes in the ways network planners build "spare" capacity into the design process (*e.g.*, by reducing cell size below what traditional hybrid coverage/capacity models might suggest).

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[11] The frame error rate is the ratio of the call data received with errors to the total call data received. A 1% frame error rate means that one frame out of 100 is in error. If the FER is too high, the call may be dropped.

The complexity and diversity of the data performance metrics relative to voice mean that designing for, measuring and responding to QoS-oriented performance metrics is more difficult and subject to greater error. Quantifying QoS for data services becomes even more complex when multiple classes of QoS are considered. For example, there are nine levels of QoS supported in LTE. Different QoS classes in LTE have different targets for packet error rate and the system designer must take this into account.

4.3 The Increasing Influence of Capacity and QoS on Network Planning and Design

Figure 4.2 summarizes how capacity and QoS considerations have significantly altered a coverage-driven design philosophy that had dominated first three generations of cellular technologies. The main outcome of the emerging design philosophy is that the planning process must recognize that more cell-sites will be required to cover a given area – at target performance levels – compared to the number of cell-sites that might have been deployed under legacy design philosophies that placed heavier emphasis on a pure coverage-driven deployment.

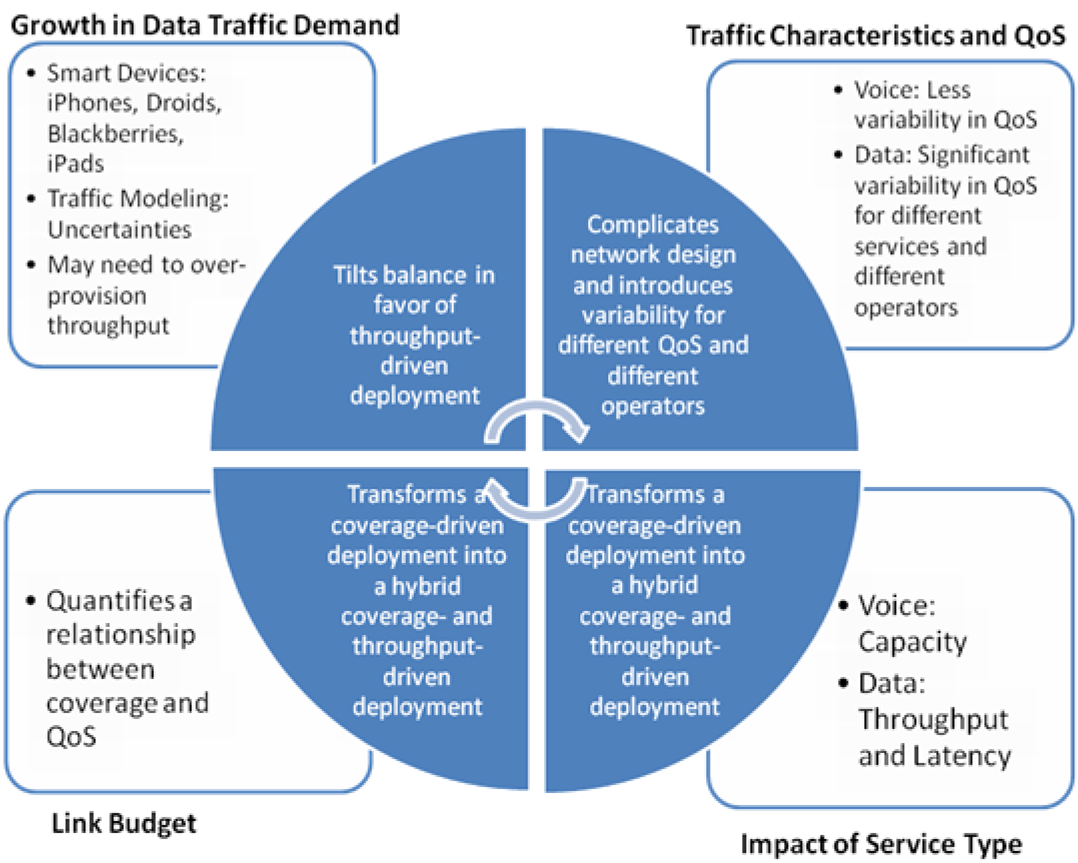

Figure 4.2. Influence of Capacity and QoS on Network Planning and Design

The increasing popularity of multimedia devices and interactive (and often video streaming-focused) websites has resulted in exponential increases in data traffic. An effective network planning and design approach must consider not only current demand (which may be relatively light at initial deployment when there are few subscribers, and devices and applications that take full advantage of the new technologies capabilities have yet to be embraced by consumer), but also estimates of expected future traffic demand.

Network planners have learned from experience that this will often mean capacity-based, not coverage-based design, where cell size is determined not by the propagation characteristics of the particular spectrum frequency being used, but by the number of simultaneous data users that can be supported given the channel bandwidth that is available.

But if recent experience has taught cellular engineers anything, it is that estimating future traffic demand is anything but an exact science. Both inter- and intra-cell data traffic variations can be huge and very difficult accurately to predict. Modern cellular network planners may therefore respond appropriately with what would have been considered "over" provisioning under prior voice-centric design philosophies. Otherwise, the operator has to keep upgrading the network continuously to catch up with the traffic demand.

Existing wireless networks have already been strained due to heavy traffic [DataSurge_BusWk_122309]. The need to have adequate cell-site throughput to meet at least average traffic demand (and possibly even peak demand depending upon the variability and demand profile and the operator's business plan) means that throughput-driven deployment will continue to become increasingly common, not just in dense urban areas, but in urban and suburban (and even rural) areas that are likewise experiencing high data traffic demand. Thus, the number of cell-sites required to cover a given area with lower frequency spectrum that propagates particularly well could thus be much higher than the number of cell-sites predicted by a pure coverage-driven deployment or even the hybrid coverage/capacity approaches that have been employed in the past.

The shift to data-centric cellular networks that support a wide range of data – and voice – applications with differing QoS needs also means that generalizations about how many cell-sites/base stations are needed for a network deployment at a given frequency are meaningless for an additional reason. Even with a modern design approach that appropriately accounts for data-specific performance targets, the real-world network design will be heavily influenced by the specific operator's business plan and mix of customers, services, devices and applications. Significant QoS variations exist not only for different services but also for different service providers. There are no standardized data rates that the service providers aim for, and, hence, different service providers may have different QoS targets. In practice, such complexities and distinctions in service goals could lead to different numbers of cell-sites for different operators to cover the same number of subscribers in a given geographic area even if both employ the same frequency band.

5. Low-band and High-band Network Deployments: Is One "Better" Than the Other?

Commercial deployments of cellular networks in the U.S. initially occurred at 850 MHz because those "cellular" bands were the first frequency bands designated by the FCC for cellular networks. Today, U.S. cellular network operators employ spectrum ranging from 700 MHz to 2.5 GHz. Different operators have different spectrum holdings with some having only high bands, some having primarily low bands, and some relying heavily on both low bands and high bands. In Europe the spread is even greater, with successful cellular deployments at frequencies as low as 450 MHz and as high as 3.5 GHz. Given the different characteristics of individual spectrum bands, how have network operators and engineers enjoyed success with such widely varying frequency deployments?

The answer is two-fold. First, radio environments themselves vary widely: from congested dense urban developments to sparsely populated rural areas, from barren, flat plains to hilly and heavily vegetated areas, from rainy to dry, and from glass-dominated structures to reinforced concrete and steel structures. There are also wide variations in network operator business models, ranging from networks that focus on the most cost effective "basic" voice and data services (often prepaid) to networks that have built their reputations on introducing the latest smartphones, computers and other devices favored by the most data-intensive customers. But as the preceding sections make clear, there is no one-size-fits-all frequency band. All frequency bands have their own unique limitations, and there is no frequency band that is the best in all environments and circumstances. Thus, for example, one operator's coverage advantages become capacity disadvantages, and another operator's coverage disadvantages are offset by capacity advantages. And depending upon their legacy network deployments and spectrum holdings and future business and expansion plans, two operators may well reach opposite conclusions regarding whether low-band or high-band frequencies are "better."

Second, as is often the case in the innovative wireless space, technology advances that we explore further in this section are rapidly responding to the unique challenges associated with given frequency bands. That is particularly true with respect to the coverage/cell-edge challenges, for which high-band spectrum is well-suited for advanced antenna techniques and other engineering responses to such challenges. In other words, although differences in relative propagation characteristics may remain constant, engineering solutions do not, and modern network planners and operators employ numerous innovative techniques to get the most out of the spectrum available to them.

We summarize the key advantages and disadvantages of low- and high-band deployments in Sections 5.1 and 5.2. We describe coverage enhancement techniques in Section 5.3, capacity/throughput enhancement techniques in Section 5.4, and in-building solutions in Section 5.5. When all relevant factors and technologies are considered, it is clear that blanket statements that certain frequency bands are inherently superior to others simply cannot be supported.

5.1 Low-band Deployments: Advantages and Disadvantages

As noted, a lower band offers propagation advantages relative to a higher band due to smaller path loss. When coverage is the primary concern in a given area and throughput is *not* a factor in that area, a lower band deployment can therefore be attractive as, all else being equal, fewer base stations would be required to cover the area. As we have seen, however, in geographic areas where capacity and QoS must be considered due to high demand and subscriber densities, these lower-band propagation advantages are diminished (and may be eliminated altogether).

To the network operator contemplating a real world cellular network deployment this means that the initial capital investment to launch a lower-band network may be lower (although, as we have explained, only in the areas where, and to the extent that, initial capacity/throughput targets do not require capacity-driven, rather than coverage-driven, cell sizing).

However, the larger cell sizes also mean that the operator will incur greater capital expenditures to expand capacity – by adding base stations or carrier frequencies – sooner relative to a higher-band deployment. Furthermore, if subscriber growth (or average subscriber usage) exceeds expectations, capacity expansion expenditures may be required in very short order, negating the initial capital expenditure savings advantage. The capacity expansion process is also likely to be more complex relative to a higher band deployment, both because there is simply less available spectrum in the lower frequency bands and, as we explain below, because the greater wavelengths and other propagation characteristics of lower frequency bands limit the benefits that can be achieved from advanced antenna technologies.

Moreover, as noted above, if an operator must deploy multiple carrier frequencies across different frequency bands to meet minimum throughput requirements or to stay competitive, a lower band may not bring *any* coverage advantage because the coverage for the multiple carrier frequencies in multi-carrier deployment must typically match. Thus, it is the propagation characteristics of the higher frequency band that will typically drive network design, cell sizes and base station deployment. Compared to a single carrier frequency deployment, a multi-carrier deployment with frequencies from widely-separated frequency bands also increases the complexity and cost of base station transceivers, device transceivers, and antenna systems and complicates the process of RF optimization. In short, the coverage vs. capacity tradeoff in lower-band deployments relative to higher band deployments is substantial and complex.

Lower frequency spectrum may provide better building penetration in some circumstances, although, as noted above, a number of studies have shown that higher frequency signals may often experience *less* penetration loss in some conditions. But even in conditions in which lower bands (*e.g.*, 700 MHz) penetrate buildings (and cars) better than higher bands, it may not often be relevant to network design and spectrum choice for several reasons. First, whatever frequency is used, a network operator's link budget typically includes a building penetration margin (*e.g.*, the link budget may assume a 20 dB penetration loss). As long as the actual building penetration loss is less than the design target (as can be designed for in both lower- and higher-band deployments) actual performance can meet target performance.

Second, an in-building signal strength advantage may not translate into a real world throughput advantage. That is because throughput is primarily a function of signal-to-interference ratio (SIR), and not a function of *absolute* signal strength. Outside the building, both signal and interference are strong. Inside the building both signal and interference are relatively weaker. But SIR may remain almost the same.[12] And, as we describe in Section 5.4, advanced antenna techniques that may perform better in higher frequency deployments are available specifically to address cell-edge throughput and reliability challenges – *e.g.*, improvements in *receive* SIR/SNR can be achieved by the using so-called diversity techniques.

Third, although indoor penetration can in some instances be better for lower frequency systems, in-building performance may fall short of target levels for lower- and higher-frequency networks alike in buildings that are constructed of materials (*e.g.*, steel or reinforced concrete) that are particular resistant to RF signals or that are very large (and where customers demand deep in-building reception). In these environments, *all* operators, regardless of the frequency bands utilized, may have to turn to in-building solutions such as Wi-Fi or pico/femto cells, and here too, as we explain below, there may be advantages to higher frequency deployments because of the differing interference characteristics of low and high band spectrum. In fact, there are some inherent advantages of using higher frequencies for indoor cellular systems such as femto cells since these systems would likely cause less interference to the macro cellular system.

5.2 High-band Deployments: Advantages and Disadvantages

A high-band deployment, too, has both advantages and drawbacks, and, even more so than with a low-band deployment, technology solutions have developed to address shortcomings.

A higher-band deployment exhibits the flipside of a lower-band deployment. All else being equal, the higher band's smaller cell sizes in some areas may require higher capital expenditures during the initial launch of a new cellular technology. However, that initial investment will yield nice dividends. Higher throughput per unit area means that capital expenditures for capacity growth can be postponed relative to a low-band deployment scenario.

[12] A signal strength advantage is more likely to translate into an in-building throughput advantage in the uplink. The uplink power control ensures adequate SIR (and transmit power from the device) to meet a target packet error rate. Better building penetration could yield a "measurable" throughput gain is at the cell-edge, because the device inside the building at a cell edge may not be able to increase its transmit power to reach the target SIR in the uplink. More retransmissions would be required in such a case, resulting in a lower throughput. In many cases, however, better building penetration is unlikely to yield a significant improvement in throughput.

Moreover, larger spectrum chunks are more readily available in the higher bands, and the use of larger blocks of contiguous spectrum increases the achievable throughput per cell. Even if contiguous spectrum is not available, a multicarrier deployment in a given frequency band (or across "close-by" frequency bands) is much simpler and less expensive than a multicarrier deployment across widely-separated frequency bands (as might be required to augment capacity in a lower-band network deployment).

As noted, when devices are inside buildings near the cell-edge, a higher band deployment may see some degradation in throughput. In other cases, however, in-building network performance is expected to be similar for lower-band and higher-band deployments. Moreover, as we explain below, advanced antenna techniques such as beamforming and MIMO tend to work better at higher frequency bands, and in-building engineering solutions may also be used.

5.3 Coverage Solutions

Figure 5.1 shows the three categories of coverage solutions:

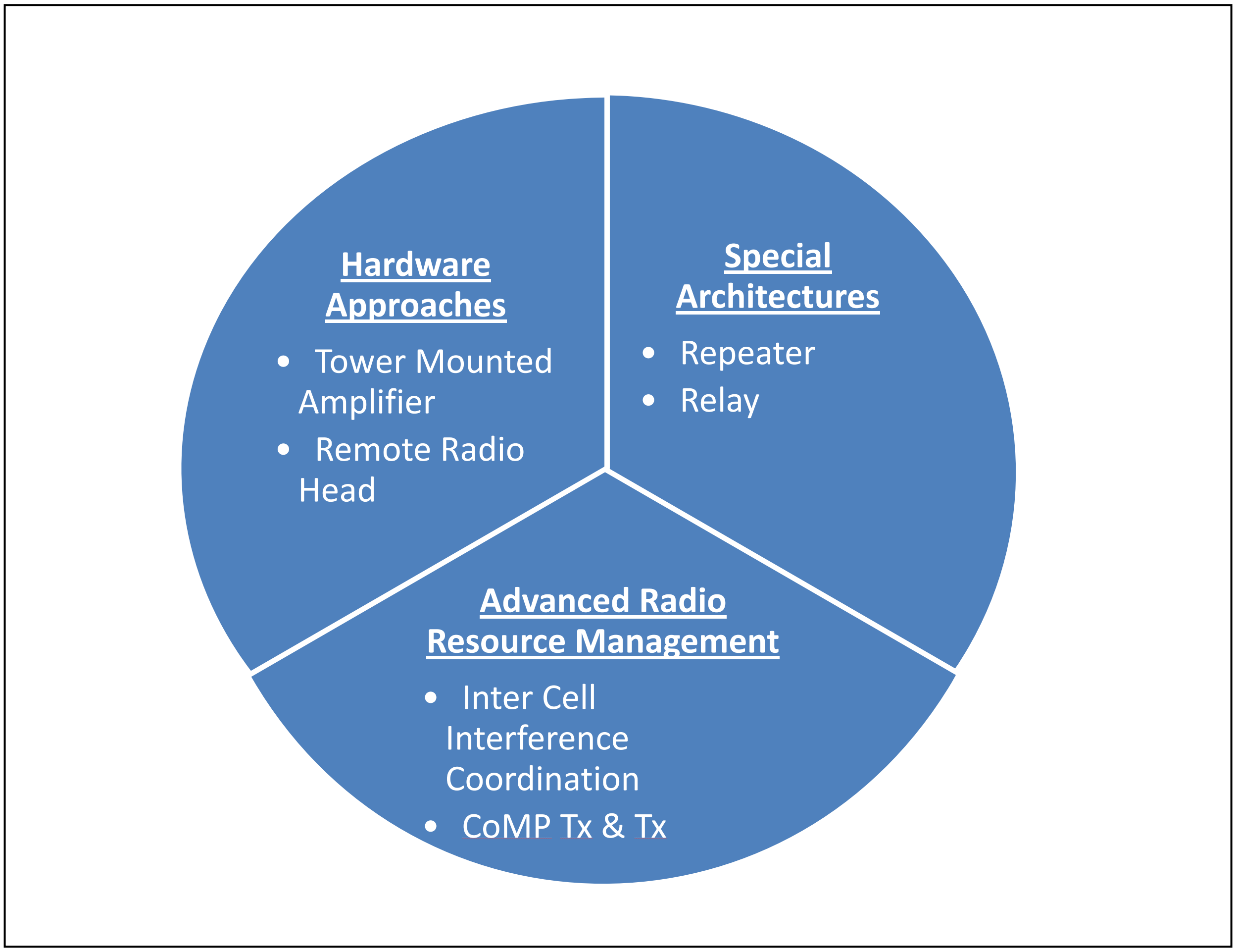

Figure 5.1. Coverage Enhancement Mechanisms

Hardware approaches use specialized hardware such as "tower mounted amplifiers" (TMA)[13] and "remote radio heads" (RRH). These hardware components improve the link budget (typically by about 2.5 dB), increasing the supportable cell size. Recall that the link budget is usually uplink-limited. The RF cable that brings the uplink RF signal from the antenna to the bottom of the tower could cause about 3 dB loss. This cable loss increases the overall noise in the receiver and is one of limiting factors in the link budget. TMAs and RRHs reduce this overall noise by reducing the impact of the cable loss on the link budget. A TMA amplifies the received signal using a high-gain "low noise amplifier," reducing the effective cable loss. An RRH eliminates the RF cable loss altogether by carrying a digital signal between the top of the Base Station tower and the bottom of the Base Station tower.[14]

In an indoor environment, a distributed antenna system (DAS) can help with filling in coverage that might be lost due to blockage. Such antennas can be incorporated into a new building design or retro-fitted to existing buildings. In such systems, the lower penetration for higher frequencies then becomes an advantage by reducing potential interference to macro-cellular systems.

Special architectures refers to the use of repeaters and relays to increase coverage when capacity or throughput is not a concern. Assume that the regular cell radius is 5 km, implying that to maintain reliable communications a device can be no more than 5 km away from the base station. Assume further that the network operator installs a repeater (which amplifies and retransmits signals to and from the base station). If the repeater is 5 km away from the base station, a device 5 km away from the *repeater* (and 10 km away from the regular base station) may now communicate with the network.

A relay is a more advanced form of a repeater. While a repeater amplifies both signal and noise, a relay can avoid amplifying the noise by decoding the original packet and by transmitting the packet just like a regular base station. A relay carries out extensive and complex processing and thereby provides even better performance than an ordinary repeater.

New technologies such as LTE and LTE-Advanced also incorporate advanced radio resource management mechanisms to improve coverage and cell-edge performance. For example, LTE has a feature called "inter cell interference coordination" (ICIC) to improve throughput near the cell-edge. As part of the ICIC feature, neighboring base stations coordinate allocation of radio resources to minimize interference, thereby increasing cell-edge throughput. LTE-Advanced has a similar, but even more advanced, feature called "coordinated multipoint" (CoMP) transmission

[13] A TMA may also be referred to as a "tower top low noise amplifier" (TTLNA).

[14] The use of TMAs and RRHs to improve coverage has previously been limited by reliability concerns – if a TMA or RRH fails, the cell may remain "down" for an extended period. However, recent design changes that incorporate redundancy have greatly improved reliability.

and reception. During CoMP transmission, multiple base stations transmit the same packet to the device to increase reliability of the received signal. In CoMP reception, multiple base stations receive the uplink signal from the device and one of the base stations combines the signals to retrieve the packet transmitted by the device. CoMP transmission improves downlink cell-edge performance; CoMP reception increases uplink cell-edge performance.

Uplink coverage can also be improved through the use of receive diversity in the uplink, a technique that is prevalent even in current commercial deployments of 2G, 3G, and 4G technologies. Legacy deployments typically use 2-antenna receive diversity for the uplink. But as many as 4 receive antennas are supported in LTE and as many as eight antennas are supported in LTE-Advanced (and given antenna size and spacing requirements, such 4-way or 8-way receive diversity solutions are more readily achievable with higher frequency spectrum bands).

Finally, it is important to recognize that it does not follow that a higher-frequency network operator would necessarily have materially higher overall costs if it was required to deploy more base stations to obtain equivalent coverage. While the number of base stations deployed is certainly one important driver of wireless costs, there are many others. The cost per base station is also important and, here, high-frequency deployments may have some cost advantages. Antennas for higher-frequency spectrum tend to be shorter and smaller and can be placed closer together. To the extent a provider is able to amass large (contiguous) blocks of a single (higher) frequency rather than relying upon multiple smaller blocks across multiple frequency bands (e.g., 700 MHz and AWS bands), less equipment may be needed – both in base stations and in end user equipment. Duplexer costs may likewise be reduced in higher frequency installations. And equipment costs – of both base station and user equipment – may be less for higher-frequency deployments due to manufacturing economies of scale resulting from the large market of worldwide network deployments that use higher-frequency spectrum.

5.4 Capacity Solutions

Emerging cellular technologies use features such as Orthogonal Frequency Division Multiplexing (OFDM), high-order modulation such as 64-Quadrature Amplitude Modulation (64-QAM), larger channel bandwidths, fast and channel-sensitive scheduling, and advanced antenna techniques to achieve very high spectral efficiency and throughput. However, rapidly rising traffic demand has resulted in an enormous amount of data traffic passing through wireless networks. Capacity and throughput enhancing techniques are coming to the forefront.[15]

As noted, the simplest solutions to capacity constraints involve the use of smaller macro cells and micro cells (so that the available channel bandwidth is shared among fewer simultaneous users) or to use larger blocks of spectrum (so that the available channel bandwidth is increased).

[15] We omit temporal interference rejection techniques because they apply to all bands equally.

A lower band deployment has the disadvantage of "achievable capacity," since narrower spectrum chunks are available at lower bands due to both laws of physics and government regulations. At frequency bands above 2.5 GHz, even larger spectrum chunks can be expected because of laws of physics. It is much easier to find several hundred MHz of contiguous spectrum at 3 GHz – indeed, it is physically impossible to have similar bandwidths at 450 MHz or 700 MHz. This is important, because new cellular technologies contemplate channel bandwidths that are very large relative to legacy deployments. LTE-Advanced, for example, is a 4G technology that supports bandwidths as large as 100 MHz.[16]

Figure 5.2 illustrates three additional capacity solutions: multi-carrier deployments, advanced antenna techniques and carrier and spectrum aggregation. As we explain, the achievable benefits from these techniques may differ between lower- and higher-band deployments.

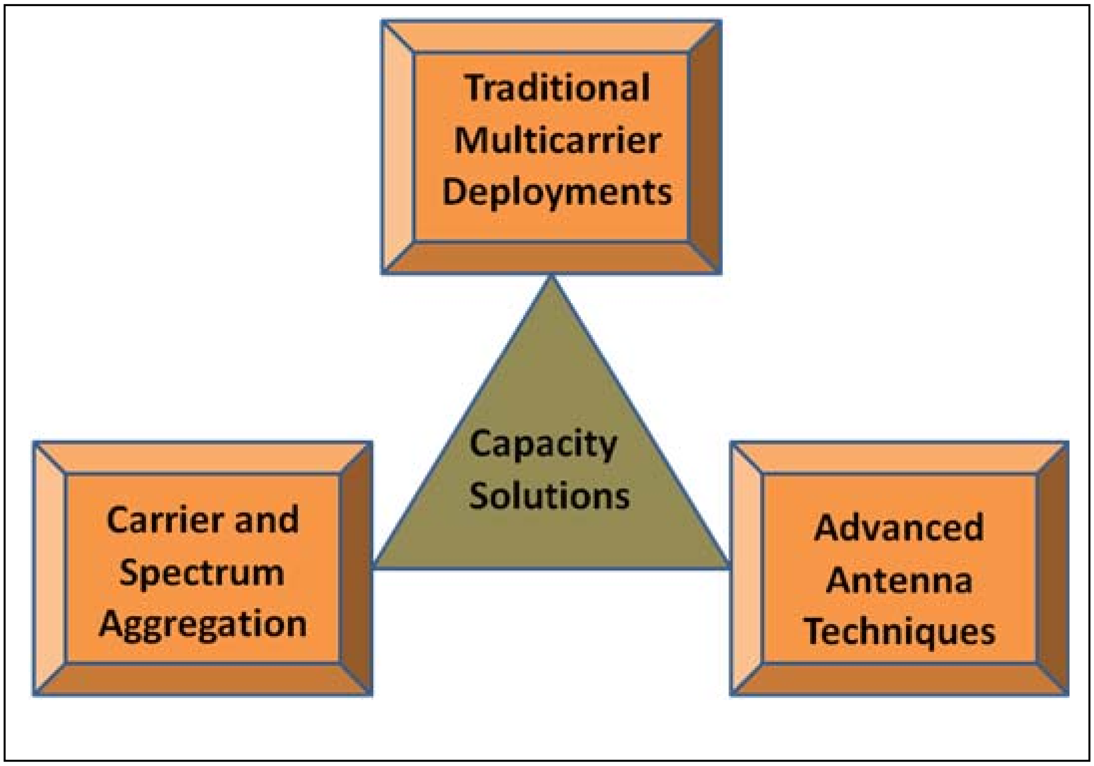

Figure 5.2. Capacity Solutions

When one carrier frequency is inadequate to meet the capacity and throughput requirements, multiple carrier frequencies are deployed. Current 3G networks have already been using multiple carrier frequencies, which points to increasing capacity and throughput requirements. A

[16] It should be no surprise that the standards bodies have already identified the larger chunks of higher frequency spectrum as likely candidates for LTE-Advanced.

multicarrier deployment increases throughput in a given area and throughput supported by the base station. A traditional multicarrier deployment also increases voice capacity.

Although multi-carrier deployments can provide significant increases in the number of simultaneous users that can be supported in a cell (cell throughput), they typically do *not* increase peak *user* throughput. Any given user can typically process one carrier frequency. This makes higher frequency and wider band spectrum even more attractive since it can not only provide more economical capacity expansion, but also has the capability of delivering higher peak data rates to any individual user because of its higher bandwidth. In fact, because of this bandwidth advantage, higher frequency deployments will likely benefit more from emerging technologies such as LTE-Advanced.

Carrier aggregation enables the base station to allocate multiple carrier frequencies to a given user, increasing user throughput as well as cell throughput. Carrier aggregation does increase complexity and cost of the base station transceiver and the device transceiver. When carrier aggregation occurs across different frequency bands, it is referred to as spectrum aggregation. Spectrum aggregation gives even more flexibility to the service provider but it is even more complex and more expensive than carrier aggregation at a given frequency band due to the need for more components. Of course, additional overhead is necessary to support this feature. Certainly, a higher band operator that has access to 100 MHz of spectrum in a single band or contiguous bands (*e.g.*, Clearwire/Sprint) may not need to incur the costs or complexities of spectrum aggregation.

Advanced antenna techniques are also being exploited to increase average throughput, capacity, cell-edge throughput, and cell-edge reliability. Different advanced antenna techniques yield different benefits. As noted above, techniques such as MIMO and beamforming increase cell throughput and user throughput. Traditional beamforming techniques, for example, use horizontal antenna arrays to form beams to increase SIR, thereby increasing throughput at a given location. Commercial WiMAX deployments using higher band spectrum have widely used this antenna technique. At a lower frequency band, the larger wavelengths would require a very long antenna array to be installed on the base station tower, creating logistical challenges and sub-optimal antenna configurations that would reduce the beamforming gain [3GAmericas_MIMO].

MIMO or Spatial Multiplexing (SM) can likewise significantly increase throughput but requires multiple transmit antennas and multiple receive antennas. At lower frequency bands, it is difficult to ensure adequate “separation” in the handheld device due to the larger wavelengths of lower frequencies. Here, too, while MIMO solutions should work in lower band deployments, the achievable gains are likely to reduced as compared to higher-band deployments.[17]

A MIMO technique with two antennas at the base station[18] and two antennas at the device is quite popular in recent deployments. LTE supports up to 4 antennas at the base station and 4 antennas at the device. LTE-Advanced allows up to eight antennas at the base station and eight antennas at the device. Squeezing four or eight antennas into a tiny handset with adequate antenna separation is likely to be quite a challenge, especially at 700 MHz (with its larger antennas). Another technique called Space/Spatial Division Multiple Access (SDMA) combines MIMO and beamforming concepts to improve capacity, throughput, and coverage.

Custom solutions such as pico cells to cover a building and femto cells to cover a home can also alleviate the capacity burden from the larger macro-cellular and microcellular networks. Again, attenuation at higher frequencies becomes very attractive for femto cells since building attenuation losses work to reduce interference between the femto cell and the macro cell. Technology-specific features such as high-order modulation would also certainly increase the throughput capability of the system. As noted earlier, higher order modulation can improve the bits/sec/Hz capability of the signal but would require a higher SIR.

In sum, although there are a wide range of capacity-enhancing solutions available to cellular network operators, all are costly. A lower band operator faced with capacity constraints can either respond by reducing cell size (giving up coverage advantages), adding more spectrum to increase channel bandwidth (spectrum is not cheap!) or deploying additional equipment to take

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[17] Single User- Multiple Input Multiple Output (SU-MIMO), for example, exploits spatial variations in the radio channel to increase throughput. If the antenna separation is larger, the antenna signals are more likely to be dissimilar (*i.e.*, uncorrelated) and the benefit of SU-MIMO technique would be higher. There are obvious limits on antenna spacing at the handset. Hence, for a given antenna separation at the handset, a higher band would yield better SU-MIMO performance than a lower band. For example, there is a loss of about 1.3 bps/Hz when a 780 MHz band is used instead of a 2.6 GHz band. More specifically, at signal-to-noise ratio of 10 dB, the spectral efficiency decreases from 4.7 bps/Hz at 2.6 GHz to 3.4 bps/Hz at 780 MHz, which is about 25% loss in efficiency at 780 MHz [3GAmericas_MIMO]. As another data point, the spectral efficiency decreases from 7.2 bps/Hz at 2.6 GHz to 5.3 bps/Hz at 780 MHz when signal-to-noise ratio (SNR) is 15 dB [3GAmericas_MIMO].

[18] These antennas requirements are per cell. When a base station controls three cells or sectors (at 120 degree spacing), it would have a total of six antennas. Furthermore, when polarization diversity is used instead of space/spatial diversity, a single antenna box or radome houses two antennas.

advantage of antenna, in-building or other engineering solutions – or, most likely, combinations of the above.

5.5 In-building Coverage And Capacity: Challenges and Solutions

When assessing in-building coverage, it is important not to over generalize, because any theoretical signal strength advantages may not translate into real-world throughput or coverage advantages. In the majority of situations, relatively higher in-building signal strength (due to smaller path loss at a given distance from the Base Station) in higher band deployments may not pose a serious challenge and in some cases can actually be a benefit by reducing interference between the indoor cellular system and the outdoor macro cellular system.

Custom solutions to improve in-building coverage, capacity, and throughput are also available. A Distributed Antenna System (DAS) is often installed inside buildings to distribute downlink signals to devices and to collect uplink signals from devices on different floors. In-building pico cells increase both throughput and coverage and can be thought of as very small cells covering buildings.

Femto cells further reduce the cell size and can be put in homes and office buildings. Technologies such as LTE utilize the concept of a Closed Subscriber Group (CSG), where "CSG members" can share the home Base Station (called home eNodeB) and get coverage and throughput benefit. To reduce the cost to subscribers while improving coverage and throughput, it is possible to have a hybrid cell that appears as a CSG cell to its members and a regular cell to non-members. In fact, as stated earlier, there are some inherent advantages of using higher frequencies for indoor cellular systems such as femto cells since these systems would likely cause less interference to the macro cellular system – the net result is an increase in capacity.

6. The Impact of Spectrum Choices on the User Experience and Lessons for Regulatory Policy

As the current U.S. wireless marketplace structure vividly illustrates, there are many viable spectrum paths for a cellular network operator and no one path is inherently superior to others from a network design, optimization and expansion viewpoint. Each service provider faces different hurdles along the technology lifecycle from design to optimization to expansion. Thus, as we have explained, a higher-band operator may incur larger capital expenditures in an initial coverage-driven deployment compared to a lower-band operator deploying the same technology, but these costs may even out when the entire technology lifecycle is considered. But if both the lower band and the higher band operators execute well, both can be successful and the end-user should not perceive any difference between the lower-band network deployment and the higher-band network deployment. This focus on how consumers, rather than providers, are affected is, to us, critically important from a public policy viewpoint. Both are equally capable of delivering high quality voice and data services to meet the evolving needs of demanding consumers and businesses.

In our view that desirable outcome – and the positive competitive environment it engenders – is due, in no small part, to the flexibility network operators have enjoyed to set their own courses on matters of spectrum and technology choices, limited only by their willingness to pay for the spectrum and other resources they deem optimal for their individual approaches. As we explain below, enlightened regulatory policies that preserve flexibility are likely to prove even more important as rapidly rising wireless data usage and evolving applications place ever greater demands on cellular networks.

What are the key factors that regulatory policymakers should consider to create an environment that results in healthy competition, spurs growth in wireless subscribers, enhances the user experience, and enables the network to maximize efficiency and performance and reduces the cost for consumers?

The single most critical factor that can facilitate the success of emerging wireless technologies such as LTE and WiMAX is the availability of more spectrum, preferably in large and contiguous spectrum blocks.

LTE supports channel bandwidths of up to 20 MHz. LTE-Advanced will support channel bandwidth as wide as 100 MHz. Technologies such as LTE and WiMAX use scalable Orthogonal Frequency Division Multiple Access (OFDMA) that provides larger cell throughput (and end user throughput) for larger bandwidths. For example, LTE can support a theoretical peak data rate of 300 Mbps in the downlink if the downlink channel bandwidth is 20 MHz; the theoretical peak data rate decreases to 150 Mbps if the channel bandwidth is constrained to 10 MHz (both estimates assume 4 X 4 MIMO). Narrower channel bandwidth is one of the main reasons why current and planned near term LTE deployments cannot realize the full potential of LTE.

As both data usage and end user throughput expectations continue to rise dramatically in the 4G environment, it is thus essential that cellular network operators have maximum flexibility to acquire additional spectrum. As we have explained, services can be delivered most efficiently if large blocks of a single frequency band or combinations of adjacent or near-adjacent bands are combined. Hence spectrum policies should strive to encourage, not discourage, individual providers from expanding their spectrum portfolios with an eye to provide frequencies within the bands in their existing spectrum holdings.

The FCC should extend maximal flexibility to network engineers so that each network can operate with the highest possible efficiency. While some European countries have imposed constraints on spectrum holdings below 1 GHz, any such constraint could be highly counter-productive. Different operators have different spectrum holdings, business strategies, and preferences for spectrum. Limiting the amount of spectrum that an operator can have at a given frequency band (lower or higher) could put severe limits on the achievable network performance at a target level of cost and complexity. Assume that an operator currently has a narrow channel bandwidth at a given band. If this operator acquires new spectrum through auctions or secondary market transactions, a wider channel bandwidth becomes feasible, significantly improving the user experience and network performance with lower deployment costs. Even if the newly-acquired spectrum is not directly adjacent to the original spectrum used by the operator, the complexity of transceivers, network optimization, and radio resource management would be relatively manageable when carrier aggregation is exploited. We strongly caution the FCC against spectrum discrimination, because drawing any line at 1 GHz (or any other carrier frequency) has a strong potential of unintended consequences on user experience and network performance. In particular, costly, complex, and/or sub-optimal engineering solutions may be required in the presence of regulatory constraints on spectrum holdings, increasing the cost of the device and services and limiting the achievable user experience.

The FCC could also continue to address zoning and other regulations that may act as barriers to the implementation of advanced antenna techniques. As mentioned earlier, LTE supports 4 antennas at the Base Station and LTE-Advanced supports eight antennas. Simpler and network-friendly zoning regulations would enable network engineers to derive maximum benefit from the promising advanced antenna techniques. Instead of settling for a sub-optimal antenna configuration to meet local zoning regulations, engineers could implement the best configuration to maximize performance if zoning restrictions give engineers more "room" to work with. As an example, at the locations where antennas already exist, replacement of existing antennas with more advanced antenna arrays should not trigger a lengthy regulatory process. In the end, fewer cell sites may be needed to serve a given region.

In summary, the categorical suggestion that spectrum above 1 GHz is inherently inferior to, and should be treated differently than, spectrum below that arbitrary line fails to account for real-world issues such as constraints on cell-site locations and the impact of explosive growth in wireless data traffic on network design, optimization, and network expansion strategy. Rather than attempting to draw an arbitrary line between "good" and "better" spectrum based upon simplistic propagation differences and their perceived impacts on cellular network operators, regulatory policymakers should instead employ a consumer-centric approach that focuses on getting as much spectrum into the mobile wireless marketplace as possible, in the largest practical blocks, and with maximum flexibility through the operation of auctions and secondary market transactions. This approach would provide the most efficient utilization of spectrum and allow spectrum utility to adapt to changing technologies and applications.

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CURRICULUM VITAE

JEFFREY H. REED

Jeffrey H. Reed, Ph.D.

Willis G. Worcester Professor of ECE
The Bradley Department of Electrical and Computer Engineering
Director of Wireless at Virginia Tech
Interim Director, Ted and Karyn Hume Center for National Security and Technology
Virginia Tech
432 Durham Hall, Mail code 0350
Blacksburg, VA 24061
Voice: (540) 231-2972
FAX: (540) 231-2968
Email: reedjh@vt.edu
www.wireless.vt.edu
http://www.cnst.ictas.vt.edu/

Vitae

Section I: Experience & Education

Current Position:

Director of Wireless at Virginia Tech (Wireless@VT), 2005-present
Professor of the Bradley Department of Electrical and Computer Engineering, June 2002- Present
Interim Director, The Ted and Karyn Hume Center for National Security and Technolgy, January 2010 - Present
CTO, Cognitive Radio Technology, 2007-present
Willis G. Worcester Professor of ECE, 2005-present

Professional Interest:

Research and teaching in signal processing and communication systems

Specific Research Interests	**Specific Teaching Interests**
Software Radios	Software Radios
Smart Antennas	Digital and Analog Communications
Interference Rejection	Discrete Time and Digital Signal Processing
Wireless Networks	Cellular and Personal Communications
Cognitive Radio	DSP-based Communication System Design
Location Technology	Adaptive Filtering

Education:

Ph.D.
Electrical and Computer Engineering, December 1987, University of California, Davis
Awarded American Electronics Fellowship for Faculty Development
Major: Statistical Signal Processing; Minor: Control Systems and Statistics
Dissertation: *Interference Rejection Using Time-Dependent Adaptive Filters*
Attended part-time at University of Santa Clara, September 1980 through June 1983

M.S.
Electrical and Computer Engineering, June 1980, University of California, Davis
M.S. Project Topic: An EEG Data Acquisition and Analysis System

B.S.
Electrical and Computer Engineering, March 1979, University of California, Davis

Employment:

Professor, Virginia Tech, April 2001-present
Director, MPRG 200-2002
Associate Professor, Virginia Tech, 1997-2001
CTO and co-founder, Cognitive Radio Technologies, 2007-present
Co-founder, Dot Mobile, Inc., March 2000-2001
Consultant, Reed Engineering (Self-Employed), 1987-present
Assistant Professor, Virginia Tech, 1992-1997
Research Engineer, University of California, Davis, 1992
Lecturer, University of California, Davis, 1988-1992
Associate Instructor, University of California, Davis, 1985-1987
Teaching Assistant, University of California, Davis, 1984-1985
Member of Technical Staff, Signal Science, Inc., Santa Clara, CA and Hanover, MD, 1980-1985

Professional Affiliations:

Member of **Tau Beta Pi Honor Society**
Member of **Phi Kappa Phi Honor Society**
Member of AFCEA
Fellow of the IEEE

Professional Awards:

Named Willis G. Worcester Professor of ECE, summer 2005, Fall 2010
Industry Achievement Award, SDR Forum 2004
Institute of Electrical and Electronics Engineers Fellow, Dec. 2004
Virginia Tech College of Engineering Outstanding Researcher Award, 2001

Section II: Funded Research
(Principal Investigator or Co-Principal Investigator)

SDR Technology Development Support, Maryland Procurement Office, 9/30/10 – 9/29/2010 $1,562.300

Mobile Cognitive Radio Testbed, ICTAS, 7/1/10 – 6/30/11 $213,566 (co-PI)

Experimental Develoment Capability for Software Defined Radio with Agile Hardware, ONR, 1/27/2010 – 1/26/2011 co-PI)

Collaborative Research: Enhancing Access to the Radio Spectrum (EARS) Workshop, NSF 4/15/2010 – 03/31/2011 $21,860.00

Recommendations for Transitioning Silvus MNM FPGA Core IP, DARPA (Silvus Technologies) 2/18/2010 – 2/17/2011, $39,970.00 (co-PI)

Updates to OSSIE Core Framework to Enhance Compatibility with Open CPI, Mercury Federal Systems 4/8/10 - $39,998.00 (co-PI)

NSWC-TO13-Wireless Distributed Computing: Concept to Reality, Naval Secure Warfare (DARPA) Center 6/22/2010 - $498.798.00

Autonomous Cognitive Mobile Robotic Radio Network Testbed, Defense University Research Instrumentation Program (DURIP), 9/9/2010 - $361.786.00

Investigating the Relationship of OSSIE to Higher Layers, NSF 8/1/2009 – 2/28/10 $76,040

VT-Cornet: Virginia Tech Congitive Radio Network, ICTAS, 7/1/08 – 6/30/09 $142,580

Cryptographic API and Subsystem Simulator, SCA Technica, 1/1/09 – 9/26/09 $39,000

Cognitive Radio Network Testbed Instrumentation, Office of Naval Research, 4/15/09 – 4/14/10 $347,979

VT-Cognet: Virginia Tech Cognitive Radio Network Testbed Phase 2, ICTAS 1/12/09 – 1/11/10 $149,959 (co-PI)

CT-ISG: Assuring Security in Spectrum Agile Radio Networks, NSF, 01/01/07 - 12/31/10 $499,997 (co-PI).

Improved Distribution and Error Recovery of the OSSIE Core Framework, SAIC 3/01/2009 – 9/30/2009 $75,000

IC CAE: Emerging Tehcnologies IC CAE, Howard University 9/23/2009 – 9/22/2011 $2.5M

REU Supplement to award #0520418 Nets: Oriwub:An Open Systems Approach for Rapid Proto-typing Waveforms for Software Defined Radio, NSF $41,800

Nets Prowin: An Open Systems Approach for Rapid Prototyping Waveforms for Software Defined Radio**,** National Science Foundation, 8/1/08 – 7/31/09 $12,000 (asking for additional REU funding)

Enhancements to OSSIE: (Open Source SCA Implementation: Embedded), Science Applications International Corporation, 4/1/07 – 90/07 $75,000

Collaborative Research: CT-T TRIESTE: A Trusted Radio Infrastructure For Enforcing Spectrum Etiquettes*,* NSF, 10/01/07 – 9/30/10, $150.000 (Reed Co-PI)

Development Design of a Cognitive Engine and Anyalysis of WRAN Cognitive Radio Algorithms, ETRI, 7/01/07 – 12/31/07 $119,999

An Integrated Tool for SCA Waveform Development, Testing, and Debugging and A Tool for Automated Estimation of DSP Resource Statistics for Waveform Components, US-Army-CERDEC Office, 6/12/07 – 6/11/08, $326,125

Software Defined Radio Waveform and Device Development and Component Deployment Using OSSIE, DOD, 7/19/07 – 7/18/10, $975,639 ($184,744 awarded to this point)

Reasoning and Learning in Adapative Wireless Networks, BBN Technologies, 10/1/07 – 12/31/10, $913,196 (co-PI)

US/Ireland International Workshop on Next Generation Open Architectures for Software-Defined Radio, NSF, 9/15/07 – 8/31/08, $35,963

VT-CogNet: Virginia Tech Cognitive Radio Network, ICTAS, 1/1/08 – 6/30/09,$160,170 (Reed, Bose PIs)

Trade Study Of Implementation of SDR: Fundamental Limitations and Future Prospects (DARPA SEED), US Army Aviation & Missile Command, 9/11/07 – 6/30/08 (Reed PI) $115,364

Distributed Computing for Collaborative Software Radio*,* Office of Naval Research, 02/05/07 - 02/04/10, $533,722 ($108,728 awarded first year)

A Panel of Commercial GSM Experts For Supporting JIEDDO Operations, JIEDDO, 12/18/06 - 2/28/07 $38,275

Cognitive Radio Test-bed, Virginia Space Grant Consortium, 08/16/06 - 08/15/07 $5,000

Emerging Wireless Technologies (EWT) Technology Assessment, Rosettex, 07/03/06 - 12/31/07 $91,000

Development of a Cognitive Engine and Analysis of WRAN Cognitive Radio Algorithms, ETRI, 06/16/06 - 12/31/06 $175,554.

Wireless@Virginia Tech Group Start-up, Institute for Critical Technology and Applied Science – ICTAS, 01/01/06 - 06/30/07 $500,000.

A Low-Cost All-Band/All-Mode Radio for Public Safety, National Department of Justice (Dept. of Justice), 10/01/05 - 09/30/08 $399,816 (Reed Co-PI)

Applying Artificial Intelligence Techniques to the Development of a Cognitive Radio Engine: Assessment, Evaluation, and Implementation, Army Research Office, 10/01/05 - 06/30/06 $49,995.

Analysis of WRAN Algorithms, ETRI, 10/01/05 - 12/31/05 $86,275

NeTS PROWIN: An Open System Approach for Rapid Prototyping Waveforms for Software Defined Radios, 08/15/05 - 08/14/09 $999,995 (Reed Co-PI)

Cognitive Radios, Virginia Space Grant Consortium, 08/10/05 - 08/09/06 $5000

A Software Defined Ultra Wideband Communication System Testbed, Virginia Space Grant Consortium, 08/10/05 - 08/09/06 $5,000

Advanced Wireless Integrated Network: AWINN, Office of Naval Research, 12/20/04 - 06/24/06 $484,200 (Reed portion)

Software Defined Radios: Evolution and Application Areas, Booz Allen Hamilton, 1/1/05 - 3/15/05 $74,497

Ossie and Harriet, SAIC, 08/16/04 - 12/31/05 $300,519

CDMA 2000 System Modeling and Simulation Program, Magnolia Broadband, Inc.**,** 12/15/03 - 12/14/04 $84,500

Policy-based Resource Management in a Vehicular Ad-Hoc Network for First Responders, Naval Postgraduate School, 09/24/03 - 09/30/04 $25,431

System Level Design Approach and Methodologies For Software Defined Radios, National Imagery and Mapping Agency, 7/25/03 - 7/24/06 $189,282

Smart Antennas Research At The MPRG, Army Research Office, 06/01/03-12/31/04 $37,500

Proposal for GDDS Cluster X-SCA-Lite Architecture, General Dynamics, 05/01/03-10/31/03 $85,691.

Game Theoretic Analysis Of Radio Resource Management For Ad-Hoc Networks**,** Office of Naval Research, 04/01/03-03/31/06 $589,411.

Game Theory in Radio Resource Management*,* Motorola University Partnership in Research, 09/01/02 - 05/31/04 $60,000

Software Radios and Smart Antennas: Challenges for Creating Seamless Networks, *Samsung Electronics, 04/08/03 - 05/15/04 $520,785*

UWB Propagation Measurements, Modeling, and Communication System Enhancements, DARPA, 08/16/01 - 12/31/03 $688,620

Tactical Communications Architecture and Implementation Plan for the U.S. Customs Service, Naval Surface Warfare Center, Dahlgren, 8/16/01 - 8/15/02 $402,000

ACN Independent Innovative Research Component, Raytheon Systems, 12/1/01 - 11/30/02 $11,250

Foundation Wireless Network for Medical Applications, Carilion Biomedical Institute, 8/6/01 - 8/10/02 $75,000

Interference, Propagation, and Antenna Placement Issues for XM Radio, GM, 3/26/01 - 9/25/02 $583,527

AOL Fellowship in Wireless Home Networking Technologies, AOL, 01/01/01 - 05/15/03 $84,583

Reconfigurable Apertures and Space-Time Processing, Raytheon Systems, 05/00 - 09/02 $841,350

Advanced Wireless Technology for Aerospace Communications, Virginia Space Grant Consortium, 08/00 - 05/03 $15,000

Research and Development for IMT-2000, LG Electronics, 05/15/00 - 09/31/01 $350,000

Motorola University Partnership in Research: Overloaded Array Processing, Motorola, 09/01/00 - 08/31/02 $84,944

Multiuser Detection for Overloaded Antenna Arrays, Raytheon, 05/00 - 05/02 $1,126,194

An Investigation of Base Station Diversity For Cellular Applications - Phase II, Metawave, 02/29/00 - 02/28/01 $104,000

Broadband Channel-Adaptive Radio Modem for NGI Network Extension and Access, Hughes Research Laboratory, 10/01/99 - 11/30/01 $81,412

Research Into Signal Recovery Algorithms in Support of Spectral Spatial Interference Cancellation System (SSICS) – Phase II Research Effort, Raytheon Company, 02/01/00 - 05/15/01 $149,756

Navy Collaborative Integrated Information Technology Initiative (NAVCIITI), Office of Naval Research, 04/00 - 06/04 $9,651,087 (Reed portion $534,089)

Research into Spatial Signal Recovery Algorithms in Support of Spectral Spatial Interference Cancellation System - Phase I (SSICS), Raytheon Company, 080/2/99 - 01/10/00 $97,857

Low Power and Robust Communications Using Hand-Held Smart Antennas for Receiving and Transmitting, Texas Instruments, 07/01/98 - 06/30/00 $331,993

An Investigation of Base Station Diversity for Cellular Applications, Metawave Communications, 03/01/99 - 02/28/01 $179,706

International Wireless Communication Research Program, Virginia Tech Research and Graduate Studies' SEED Program, 01/01/99 to 06/30/00 $7,500

Navy Collaborative Integrated Information Technology Initiative (NAVCIITI), Office of Naval Research, 11/14/98 - 09/30/00 $2,700,000.

Enhancing the Capacity of IMT-2000 Through Turbo Coding and Smart Antennas, LGIC, 10/01/98 - 09/30/99 $122,904

Low Power and Robust Communications Using Hand-Held Smart Antennas for Receiving and Transmitting, Texas Instruments, 07/01/98 - 06/30/99 $132,000

Techniques for Evaluating Location Technologies, Comcast, 05/01/98 - 12/31/98 $112,154

Development of Tools for CDMA Cellular Network Planning, Innovative Global Solutions (IGS), 04/01/98 - 01/31/99 $42,889

Configurable and Robust Wireless Communications Nodes, DARPA, 07/01/97 - 12/30/00 $2,015,431

Support of Telelink System Test*,* Global-Net, Inc., 09/25/96 - 09/24/97 $50,000

Sprint RFI and Evaluation*,* Sprint Spectrum L. P., 09/26/96 - 12/31/96 $31,158

Rural MayDay/800 Call-in System Feasibility, I-95 Corridor Coalition/ Virginia Department of Transportation, 02/01/96 - 01/31/97 $299,176 (MPRG share $157,988)

A Study of Reconfigurable Receivers for Cellular and PCS*,* Texas Instruments, 08/25/95 - 08/25/96 $35,000

CDMA/FM Evaluation Effort*,* Comdial Corporation/Sigtek, 08/28/95 - 12/31/95 $25,000 (plus $7,500 CWT match)

Measured DECT System Performance in Actual Radio Channels*,* National Semiconductor, 10/01/94 - 2/15/96 $35,024

Investigation of BMP Impacts on Nonpoint Source Pollution Using System Analysis Procedures*,* Virginia Water Resource Center/U.S. Dept. of Interior, 04/01/95 - 04/30/96 $9,963

Development and Implementation Of Interference Rejection Techniques for Cellular Communications*,* SAIC, Center for Wireless Telecommunications (CWT), $50,000 (SAIC, 03/22/95 to 12/31/95) $25,000 (CWT, 07/01/95 to 06/31/96)

Expanded Testing of a High Capacity Adaptive Wireless Receiver*,* ARPA/AASERT, 08/01/95 - 07/31/98 $125,522

Co-Channel Interference Rejection for FM Mobile Phone Systems, Motorola, 01/16/95 - 09/15/9, $33,000

Curriculum Innovation for Simulation and Design of Wireless Communications Systems*,* National Science Foundation, 08/16/95 - 07/31/98 $289,291

A High Capacity Wireless Receiver Implemented with A Reconfigurable Computer Architecture, ARPA/WAMIS, 09/94 - 08/30/97, $1,727,230 ($533,250 for the first year, $586,750 second year)

Development of a Low Power High Data Rate Spread-Spectrum Modem**,** Grayson Electronics, Virginia's Center for Innovative Technology (CIT), Center for Wireless Telecommunications (CWT), $29,833 (Grayson, 03/01/94 - 11/30/94), $13,204 (CIT, 03/01/94 - 10/31/94) and $16,000 (CWT matching funds, 04/01/94 - 06/30/95)

***Rejection of Interference in AMPS Cellular Communication**,* ARGO Systems, VA's Center for Innovative Technology (CIT), $25,000 (ARGO Systems, 12/10/93 - 05/10/94) and $12,500 (CIT, 04/01/94 - 07/31/94)

***Capacity and Interference Resistance of Spread-Spectrum Automatic Vehicle Monitoring Systems in the 902-928 MHz Band**,* Southwestern Bell Mobile Systems, 10/01/93 - 08/15/94 $70,007

***University Road Connection - A Smart Highway**,* Virginia Dept. of Transportation, 07/01/94 - 11/01/94 $19,523.79

***Development of a Spread Spectrum Transceiver for the DECT System**,* National Semiconductor, 07/01/94 - 06/30/95 $30,000

***Investigation of a Dynamic Range Enhancer for an Electro-optic Interface**,* Southwestern Bell Technology Resources, Inc., 08/01/93 - 06/01/94 $45,000

***IVHS Research Center of Excellence**,* Federal Highway Administration (FHWA), 1993 - 1998, $1 million/year for 5 years (MPRG total approximately $390,000 over performance period, $330,000 received in 93-94, 94-95, 95-96, 96-97 contract years)

***Center for Wireless Communications**,* Center for Innovative Technology, 09/01/93 - 08/31/98, $300,000 for first year. (Anticipated total funding approximately $1,490,835 plus an additional $357,551 of cost sharing by Virginia Tech)

***The Performance and Feasibility of Time-Dependent and Non-Linear Adaptive Filters for Rejecting High-Power Co-Located Co-Channel Interference**,* US Navy via Systems Research Center, 05/15/93 - 09/01/93, Amount: 1/2 summer session support (value approximately $3,750)

***Evaluation of an NTP-Based Protocol for Paging and Advanced Data Services**,* MobileComm, 07/01/93 - 09/30/93 $39,986

Grants & Gifts:

Ted and Karyn Hume center for National Security and Technology Endowment Fund
January 2010, $5,000,000 (Note that most of this money goes for student fellowships, with $200k provided for center support.)
Total Amount - $5,209.010.00

Intel – Jan. 2010, gift for unrestricted research $50,000.00

Tektronix, reconditioned real time spectrum analyzer and two portable analyzers, ~ $130,000

Tektronix - Dec. 2009, reconditioned Arbitrary Function Generator, 100 Mhz, 2 Channel $5,110.00

Wireless@VT Industrial Affiliates Membership 2006-2009:

Affiliate Funding for the year 2009 – 2010 for Dr. Jeffrey H. Reed is $66,960.
Affiliate Funding for the year 2008 - 2009 for Dr. Jeffrey H. Reed is $40,534

Intel Coporation:: 2009 to support the research in "Cognitive Radio for Minimizing Power Consumption" $44,000

Tektronix*,* 12/2005, cash gift $20,000

Texas Instruments*,* 08/2005, cash gift $27,519

Tektronix, 07/2005, cash gift $20,000

Texas Instruments. 12/2004, cash gift $99,000

Tektronix, spring 2004, cash gift $20,000

CISCO Systems, 08/2003 and 02/2005, cash gift $176,000

Mercury Computer Systems, Inc., 2003, cash gift $50,000

Analog Devices, 2001-2002*,* cash gift $37,500

HRL, ***Smart Antenna Research,*** 2000, cash gift $40,000

Rockwell, Flexible Communications Using Reconfigurable Computing, 1998, $25,000 cash gift

Investigation of CDMA, donation from ITT, 1996, cash gift $100,000

MPRG Industrial Affiliates Membership 1993-2006: Grant total split between the five MPRG faculty (total paid $4,866,500 and an additional $110,000 committed to date). Services provided to sponsors include advanced copies of thesis and dissertations, informal consulting, and special opportunities to employ students.

Intel, 10/2007, $40,000, Support research in "Cognitive Radio for Minimizing Power Consumption," 5/2008, $44,000

Texas Instruments, Evaluation Module Kit, 01/2007, $995

Tektronix, Arbitrary Waveform Generator, 02/2007, $138,000.

Xilinx, Inc., Xilinx System Generator, ChipScope Pro, Xilinx Real-PCI interface, AccelDSP Synthesis Tool with AccelWare DSP IP Toolkits, VLYNQ Interface LogiCORE, ISE Foundation, University Option Embedded Development Kit, 01/2007, $39,615

Tektronix, equipment, $114,000

Texas Instruments, 06/2006, $49,500

Mercury Systems, AdapDEV 1280 Chassis with 900 MHz processor, 08/2003

Spectrum Signal Processing, Inc., Hardware necessary to implement a true software defined radio, 08/2002, $62,329

Grayson Wireless, Cellular test and measurement system, 08/2002, $66,312

Signia-IDT (formerly BAE), RF Front-end valve, 2002, ~$6,000

Altera*,* MAX + Plus II Fixed Node Subscription (FPGA board), $2,000

Texas Instruments, Evaluation Module incl. Code Composer Studio, 06/2001, $19,960

Texas Instruments, ADC-Converter, 03/2001, $99

Analog Devices, Evaluation Boards (5), Visual DSP software (2), In-Circuit Emulators (2), $3,790

Wireless Valley Communications, 2 copies SitePlanner w/LanFielder $49,980, 1 copy SiteSpy on SMT $995, 2005, $50,975

Analog Devices, receiver, processor, and receiver chip set, $645

Texas Instruments, boards, 2001, $2,495

HRL, 2000, Diversity Antenna, $200

Altera, development package, 2000, $995

Altera, (2) MAX+ PLUS II Fixed Node Subscription for PC, (1) design lab package, (1) Micro-Chip; $4,765

Motorola, 56311EVM computer board with DSP and 56311 on it, software, documentation, tutorial, and input/output capabilities, 12/2000, $2000

Texas Instruments, Evaluation software and manuals, 1998, $2,500

Texas Instruments, Evaluation Software, 1997, $1,000

Altera, Development Tools for Programming Configurable Logic Devices, $350

Texas Instruments, DSP Development Systems and Software, 1997, $11,475

Texas Instruments, DSP Hardware and Software, 1997, $27,500

Analog Devices, DSP Development Boards, 1996, $3,200

Altera, Software Materials, 1996, $5,000

SIGTEK, Spread Spectrum Receivers, 1995, $10,000

Section III. Teaching & Advising

Classes Taught:

Graduate Courses

Cellular and Personal Communications (ECE6644)
Software Radios: A Modern Approach to Radio Engineering (ECE5674)
Digital Signal Processing (ECE5624)
Cellular (ECE 5664)

Undergraduate Courses

Implementation of Communication Systems (ECE4654)
Signal Processing (ECE4624)
Communication Systems (ECE3604)

Courses Developed:

Major Revision of ECE course 5664 to focus on systems level description and design considerations of cellular standards this will take two more years to complete and result in a textbook.
Implementation of Communication Systems (ECE 4654)
(Lab materials also developed)
Software Radios (ECE 5674)
Major Revisions on over half of lecture material (ECE 5664)

Advising: Completed Ph.D. Dissertations:

Lizdabel Moarles Tirando, "An Approach to Using Cognitive in Wireless Nwtworks," December 2009

Kyou Woong Kim, "Exploiting cyclostationarity for radio environmental awareness in cognitive radios," May 2008

Youping Zhao, "Enabling cognitive radios through radio environment maps," May 2007

Rekha Menon, "Interference avoidance based underlay techniques for dynamic spectrum sharing," April 2007 (co-advised with Dr. Michael Buehrer)

Jong-Han Kim, "On the impact of MIMO implementations on cellular networks: An analytical approach from a system perspective," March 2007

Ramesh Chembil Palat, "Performance analysis of cooperative communications for wireless networks," December 2006

Jody Neel, "Analysis and design of cognitive radio networks and distributed radio resource management algorithms," September 2006

Chris Anderson, "A software defined ultra wideband transceiver testbed for communications, ranging, or imaging." September 2006

James Hicks, "Novel approaches to overloaded array processing," August 2003

Raqibul Mostafa, "Feasibility of smart antennas for the small wireless terminals," April 2003

William Newhall, "Radio channel measurements and modeling for smart antenna array systems using a software radio receiver," April 2003

Pablo Max Robert, "Reduction in coexistent WLAN interference through statistical traffic management," April 2003

Tom Biedka, "Analysis and development of blind adaptive beamforming algorithms," August 2001

Srikathyayani Srikanteswara, "Design and implementation of a soft radio architecture for reconfigurable platforms," July 2001

Rich Ertel, "Antenna array systems: Propagation and performance," July 1999

Nitin Mangalvedhe, "Development and analysis of adaptive interference rejection techniques for direct sequence code division multiple access systems," July 1999

Nishith Tripathi, "Generic handoff algorithms using fuzzy logic and neural networks," November 1997

Paul Petrus, "Novel adaptive array algorithms and their impact on cellular system capacity," April 1997

Jeff Laster, "Robust GMSK demodulation using demodulator diversity and BER estimation," January 1997

Rong He, "AMPS co-channel interference rejection techniques and their impact on system capacity, August 1996

Completed M.S. Theses:

Sabares S. Moola defended his master's thesis, "Rapid Prototyping of Software Defined Radios using Model Based Design for FPGAs," on July 22, 2010

Ishtiaq Rouf, "Statistical Analysis of Wireless Communication Systems Using Hidden Markov Models," July 2009

Matthew Carrick, "Logical representation of FPGA's & FPGA circuits within the SCA," July 2009

Patrick Farrell, "Digital hardware designing decisions & trade-offs for software radio systems," May 2009

Philip Balister, "A software defined radio implemented using the OSSIE core framework deployed on a TI OMAP processor." December 2008

Jacob DePriest, "A practical approach to rapid prototyping of SCA waveforms," April 2006

Srinivasan Vasudevan, "A simulation for analyzing the throughput of IEEE 802.11b wireless LAN systems," January 2005

Brian Donlan, "Ultra-wideband narrowband interference cancellation and channel modeling for communications," January 2005

Anil Hebbar, "Empirical approach for rate selection in MIMO OFDM," December 2004

Seshagiri Krishnamoorthy, "Interference measurements and throughput analysis for 2.4 GHz wireless devices in hospital environments," April 2003

Yasir Ahmed, "A model-based approach to demodulation of co-channel MSK signals," December 2002

Ramesh Chembil Palat, "VT-Star – Design and implementation of a test bed for differential space-time block coding and MIMO channel measurements," October 2002

Jody Neel, "Simulation of an implementation and evaluation of the layered radio architecture," December 2002

Bing-Leung (Patrick) Cheung, "Simulation of adaptive algorithms for OFDM and adaptive vector OFDM systems," August 2002

Shakheela H. Marikar, "Resource management in 3G systems employing smart antennas, January 2002

M. Soni, "Computing engine for reconfigurable software radio," Oct. 2001

Christian Rieser, "Channel sounder for LMDS," May 2001 (co-advisor)

James Hicks, "Overloaded array processing with spatially reduced search joint detection," May 2000

Zhong Hu, "Evaluation of joint AOA and DOA estimation algorithms using the antenna array systems," May 1999

Kim Phillips, "Probability density function estimation for minimum bit error rate equalization," May 1999

Pablo (Max) Robert, "Simulation tool and metric for evaluating wireless digital video systems," May 1999

Steven F. Swanchara, "An FPGA-based multiuser receiver employing parallel interference cancellation," July 1998

Don Breslin, "Adaptive antenna arrays applied to position location," August 1997

Steve Nicoloso, "Investigation of carrier recovery techniques for PSK modulated signals in CDMA and multipath mobile environments," May 1997

Brian Fox, “Analysis and dynamic range enhancement of the analog-to-digital interface in multimode radio receivers,” February 1997

Nena Zecevic, “Interference rejection techniques for the mobile unit direct-sequence CDMA receiver, August 1996

Kevin Saldanha, “Performance evaluation of DECT in different radio environments,” August 1996

Milap Majmundar, “Adaptive single-user receivers for direct sequence CDMA systems,” February 1996

Yash Vasavada, “Performance evaluation of a frequency modulated spread spectrum system,” February 1996

Scott Elson, “Simulation and performance analysis of CDPD,” January 1996

Matthew Welborn, “Co-channel interference rejection using model-based demodulator,” January 1996

Francis Dominique, “Design and development of a frequency hopper based on the detection system for the 902-928 MHz ISM band,” December 1995

Nitin Mangalvedhe, “An Eigenstructure technique for direct sequence spread spectrum synchronization,” April 1995

Paul Petrus, “Blind adaptive arrays for mobile communications,” December 1994

Sihano (Raymond) Zheng, “Channel modeling and interference rejection for CDMA automatic vehicle monitoring systems,” November 1994

Fu-Sheng (Frank) Cheng, “A new approach to dynamic range enhancement,” September 1994

Volker Aue, “Optimum linear single user detection in direct-sequence spread-spectrum multiple access systems,” March 1994

Current Ph. D Students:

Carlos Aguayo Gonzalez – Ph.D expected completion date December 2010

Ashwin Amanna – Ph.D expected completion date May 2012

Sounava Bera – Ph.D expected completion date May 2013

Xuetao Chen – Ph.D (Co-Advised Dr.Bose and Dr. Reed) completion date March 2011

Dinesh Datla – Ph.D expected completion date May 2011

Manik Gadhiok – Ph.D expected completion date July 2011

Joseph Gaeddert – Ph.D expected completion date August 2010

An He – Ph.D expected completion date December 2011

Benjamin Hilburn – Ph.D expected completion date December 2012

Eyosias Iman – Ph.D expected completion date December 2012

Sahana Raghunandan – Ph.D expected completion date July 2011

Kunal Rele - Ph.D – expected completion date December 2012

Karim Said – Ph.D expected completion date May 2012 (currently at the Egypt campus)

Abid Ullah – Ph.D expected completion date December 2012

Matthew Vondall Pd.D – (Co-Advised/Amir Zaghoul) expected completion date May 2011

Hazem Shatila - (Co-Advised/Dr. Mohamed Khedr at VT MENA) expected completion date March 2011

Current M.S. Students:

Michael Benonis – M.S. expected completion date May 2011

Thomas Cooper – B.S./M.S. expected completion date May 2012

Shawn Hymel – M.S. expected completion date May 2011

Hermie Mendoza – M.S. expected completion date May 2011

Matthew Price – M.S. expected completion date May 2011

Peter Sahmel – M.S. expected completion date January 2011

Thomas Tsou – M.S. expected completion date December 2012

Section IV. Publications List

Books Authored or Co-Authored:

1. J. H. Reed, ed., An Introduction to Ultrawideband Communications Systems, Prentice Hall, March 2005, ISBN: 0-13-148103-7.

2. J. H. Reed, Software Radio: A Modern Approach to Radio Design, Prentice Hall, May 2002, ISBN: 0-13-081158-0.

3. N. D. Tripathi, J. H. Reed, and H. F. VanLandingham, Radio Resource Management in Cellular Systems, Kluwer Academic Publishers, Spring 2001.

Books & Proceedings Edited:

1. "The Radio Environment Map", (Book Chapter) Cognitive Radio Technology, Dr. Bruce Fette, ed., Y. Zhao, S. Mao, J. Neel, and J.H. Reed2nd edition, 2 April 2009

2. J. Neel. J. Reed, A. MacKenzie, Cognitive Radio Network Performance Analysis in Cognitive Radio Technology, B. Fette, ed., Elsevier, 2nd edition, 2 April 2009.

3. W. H. Tranter, B. D. Woerner, J. H. Reed, T. S. Rappaport, and P. M. Robert, Wireless Personal Communications – Bluetooth and Other Technologies, Kluwer Academic Publishers, 2000.

4. W. H. Tranter, B. D. Woerner, T. S. Rappaport, and J. H. Reed, Wireless Personal Communications – Channel Modeling and Systems Engineering, Kluwer Academic Publishers, 1999s.

5. W. H. Tranter, T. S. Rappaport, B. D. Woerner, and J. H. Reed, eds., Wireless Personal Communications: Emerging Technologies for Enhanced Communications, Kluwer Press, 1998.

6. T. S. Rappaport, B. D. Woerner, J. H. Reed, and W. H. Tranter, eds., Wireless Personal Communications: Improving Capacity, Services, and Reliability, Kluwer Press, 1997.

7. J. H. Reed, B. D. Woerner, and T. S. Rappaport, eds., Wireless Personal Communications: Advances in Coverage and Capacity, Kluwer Press, 1997.

8. T. S. Rappaport, B. D. Woerner, and J. H. Reed, eds., Wireless Personal Communications: The Evolution of PCS, Kluwer Press, 1996.

9. B. D. Woerner, T. S. Rappaport, and J. H. Reed, eds., Wireless Personal Communications: Research Developments, Kluwer Press, 1995.

10. T. S. Rappaport, B. D. Woerner, and J. H. Reed, editors, Wireless Personal Communications: Trends and Challenges, Kluwer Press, 1994.

Book Contributions:

1. Y. Zhao, S. Mao, J. Neel, and J. H. Reed, "The Radio Environment Map" (Book Chapter) in Cognitive Radio Technology, B. Fette, ed., 2nd ed., Elsevier, April 2009.

2. J. Neel. J. Reed, and A. MacKenzie, "Cognitive Radio Network Performance Analysis" (Book Chapter) in Cognitive Radio Technology, B. Fette, ed., 2nd ed., Elsevier Inc., April 2009.

3. Y. Zhao, B. Le, and J. H. Reed, "Network Support: The Radio Environment Map" (Book Chapter) in *Cognitive Radio Technology*, by B. Fette, Elesvier Inc., pp. 337-363, August 2006, ISBN: 978-0-7506-7952-7.

4. J. O. Neel, J. H. Reed, and A. B. MacKenzie, “Cognitive Radio Performance Analysis” (Book Chapter) in *Cognitive Radio Technology*, by B. Fette, Elesvier Inc., pp. 501-579, August 2006, ISBN: 978-0-7506-7952-7.

5. B. M. Donlan, R. M. Buehrer, and J. H. Reed, “Ultra-wideband Wireless Systems,” in the *Encyclopedia of RF and Microwave Engineering*, pp. 5411-5423, Spring 2005, ISBN: 0-471-27053-9.

6. N. D. Tripathi, J. H. Reed, and H. F. VanLandingham, “Application of a Neurofuzzy System to Handoffs in Cellular Communications” (Book Chapter) in *Neuro-Fuzzy and Fuzzy-Neural Applications in Telecommunications (Signals and Communication Technology)*, by P. Stavroulakis, Springer Publishing, May 2004, ISBN: 3540407596.

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Papers, Talks, & Lectures Presented at Professional Meetings:

1. Keynote Presentation, "The Future of Cognitive Radio," Univ of Texas and Austin Technology Incubator. A group of faculty and VCs.

2. Invited Presentation, "The Second Wave of Wireless: A New Wave of Disruptive Technology," Atlantic Council (DC think-tank) to help inform international decision makers, Oct. 2010.

3. Cognitive Wireless Networking (CoRoNet), Keynote Speaker, Chicago, Illinois, September 20, 2010

4. The Ted & Karyn Hume Center Inauguration Reception and Board Meeting, Arlington, VA August 18, 2010.

5. Invited talk, "Cognitive Radio Research at VT," ISART, NTIA, July 2010.

6. DoD Technical Exchange Meeting at the Finnish Embassy under the aegis of the Secretary of Defense, Washington D.C. May 2010

7. Speaker, Oak Ridge National Laboratory Board of the Governors, May 2010

8. JASON, an independent group of scientists which advises the United States Governement on matters of science and technology - San Diego, CA May 2010

9. Dr. Jeffrey Reed and Dr. Nishith Tripathi, *Wireless Net Neutrality Regulation: A Response to Afflerbach and DeHaven, March 2010*, submittedd to the FCC.

10. Jeffrey H. Reed & Nishith D. Tripathi, *The Application of Network Neutrality Regulations to Wireless Systems: A Mission Infeasible,* submitted to the FCC, Jan. 2010

Note the two reports above are *responses to the FCC Notice of Proposed Rule Making on Network Neutrality (a highly controversial subject that poses a major threat to the US wireless industry)*

11. "The Nexus of Security and Technological Leadership, Deemed Export Rule Recommendations and Zero-based Methods to Identify Technologies that Require Deemed Export Control', Submitted to the Security of Commerce by the Emerging

Technologies and Research Advisory Committee, A Federal Advisory Committee Appointed by the Secretary of Commerce To examine EARS Regulations. 2009.
Note current EARS regulations currently represent a major challenge to US industry and academia for engaging international personnel in research and this committee addressed this challenge.

12. Institute for Defense and Government Analysis Conference – Security Issues in Cognitive Radio, 2010.

13. Army Research Lab Seminar, Sept. 2009

14. Lectured VT-MENA in Alexandria, Egypt Nov. 2009

15. Technical seminar at Cairo University, Nov. 2009

16. Presented to NTIA, the telecom regulatory authority in Egypt, Nov. 2009

17. Korean US Communications Technology Symposium, July 2009

18. Finnish Embassy – US Military Collaboration with Finnish Government, March 10-11, 2008

19. Institute for Defense and Government Analysis Conference -- VT's Cognitive Radio and Security Research, March 2009

20. J. H. Reed, IEEE presentation to the IEEE San Diego Section, April 7, 2009 San Diego, CA.

21. J. H. Reed, "Distributed computing in collaborative software radio," presented to the Office of Naval Research, May 1, 2007.

22. J.H. Reed, Keynote Speaker at the *Communications Technology Program Review, Planning Assessment Meeting*, "Distributed computing for collaborative software defined radio," Naval Research Laboratory, May 2007.

23. J. H. Reed, "Issues in cognitive wireless networks," talk presented at the *Intel Research Forum Seminar Series*, Portland, OR, March 28, 2007.

24. J. H. Reed, "Issues in cognitive wireless networks," talk presented at NIST, March 2, 2007.

25. J. H. Reed, "Understanding the issues in software defined cognitive radios," seminar presented at the University of Pennsylvania, October 16, 2006.

26. J. H. Reed, "Issues in cognitive wireless networks," talk presented at the *IEEE Workshop Networking Technologies Software Defined Radio (SDR) Networks*, (held in conjunction with *SECON*), Reston, VA, September 25, 2006.

27. J. H. Reed, "Applications of Markov modeling to cognitive radio," presented at the *SASDCRT Conf.*, Naval Post Graduate School, Monterey, CA, September 12-13, 2006.

28. J. H. Reed, "Understanding the issues in software defined cognitive radios," seminar presented at Clemson University, SC, July 21, 2006.

29. J. H. Reed, "Understanding the issues in software defined cognitive radios," seminar presented at Kyung Hee University, Korea, June 12, 2006.

30. J. H. Reed, "Open architecture bridging the gap in emergency communications," guest speaker at the *International Wireless Communications Expo – IWCE Conf. Tektronix Symposium,* Las Vegas, NV, May 19, 2006.

31. J. H. Reed, "An introduction to cognitive radio and some research trends in cognitive radios," talk presented at *ETRI Cognitive Radio Workshop*, Seoul, Korea, April 2006.

32. J. H. Reed, S. Srikanteswara, and J. A. Neel, "Design choices for software radios," DVD tutorial. Available: http://sdrforum.org/store.html

33. Presentation titled "Software radio: The key for enabling 4G wireless networks," at the *International Forum - 4th Generation Mobile Commun.*, Centre for Telecommunications Research, May 2003.

34. J. H. Reed, "Key challenges in the design on software radios," workshop presented at *IDGA Software Radio Conf.*, Alexandria, Va., February 23, 2004.

35. J. H. Reed, "Issues in software radios," presented at Microsoft, Seattle, WA, March 3, 2003.

36. J. H. Reed, "Wireless convergence paradox," presented at *Samsung Telecom Forum*, Seoul, Korea, March 16-23, 2003.

37. W. H. Tranter, J. H. Reed, D. S. Ha, D. McKinstry, R. M. Buehrer, and J. Hicks, "High capacity communications using overloaded array," presented at *COMMTEC*, Chantilly, VA, September 16-20, 2002.

38. R. M. Buehrer and J. H. Reed, "Robust ad-hoc, short-range wireless networks for tracking and monitoring devices," presented to the Marine Corp., April 2002.

39. J. H. Reed, "Overloaded array processing with spatially reduced search joint detection," presented at the Dresden University of Technology, September 24, 2001.

40. J. H. Reed, Invited lecture series to several Korean companies, compliments of Samsung Advanced Institute of Technologies. The list of companies included: Samsung, LGIC, and ETRI. Spring 2000.

41. J. H. Reed, "The future of wireless," invited talk, Atlantic City, NJ, November 15, 1999.

42. J. H. Reed, "Software radios," *Motorola Futures Forum*, invited talk to corporate strategists, Pheonix, AZ, November 8, 1999.

43. P. Robert and J. H. Reed, "Digital video transmissions in a wireless system," *9th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1997. (Poster session.)

44. M. Hosemann and J. H. Reed, "Synchronization techniques for spread spectrum signals," *8th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1998. (Poster session.)

45. S. Srikanteswara and J. H. Reed, “Development of a software radio architecture using reconfigurable computing,” *8th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1998. (Poster session.)

46. J. Hicks, P. Roy, J. Tilki, L. Beex, J. H. Reed, and W. Farley, “Simulation tool for speech recognition over wireless,” *8th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1998. (Poster session.)

47. R. Ertel and J. H. Reed, “Optimum SINR antenna array performance analysis,” *8th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1998. (Poster session.)

48. R. Banerjee, B. D. Woerner and J. H. Reed, “Case studies in software radios,” *8th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1998. (Poster session.)

49. P. M. Robert, A. M. Darwish, and J. H. Reed, “Fast bit error generation for the simulation of MPEG-2 transmissions in wireless systems,” *IEEE Wireless Commun. Networking Conf.*, September 21-24, 1999. (Invited paper; proceedings on CD Rom.)

50. J. H. Reed and S. Srikanteswara, “Software radio architecture for a reconfigurable computing platform,” *IEEE Commun. Theory Workshop*, Aptos, CA, May 23-26, 1999.

51. R. Ertel , Z. Hu and J. H. Reed, “Antenna array vector channel modeling and data collection system,” *8th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1998. (Poster session.)

52. P. M. Robert and J. H. Reed, “Digital video transmissions in a wireless system,” *8th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1998. (Poster session.)

53. S. Swanchara, S. Srikanteswara, P. Athanas, and J. H. Reed, “Implementation of a multiuser receiver on a recongifugurable computing platform,” *8th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1998. (Poster session.)

54. Maheshware, et al., “Reconfigurable software radio,” *8th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1998. (Poster session.)

55. K. Phillips and J. H. Reed, “PDF estimation,” *8th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1998. (Poster session.)

56. N. Mangalvedhe and J. H. Reed, “Performane of reduced complexity algorithms in adaptive CDMA receivers,” *8th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1998. (Poster session.)

57. R. Mostafa and J. H. Reed, “Study of smart antenna as an interference rejection technique for the handset,” *8th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1998. (Poster session.)

58. N. Mangalvedhe and J. H. Reed, “Adapative receivers for multi-rate DS-CDMA systems,” *8th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1998. (Poster session.)

59. J. H. Reed and B. D. Woerner, "Analog to digital conversion and digital signal synthesis for software radios," half-day tutorial presented at the *IEEE 9th International Symposium*

Personal, Indoor, Mobile Radio Commun., Boston, MA, September 13-16, 1998. (Invited tutorial.)

60. J. H. Reed, "The software radio: Modern radio engineering," Dresden University of Technology Guest Lecture, Dresden, Germany, November 25, 1997.

61. J. H. Reed, "Adaptive antenna arrays," Dresden University of Technology Guest Lecture, Dresden, Germany, November 26, 1997.

62. J. H. Reed, "Overview of fundamental wireless systems in today's telecommunications technology," *46th Annual International Wire Cable Symposium*, Philadelphia, PA, November 17-20, 1997. (Invited tutorial.)

63. J. H. Reed and R. D. James, "Position location: Overview and business opportunities," *Wireless Opportunities Workshop*, Roanoke, VA, October 22-23, 1997.

64. R. Ertel and J. H. Reed, "Geometrically based spatial channel models," *7th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1997. (Poster session.)

65. A. Hannan and J. H. Reed, "GloMo radio API (application program interface," *7th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1997. (Poster session.)

66. S. Swanchara, J. H. Reed, and P. Athanas, "Design and implementation of the GloMo multiuser receiver on a reconfigurable computing platform," *7th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1997. (Poster session.)

67. N. D. Tripathi, J. H. Reed, and H. VanLandingham, "High performance handoff algorithms using fuzzy logic and neural networks," *7th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1997. (Poster session.)

68. D. Breslin and J. H. Reed, "Multi-sensor testbed hardware development at the mobile and portable radio resesarch group," *7th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1997. (Poster session.)

69. N. Mangalvedhe and J. H. Reed, "Blind CDMA interference rejection in multipath channels," *7th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1997. (Poster session.)

70. K. Phillips, J. Laster, and J. H. Reed "Adaptive signal processing by bit error rate (BER) estimation," *7th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1997. (Poster session.)

71. T. S. Rappaport, J. H. Reed, and T. E. Biedka, "Position location & E-911: Techniques for wireless systems," *IEEE International Conf. Universal Pers. Commun.*, Cambridge, MA, October 1, 1996. (Invited tutorial.)

72. N. Tripathi and J. H. Reed, "DSP implementation of communications systems: An NSF sponsored curriculum development initiative," *6th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1996. (Poster session.)

73. B. Fox, G. Aliftiras, I. Howitt, J. H. Reed, and B. D. Woerner, "Flexible hardware architectures for multimode wireless handsets," *Sixth 6th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1996. (Poster session.)

74. P. Petrus and J. H. Reed, "Geometrically based statistical single bounce macrocell channel model for mobile environments," *6th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1996. (Poster session; also in *IEEE Smart Antennas: Adaptive Arrays, Algorithms, & Wireless Position Location*, 1998, pp. 483-487.)

75. GloMo team, "GloMo adaptive antenna array research," *6th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1996. (Poster session.)

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77. J. D. Laster and J. H. Reed, "Improved GMSK demodulation using non-coherent receiver diversity," *Sixth 6th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1996. (Poster session.)

78. K. Khan, J. H. Reed,and I Howitt, "Interference mitigation in AMPS/NAMPS and CMP using artificial neural networks," *6th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1996. (Poster session.)

79. N. Tripathi, J. H. Reed, and H. VanLandingham, "Neural net & fuzzy logic approaches to handoffs in cellular systems," *6th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1996. (Poster session.)

80. K. Saldanha and J. H. Reed, "Performance evaluation of an AMPS digital base station with automatic gain control," *6th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1996. (Poster session.)

81. R. He and J. H. Reed, "System capacity improvement by ysing DSP interference rejection techniques," *6th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1996. (Poster session.)

82. B. D. Woerner, T. S. Rappaport, and J. H. Reed, "Improved spectral efficiency for CDMA systems," *Wireless Technology Conf. Exposition Proceedings*, Stamford, CT, September 1995.

83. P. Petrus and J. H. Reed, "New blind multichannel filtering techniques," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

84. N. Zecevic and J. H. Reed, "Comparative study of adaptive CDMA interference rejection techniques," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

85. M. Majmundar and J. H. Reed, "Interference rejection for IS-54," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

86. D. Bailey and J. H. Reed, "MPRG: Signal processing and communications laboratory," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

87. R. He and J. H. Reed, "Co-channel interference for AMPS and NAMPS signals," *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

88. N. Mangalvedhe and J. H. Reed, “An Eigenstructure technique for soft synchronization of DSSS signals,” *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

89. M. Welborn and J. H. Reed, “Interference rejection using model-based spectral estimation,” *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

90. A. Amanna, R. James, and J. H. Reed, “Communications on the smart road,” *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

91. F. Dominique and J. H. Reed, “Development of a frequency hopping system for the 902-928 MHz ISM band,” *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

92. S. Elson and J. H. Reed, “Modeling CDPD,” *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.).

93. P. Petrus, F. Dominique, and J. H. Reed, “Spectral redundancy exploitation in narrowband interference rejection for a PN-BPSK system,” *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

94. F. Cheng and J. H. Reed, “Dynamic range enhancement techniques for RF and fiber optic interface,” *5th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1995. (Poster session.)

95. P. Petrus and J. H. Reed, " Blind adaptive arrays for mobile communications,” *4th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1994. (Poster session.)

96. R. He and J. H. Reed, “Spectral correlation of AMPS signals with applications to interference Rrejection,” *4th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1994. (Poster session.)

97. R. Zheng and J. H. Reed, “System modeling and interference rejection for spread spectrum CDMA automatic vehicle monitoring systems,” *4th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1994. (Poster session.)

98. N. Mangalvedhe and J. H. Reed, “An eigenstructure technique for soft spread spectrum synchronization,” *4th Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1994. (Poster session.)

99. R. Holley and J. H. Reed, “Time-dependent filters For CDMA interference rejection,” *3rd Annual Symposium Wireless Pers. Commun.*, Virginia Tech, June 1993. (Poster session.)

Technical Reports:

1. Y. Zhao, “Enabling cognitive radios through radio environment maps,” MPRG-TR-07- Ph.D. dissertation, May 2007.

2. R. Menon and J. H. Reed, “Interference avoidance based underlay techniques for dynamic spectrum sharing,” MPRG-TR-07-, Ph.D. dissertation, April 2007.

3. J.-H. Kim and J. H. Reed, "On the impact of MIMO implementations on cellular networks: An analytical Aapproach from a system perspective," MPRG-TR-07-, Ph.D. dissertation, March 2007.

4. R. Chembil Palat and J. H. Reed, "Performance analysis of cooperative communications for wireless networks," MPRG-TR-06-, Ph.D. dissertation, December 2006.

5. J. O. Neel and J. H. Reed, "Analysis and design of cognitive radio networks and distributed radio resources management in algorithms," MPRG-TR-06-14, Ph.D. Dissertation, September 2006.

6. C. R. Anderson and J. H. Reed, "A software defined ultra wideband transceiver testbed for communications, ranging, and imaging," MPRG-TR-06-13, Ph.D. dissertation, September 2006.

7. C. R. Anderson, S. Venkatesh, D. Agarwal, R. Michael Buehrer, P. Athanas, and J. H. Reed, "Time interleaved sampling of impulse ultra wideband signals: Design challenges, analysis, and results," MPRG-TR-06-12, technical report, August 2006.

8. J.-H. Kim and J. H. Reed, "Efficacy of transmit smart antenna at mobile station in cellular networks," MPRG-TR-06-09, Ph.D. preliminary, May 2006.

9. J. A. DePriest and J. H. Reed, "A practical approach to rapid prototyping of SCA waveforms," MPRG-TR-06-06, M.S. thesis, April 2006.

10. B. M. Donlan, R. M. Buehrer, and J. H. Reed, "Ultra-wideband narrowband interference cancellation and channel modeling for communications," MPRG-TR-05-02, M.S. thesis, January 2005.

11. S. Vasudevan and J. H. Reed, "A simulator for analyzing the throughput of IEEE 802.11b wireless LAN systems," MPRG-TR-05-01, M.S. thesis, January 2005.

12. A. M. Hebbar and J. H. Reed, "Empirical approach for rate selection in MIMO OFDM," MPRG-TR-04-11, M.S. thesis, December 2004.

13. C. R. Anderson, A. M. Orndorff, R. M. Buehrer, and J. H. Reed, "An introduction and overview of an impulse-radio ultrawideband communication system design," MPRG_TR-04-07, technical report, May 2004.

14. J. Hicks and J. H. Reed, "Novel approaches to overloaded array processing," MPRG-TR-03-19, Ph.D. dissertation, August 2003.

15. R. Mostafa and J. H. Reed, "Feasibility of smart antennas for the small wireless terminals," MPRG-TR-03-12, Ph.D. dissertation, April 2003.

16. S. Krishnamoorthya and J. H. Reed, "Interference measurements and throughput analysis for 2.4 GHz wireless devices in hospital environments," MPRG-TR-03-10, M.S. thesis, April 2003.

17. P. M. Robert and J. H. Reed, "Reduction in coexistent WLAN interference through statistical traffic management, MPRG-TR-03-09, Ph.D. dissertation, April 2003.

18. W. G. Newhall and J. H. Reed, “Radio channel measurements and modeling for smart antenna array systems using a software radio receiver,” MPRG-TR-03-08, Ph.D. dissertation, April 2003.

19. Y. Ahmed and J. H. Reed, “A model-based approach to demodulation of co-channel MSK signals,” MPRG-TR-02-24, M.S. thesis, December 2002.

20. R. Chembil Palat and J. H. Reed, “VT-STAR design and implementation of a test bed space-time block coding and MOMI channel measurements,” MPRG-TR-02-19, M.S. thesis, October 2002.

21. W. Newhall and J. H. Reed, “Radio channel measurements, modeling, and characterization for antenna array Ssystems,” MPRG-TR-02-16, Ph.D. preliminary, August 2002.

22. B.-L. Cheung and J. H. Reed, “Simulation of adaptive array algorithms for OFDM and adaptive vector OFDM systems,” MPRG-TR-02-15, M.S. thesis, September 2002.

23. R. Mostafa, R. Gozali, W. Newhall, I. Akbar, J. H. Reed, B. D. Woerner, and W. H. Tranter, “Navy collaborative integrated information technology initiative,” report #19, MPRG-TR-02-13, technical report, April 2002.

24. R. Mostafa, R. Gozali, W. Newhall, I. Akbar, J. H. Reed, B. D. Woerner, and W. H. Tranter, “Navy collaborative integrated information technology initiative,” report # 17, MPRG-TR-02-05, technical report, January 2002.

25. S. Marikar, L. DaSilva, and J. H. Reed, “Resource management in 3G systems employing smart antennas,” MPRG-TR-02-04, M.S. thesis, January 2002.

26. P. M. Robert and J. H. Reed, “Reduction in coexistent WLAN interference through statistical traffic management,” MPRG-TR-02-01, Ph.D. preliminary, August 2001.

27. R. Mostafa, R. Gozali, W. Newhall, I. Akbar, J. H. Reed, B. D. Woerner, and W. H. Tranter, “Navy collaborative integrated information technology initiative,” report # 16, MPRG-TR-01-17, technical report, October 2001.

28. M. Soni, P. Athanas, and J. H. Reed, “Computing engine for reconfigurable software radio,” MPRG-TR-01-15, M.S. thesis, October 2001.

29. T. E. Biedka and J. H. Reed, “Analysis and development of blind adaptive beamforming algorithms,” MPRG-TR-01-14, Ph.D. dissertation, August 2001.

30. R. Gozali, R. Mostafa, P. M. Robert, R. Chembil Palat, W. Newhall, B. D. Woerner, and J. H. Reed, “Design process of the VT-STAR multiple-input multiple-output (MIMO) test bed,” MPRG-TR-01-12, technical report. August 2001.

31. R. Mostafa, R. Gozali, W. Newhall, I. Akbar, J. H. Reed, B. D. Woerner, and W. H. Tranter, “Navy collaborative integrated information technology initiative,” report # 15, MPRG-TR-01-11, technical report, July 2001.

32. S. Srikanteswara and J. H. Reed, “Design and implementation of a soft radio architecture for reconfigurable platforms,” MPRG-TR-01-10, Ph.D. dissertation, July 2001.

33. R. Mostafa and J. H. Reed, “Feasibility of transmit smart antenna at the handset,” MPRG-TR-01-07, Ph,D. preliminary, December 2000.

34. J. Hicks and J. H. Reed, “Overloaded array processing with spatially reduced search joint detection,” MPRG-TR-00-08, M.S. thesis, May 2000.

35. T. Biedka and J. H. Reed, “A general framework for the analysis and development of blind adaptive algorithms,” MPRG-TR-OO-O5, Ph.D. preliminary, April 2000.

36. S. Srikanteswara and J. H. Reed, “Design and implementation of a soft radio architecture for reconfigurable platforms,” MPRG-TR-00-02, Ph.D. preliminary, November 1999.

37. R. B. Ertel and J. H. Reed, "Antenna array systems: Propagation and performance,” Ph.D. dissertation, July 1999.

38. N. R. Mangalvedhe and J. H. Reed, “Development and analysis of adaptive interference rejection techniques for direct sequence code division multiple access systems,” Ph.D. dissertation, July 1999.

39. K. Phillips and J. H. Reed, “Probability density function estimation for minimum bit error rate equalization,” MPRG-TR-99-04, M.S. thesis, May 1999.

40. Z. Hu and J. H. Reed, “Evaluation of joint AOA and DOA estimation algorithms using the antenna array systems,” MPRG-TR-99-02, M.S. thesis, December 1998.

41. R. B. Ertel and J. H. Reed, "Antenna array systems: Propagation and performance," MPRG-TR-98-12, Ph.D. preliminary, December 1998.

42. N. R. Mangalvedhe and J. H. Reed, "Development and analysis of adaptive interference rejection techniques for direct sequence code division multiple access systems," MPRG-TR-98-13, Ph.D. preliminary, December 1998.

43. P. M. Robert and J. H. Reed, "Simulation tool and metric for evaluating wireless digital video systems," MPRG-TR-98-11, M.S. thesis, September 1998.

44. S. F. Swanchara and J. H. Reed, “An FPGA-based multiuser receiver employing parallel interference cancellation,” MPRG-TR-98-06, M.S. thesis, July 1998.

45. N. Tripathi and J. H. Reed, “Generic handoff algorithms using fuzzy logic and neural networks,” Ph.D. dissertation, MPRG-TR-97-18, November 1997.

46. D. Breslin and J. H. Reed, “Adaptive antenna arrays applied to position location,” MPRG-TR-97-14, M.S. thesis, August 1997.

47. S. Nicoloso and J. H. Reed, “Investigation of carrier recovery techniques for PSK modulated signals in CDMA and multipath mobile environments,” MPRG-TR-97-11, M.S. Thesis, May 1997.

48. N. Tripathi, J. H. Reed, and H. VanLandingham, “An adaptive direction biased fuzzy handoff algorithm with unified handoff candidate selection criterion,” MPRG-TR-97-08, April 1997.

49. N. Tripathi, J. H. Reed, and H. VanLandingham, “An adaptive algorithm using neural encoded fuzzy logic system,” MPRG-TR-97-07, April 1997.

50. N. Tripathi, J. H. Reed, and H. VanLandingham, "A new class of fuzzy logic based adaptive handoff algorithms for enhanced cellular system performance," MPRG-TR-97-06, April 1997.

51. B. Fox and J. H. Reed, "Analysis and dynamic range enhancement of the analog-to-digital interface in multimode radio receivers," MPRG-TR-97-02, February 1997.

52. A. Alexander, S. Panchapakesan, D. Breslin, J. H. Reed, T. Pratt, and B. D. Woerner, "The feasibility of performing TDOA based position location on existing cellular infrastructures," MPRG-TR-96-37, December 20, 1996.

53. N. Tripathi and J. H. Reed, "Handoffs in cellular systems: A tutorial," MPRG-TR-96-35, November 1996.

54. N. Zecevic and J. H. Reed, "Interference rejection techniques for the mobile unit direct-sequence CDMA receiver," MPRG-TR-96-27, August 1996.

55. K. J. Saldanha and J. H. Reed, "Performance evaluation of DECT in different radio environments," MPRG -TR-96-28, August 1996.

56. R. He and J. H. Reed, "AMPS co-channel interference rejection techniques and their impact on system capacity," MPRG-TR-96-25, July 1996.

57. N. Zecevic and J. H. Reed, "Techniques and adaptation algorithms for direct sequence spread spectrum capacity," MPRG-TR-96-27, July 1996.

58. M. K. Khan, J. H. Reed, and I. Howitt, "Interference mitigation in AMPS/NAMPS and GSM using artificial neural networks," MPRG-TR-96-24, June 1996.

59. J. H. Reed, T. S. Rappaport, and B. D. Woerner, "What you should know before returning to school," *RF Design*, pp. 67-69, March 1996.

60. T. Biedka and J. H. Reed, "Direction finding methods for CDMA mobile wireless systems," MPRG-TR-96-20, June 1996.

61. Y. M. Vasavada and J. H. Reed, "Performance evaluation of a frequency modulated spread-spectrum system," MPRG-TR-96-13, February 1996.

62. M. V. Majmundar and J. H. Reed, "Adaptive single-user receivers for direct sequence CDMA systems," MPRG-TR-96-12, January 1996.

63. R. He and J. H. Reed, "Co-channel interference rejection techniques for AMPS signals using spectral correlation characteristics," MPRG-TR-96-11, January 1996.

64. J. S. Elson and J. H. Reed, "Simulation and performance analysis of cellular digital packet data," MPRG-TR-96-08, February 1996.

65. J. D. Laster and J. H. Reed, "Improved GMSK demodulation emphasizing single channel interference rejection techniques," MPRG-TR-96-05, February 1996.

66. M. Welborn and J. H. Reed, "Co-channel interference rejection using model-based demodulator" MPRG-TR-96-04, January 1996.

67. F. Dominique and J. H. Reed, “Design and development of a frequency hopper based on the DECT system for the 902-928 MHz ISM band,” MPRG-TR-96-02, January 1996.

68. P. Athanas, I. Howitt, T. S. Rappaport, J. H. Reed, and B. D. Woerner, “A high capacity adaptive wireless receiver implemented with a reconfigurable computer architecture,” MPRG-TR-18, November 1995.

69. N. Mangalvedhe and J. H. Reed, “An eigenstructure technique for direct sequence spread spectrum synchronization*,”* MPRG-TR-95-04, April 1995.

70. Y. M. Kim, N. Mangalvedhe, B. D. Woerner, and J. H. Reed, “Development of a low power high data rate spread-spectrum modem,” MPRG-PPR-95-01, February 1995.

71. Y. M. Kim, N. R. Mangalvedhe, B. D. Woerner, and J. H. Reed, “Development of a low power high data rate spread-spectrum modem,” MPRG-PPR-95-02, June 1995.

72. P. Petrus and J. H. Reed, “Blind adaptive antenna arrays for mobile communications,” MPRG-TR-95-01, December 1994.

73. S. Yao and J. H. Reed, “Differential detection of GMSK signals,” MPRG-TR-94-27, October 1994.

74. R. Zheng, J. Tsai, R. Cameron, L. Beisgen, B. D. Woerner, and J. H. Reed, “Capacity and interference resistance of spread-spectrum automatic vehicle monitoring systems in the 902-928 MHz ISM Band,” MPRG-TR-94-26, final report to Southwestern Bell Mobile Systems, October 1994.

75. F.-S. Cheng and J. H. Reed, “A new approach to dynamic range enhancement,” MPRG-TR-94-25, October 1994.

76. R. S. Zheng and J. H. Reed, “Channel modeling and interference rejection for CDMA automatic vehicle monitoring systems,” MPRG-TR-94-21, November 1994.

77. R. He and J. H. Reed, “AMPS interference rejection: Blind time-dependent adaptive filtering - Volume I,” final report to ARGO Systems Inc., MPRG-TR-94-19, July 1994.

78. T. H. Qazi and J. H. Reed, “Model-based demodulation of FM signals - Volume II,” MPRG-TR-94-17, final report to ARGO Systems, August 1994.

79. M. Subramanian and J. H. Reed, “Noncoherent spread-spectrum communication systems,” MPRG-TR-94-14, August 1994.

80. F. Cheng, A. Kelkar, I. Jacobs, and J. H. Reed, “Performance evaluation for the dynamic range enhancement technique (DRET),” MPRG-TR-94-10, final report to Southwestern Bell Technology Resources, September 1994.

81. V. Aue and J. H. Reed, “Optimum linear single user detection in direct-sequence spread-spectrum multiple access systems,” MPRG-TR-94-03, March 1994.

82. R. Holley and J. H. Reed, “Time dependent adaptive filters for interference cancellation in CDMA systems,” MPRG-TR-93-15, September 1993.

Other Papers & Reports:

1. P. M. Robert and J. H. Reed, "Va. Tech finds soft radio's missing link," *EE Times*, August 2004.

2. J. H. Reed, T. C. Hsia, and H. Etemad, "Differential demodulation of BPSK using time dependent adaptive filtering," final report to California MICRO Program, 1992.

3. J. H. Reed, "Adaptive filters and their application to interference rejection," *Defense Electronics*, pp. 85-86 and 89-90, May 1989.

4. W. Gardner, B. G. Agee, W. A. Brown, C. K. Chen, J. H. Reed, and R. S. Roberts, "A comparison of Fourier transformation and model fitting methods of spectral analysis," Signal and Image Processing Lab Report No. SIPL-86-4, Department of Electrical and Computer Engineering, University of California, Davis, 1986. (Also in *Statistical Spectral Analysis — A Non Probabilistic Theory*, Prentice-Hall.)

Selected Corporate Report Topics:

* A DSP-Based Receiver for the New North American Digital Cellular Standard
* Spread Spectrum Detection Techniques
* Cyclic Spectral Analysis of Modulated Signals
* Projection of Future High-Volume Digital Communication Systems
* A High Speed Digital Filter for Sample Rate Conversion
* A Least-Squares System Identification Method
* Cyclic Adaptive Filtering for Interference Rejection
* Implementation Issues of Adaptive Interference Rejection Techniques
* Investigation of Modern Spectral Analysis Techniques
* The Performance of Time-Dependent Adaptive Filtering of Real Data
* A Maximum-Likelihood Estimator for Tracking and Detecting Frequency Hopping Signals
* Digital Signal Processing Algorithms for Squelch Control
* A Low-Cost Whitening Filter for Jammer Applications
* Time-Dependent Single Channel and Multi-Channel Interference Rejection Algorithms

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Section V. Public Service / Outreach

Industrial Affiliate / Outside Agency Contacts:

Companies and Government Agencies visited in 2009 - 2010 to promote Wireless@ VT and the Hume Center:

Booz Allan Hamilton
DARPA
Army Research Lab
ZETA
SAIC
DRT
Laboratory of Telecommunications Science
John Hopkins Applied Physics Lab
NRO
NSA
CRT
Defense Spectrum Office
NIST
NRL
Northrup Grumman
ISI
RINCOM
CERDEC
Award Solution
IDA
Motorola
NSA
MA-COMM
Intel
NSF
FCC
FBI
Samsung
Aerospace Corporation
CIA
US Army
Thales Communications
Textronix
ONR
SPAWAR
ATT
Ventura Solutions
Syracuse Research Corp

Funding Agency Reviewer:

NSF
University of California, MICRO
Kansas 2000
Qtar Science Foundation
ARO
Canadian Foundation for Innovation

Sponsored Visiting Researchers:

Ahmed Darwish from Cairo University, June-September 1999
Yeongjee Chung from Korea, January-August 1999
Shinichi Miyamoto from Kobe, Japan, April 2001-March 2002
Young-Soo Kim from Seoul, Korea, February 2002-February 2003
Friedrich Jondral from Karlsruhe, Germany, April-June 2004
Francisco Portelinha from Brazil, October 2004-February 2006
Seuck Ho Won from Korea, February 2005-January 2006
Duk Kyu Park from Seoul South Korea, January 2007-February 2008
Marojevic Vuk from Spain, September 2007-January 2008
Francisco Martins Portelinha from Brazil, February 2008-March 2008
Jeong Ho Kim from South Korea, July 2008 – February 2010
Stefan Werner Nagel from Germany, August 2009 - October 2009

Conference Organization & Technical Reviewering:

Organizing Committee for Globecom 2010
Technical Program Committee for IEEE Dyspan 2009/2010
Technical Program Committee for Globecomm 2009

Technical Program Committee for VTC 2009
Technical Program Committee for COMCAS 2009 (and session chair)
Associate Editor for Proceedings of the IEEE, Issue on Cognitive Radio, April & May 2009
Associate Editor for IEEE Journal on Select Area of Communications, Issue on Cognitive Radio
Technical Program Committee for IEEE Conference on Communications
Technical Program Committee for CrownCom
Reviewer

IEEE Transactions on Antennas and Propagation
IEEE Transactions on Wireless Communications
IEEE Transactions on Communications
IEEE Transactions on Signal Processing
IEEE Transactions on Aerospace and Electronics Systems
IEEE Transactions on Selected Areas of Communications
IEEE Signal Processing Letters
IEEE Communications Magazine
IEEE Communications Letters
International Journal of Electronics

Session Chair for the SDR Forum 2007, Denver, CO, November 5 – 9, 2007
Advisory Board, *IEEE International Conf. Ultrawideband (ICU)*, September 2005.
Moderator for the paper session "Ultrawideband Design Approaches," at the *Communications Design Conf.*, March - April 2004.
Moderator for the panel, "UWB Panel on Communication Systems Design," at the *Communications System Design Conf.*, October 2003.
Chair of session titled, "Mobile Computing and Software Defined Radios," at the *International Conf. Engineering Reconfigurable Systems Algorithms (ERSA)*, June 2003.
Co-technical program chairman for the *SDR Forum Conf.*, November 2002.
General Chair for the *UWBST Conf.*, November 2003.
Technical program chairman for the *SDR Forum/MPRG Workshop Smart Antennas*, June 2003.

Federal & State:

National Science Foundation workshop co-organizer, *Enhancing Access to the Radio Spectrum*, August, 2010. Goal was to develop a major research program to support spectrum research for the National Broadband Plan. Participants include Secretary of Commerce, a Commissioner of the FCC, interim head of NSF, multiple NSF Division Directors, Whitehouse and Capitol Hill staffers.

US Dept. of Commerce Committee on EARS Regulations 2008-2009. A Federal Advisory Committee Appointed by the Secretary of Commerce To examine EARS Regulations. 2009. *Note current EARS regulations currently represent a major challenge to US industry and academia for engaging international personnel in research and this committee addressed this challenge.* 2007.

Co-Leader for the SDR Forum and Object Management Group of Smart Antenna API standardization efforts 2008-2009

Co-Leader for NSF workshop on SDR held in Ireland on May 12 – 16, 2008.

Virginia Broadband Task Force (headed by now Senator Warner and US CTO Anish Chopra) to examine steps for bridging the digital divide.

DARPA panel member to identify and create new programs for DARPA to support NSA. This activity is expected to result in $60M – $80M in new DARPA programs. 2007

Workshop help DARPA define a new program in bio-mimesis, the imitation of living organisms through electronics and mechanics.

Assisted the Army Research Office in developing their five year research plan forcommunications.

University Professional Service Current & Past:

Director Wireless @ Virginia Tech
Interim Director, Ted and Karyn Hume Center
Participation within the Center for Wireless Telecommunications (CWT)
Department Computing Committee
Faculty Advisor to the Honor System
Faculty Advisory Committee, Information Technology for VT
EE Graduate Administrative Committee (Grad AdCom)
Communications Area Committee
US Student Recruitment Strategy Task Force
Course supervisor of ECPE 5674 and ECPE 4654
ECE Department Head Search Committee
ECE Executive Committee
ECE Resource Committee
Deputy Director, MPRG
ECE Recruiting Committee

Section VI. Industrial Experience

Industrial Employment:

Cognitive Radio Technology, LLC. CTO and co-founder, 2007- Present

Co-founded Dot Mobile, Inc. March 2000-2001
(Company specializes in mobile data applications including wireless-internet based applications.)

Past Clients

ACM Systems	Grass Valley Group
Analog Devices	BRTRC
DIGCOM	E-Systems
F&S	General Dynamics
Gray Cary	Harris Broadband
Honeywell	HRL
IWT	Jones Day

NORCOMM	SAIC
Labarge	IDA
SRC	Weil
Samsung	MITRE
Shafer	SCA Technica
IIT	Navsys
US Navy	Tantivy

Founded Reed Engineering, March 1986 – Present
(Company performs consulting, expert witnessing and training in wireless communications and signal processing.)

Member, Technical Staff Signal Science, Inc., Santa Clara, CA, 1980-1985
Areas of Specialization:
- Spread spectrum detection
- Foreign technology analysis
- Computer systems administration

Past and Current Advisory Board Positions:

TechContinuum
Samsung Telecommunications
Spyrock
Totus Lighting
Airbee
FAWNA
Wayve Tech

Selected past industry projects:

- Expert Witness Wireless Email
- Software Architecture for Radios
- Company acquisition evaluation
- Expert witness in wireless location systems (multiple times)
- Evaluation of a wireless high-speed internet access system
- Evaluation of wireless/signal processing companies for acquisition
- Tutorials on software radio issues
- Tutorials on trends in wireless communications
- Adaptive interference rejection techniques
- Spread spectrum signal detection
- Expert witness for wireless power sources
- Study Panelist for NSA/DARPA programs via Schafer Corp.
- Advising on Trends in Communications: SAIC
- Provide Survey of Low Power Communications Trends: Mitre Corporation

CURRICULUM VITAE

NISHITH D. TRIPATHI

Nishith D. Tripathi, Ph. D.
419 Stone Bridge Circle, Allen, TX 75013
Tel.: 214-477-3516 and E-mail: ntripathi77@gmail.com

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***, 2011. (**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," To appear in the book titled "The Net Neutrality Debate," 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.

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

Radio Resource Management, July '99 to Sept. '01

- 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.

Management of Supplemental Channels, June '00 to Sept. '01

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

Data Traffic Modeling, Jan. '99 to Sept. '01

- 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.

Multi-Carrier Traffic Allocation, June '99 to Sept. '01

- 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.

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

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

CDMA Based Fixed Wireless Access Systems, Sept. '97 to Dec. '98

- **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
Graduated among the top 2% of the class.