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FEDERAL COMMUNICATIONS COMMISSION
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October 19, 1994

William F. Caton, Acting Secretary
Federal Communications Commission
1919 M Street, N.W., Room 222
Stop Code 1170
Washington, D.C. 20554

Re: Ex Parte Submission
PR Docket No. 93-61
Automatic Vehicle Monitoring

Dear Mr. Caton:

On behalf of Southwestern Bell Mobile Systems ("SBMS"), I am filing the original and one copy of this written ex parte communication pursuant to Section 1.1206(a)(1) of the Commission's Rules.

Transmitted herewith for inclusion in the record is the "Final Report" of Virginia Tech.

As the Commission knows, the Mobile and Portable Radio Research Group ("MPRG") of Virginia Tech has been analyzing "the relevant interference issues for real-world AVM systems."[1/2/] The evaluation focuses on "the effects of bandwidth and interference on capacity, the effect of realistic channel models and receiver implementations on system performance, and the availability of

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1/ "Capacity and Interference Resistance of Spread-Spectrum Automatic Vehicle Monitoring Systems in the 902-928 MHz ISM Band, Final Report," by Raymond Zhen, Jay Tsai, Rick Cameron, Lara Beisgen, Brian D. Woerner, and Jeff H. Reed of the Mobile and Portable Radio Research Group, Bradley Department of Electrical Engineering, Virginia Tech; October 14, 1994, p.2 (hereinafter "Final Report").

2/ Virginia Tech is one of only three institutions in the United States with the expertise to be named "Research Centers of Excellence" by the Intelligent Transportation Society of America (ITS America, formerly IVHS America). This public/private partnership has official responsibility as advisor to the Intelligent Vehicle and Highway System project of the United States Department of Transportation's Federal Highway Department.

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interference rejection techniques for mitigating interference between systems."[3] The Final Report from the Virginia Tech study is attached hereto.

The study by Virginia Tech's MPRG is the most extensive, independent evaluation ever conducted of some of the key issues in the Notice of Proposed Rulemaking in this docket.[4] The Commission will remember that Virginia Tech invited other parties commenting on the NPRM to participate in this study, including MobileVision, the Part 15 Coalition, Pinpoint, and Teletrac. None accepted that offer. Nevertheless, the system evaluation in the Virginia Tech study includes all available information about these other AVM technologies. Extensions of this research effort are being funded by ITS America; in addition, members of WINLAB, an internationally recognized wireless communications research group at Rutgers University, are also participating in the work as reviewers and consultants.

In summary, the Virginia Tech study concludes that:

- due to power control problems and other related issues, direct overlay of different AVM systems in the same spectrum is not practical;
- adjacent positioning in spectrum of the main lobes of different AVM systems is practical if spectral shaping is used to reduce adjacent channel interference;
- communication capacity increases only linearly with bandwidth;
- location capacity increases somewhat greater than linearly with bandwidth, though other techniques for creating orthogonalized channels can also provide capacity increases;
- there is no disadvantage from subdividing the current AVM bands for different systems;
- the optimum bandwidth for resolving multipath components, an important factor in determining location and maximizing the rate of data transmission in an AVM

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[3] Final Report, p.2.

[4] Notice of Proposed Rulemaking in PR Docket No. 93-61, 8 FCC Rcd 2502 (1993) ("NPRM").

system, is from 1 to 10 MHz. Only modest improvements are achieved with bandwidth increases above 1 MHz;[5/]

- subdividing the current AVM bands of spectrum should not create a problem with in-band nonlinearities;

- techniques such as Time Dependent Adaptive Filtering ("TDAF") can be used to improve interference rejection for AVM systems; and

- Part 15 in-building systems should not create harmful interference for, nor receive harmful interference from, AVM systems.

These issues are addressed in detail in the MPRG report.

Very truly yours,

Jerome K. Blask

Enclosure
cc (w/encl.) (By Hand): Chairman Reed E. Hundt
Commissioner Andrew C. Barrett
Commissioner Rachelle B. Chong
Commissioner Susan Ness
Commissioner James H. Quello
Ruth Milkman, Esquire
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5/ This assumes the use of a RAKE receiver or of a similar technique for resolving the multipath components.

# Capacity and Interference Resistance of Spread-Spectrum Automatic Vehicle Monitoring Systems in the 902-928 MHz ISM Band

**Final Report**

**submitted to**

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**October 14, 1994**

# 1. Executive Summary

Automatic Vehicle Monitoring (AVM) systems constitute an important new class of wireless service which is capable of providing position location, fleet management, vehicle security and message services to vehicles throughout a metropolitan area. Several companies are making plans to offer wideband AVM service in the 902-928 MHz frequency bands. Although substantial similarities exist between each system, each has made substantially different competing claims regarding the spectrum requirements, overlay capability, and interference resistance of their system. The Federal Communication Commission (FCC) is attempting to address these issues and formulate guidelines for the future operation of wideband AVM systems through Notice of Proposed Rulemaking 93-61.

In this study, we attempt to evaluate the relevant interference issues for real-world AVM systems. In particular, we focus on the effects of bandwidth and interference on capacity, the effect of realistic channel models and receiver implementations on system performance, and the availability of interference rejection techniques for mitigating interference between systems.

We have examined both the position location capacity and the communications capacity of spread-spectrum systems as a function of interference and bandwidth. There appears to be some advantage in position location capacity for systems which employ a larger bandwidth. However, other techniques are available which also increase the position location capacity of systems, such as orthogonal channelization techniques.

Communications capacity of spread-spectrum systems increases only linearly as a function of bandwidth, even using detailed analysis for the effects of interference. The near-far problem severely limits the system capacity of the weaker CDMA system in situations where multiple signals have disparate power levels. In order to avoid near-far effects of AVM systems operating in the same spectrum as Part 15 devices, careful siting of AVM base stations should be employed. Furthermore, signal attenuation through building walls should be sufficient to alleviate interference to indoor Part 15 systems.

Statistical two-ray channel impulse responses with time delay $\tau = 5 \sim 7$ $\mu$s and $\tau = 11 \sim 16$ $\mu$s for urban and suburban areas respectively are used in simulating the performance of spread-spectrum links. Resolution of all significant multipath components requires a system bandwidth of 10 MHz. Beyond 10 MHz, there is no significant improvement. In the range of 1 MHz to 10 MHz, wider bandwidth will result in some modest improvements in multipath rejection capability. Simulation results presented here indicate that with proper system design, even relatively narrowband spread-spectrum systems can exhibit robust performance over a wide range of channel conditions.

For the ISM band spread-spectrum AVM systems, direct overlay of different AVM systems in the same frequency band relies on power control among all users. However, universal power control does not seem to be practical. On the other hand, it is feasible to

locate the mainlobe of one AVM system over a sidelobe of a second system. For partial overlay systems, spectral shaping filtering is required before transmission to reduce adjacent channel interference. Although spectral shaping could introduce distortion in the pre-spreaded CDMA signal, the signal can be recovered by using advanced DSP techniques, such as Time-Dependent Adaptive Filtering (TDAF) processing. According to our analysis, nonlinearities within amplifiers should have little impact on the ISM band AVM system signals, if sub-bands are allocated properly.

A large number of interference rejection techniques are now becoming available for use in mitigating interference between systems. One particularly practical and promising techniques is the use of Time Dependent Adaptive Filtering (TDAF). TDAF processing of direct sequence spread-spectrum signals represents a source of potential gain for many CDMA systems. First, time dependent filtering is able to mitigate many different forms of interference common to the mobile channel as well as multipath propagation. Second, time-dependent filtering requires no knowledge of the other users in the system in order to produce marked increases in user capacity, and works for numerous modulation formats. Simulations of TDAF processing have shown significant improvements over conventional matched filter processing in interference environments which are dominated by dissimilar modulation formats. These techniques are alos effective for adjacent channel interference rejection, making the TDAF highly attractive for use in ISM band AVM systems.

## 2. Problem Statement

Innovations in wireless technology have enabled the rapid growth of a large range of mobile communications services. Although cellular telephone service and the forthcoming personal communications service have attracted the widest attention, a broad range of more specialized services are also becoming commercially viable. Automatic Vehicle Monitoring (AVM) is one such service. AVM systems might typically offer the following services:

- Fleet Management. Dispatch, routing, and position location of large fleets of vehicles within a metropolitan area. This could include taxis, delivery vehicles and service trucks.
- Vehicle Security. Tracking and location of stolen vehicles. Enabling and disabling of vehicle security alarms.
- Emergency Services. Notification and position location of roadside emergencies. Routing of service vehicles to the emergency location.
- Messaging. Transmission of alphanumeric and voice messages to vehicles within a metropolitan area.

Several companies are in the process of developing and deploying AVM systems. These companies include:

- MobileVision of Indianapolis, IN
- North American Teletrac of Walnut Creek, CA
- Pinpoint Communications of Richardson, TX
- Southwestern Bell Mobile Systems of Dallas, TX [Qui86]

Each of these AVM systems is designed to operate in the 902-928 MHz ISM band. Although implementation details vary between systems, they share several common technical features. Each employs a set of narrowband (25 to 50 kHz) channels for the forward link from the base station to the mobile receiver. This forward link carries control, status, and group and individual messaging information. The reverse link from the mobile to the base station employs a wideband direct-sequence spread-spectrum (DS/SS) signal. The characteristics of this DS/SS signal vary widely between systems. Southwestern Bell claims their system requires a 2 MHz bandwidth, while MobileVision and Teletrac claim their systems require 8 MHz bandwidth and Pinpoint has proposed a 26 MHz bandwidth system. The majority of these systems allow multiple access along the reverse link using Code Division Multiple Access (CDMA) techniques, although the Southwestern Bell system uses a combination of CDMA and Frequency Division Multiple Access (FDMA). All systems employ triangulation of the DS/SS signal for position location.

The Federal Communications Commission (FCC) has indicated its intention to create rules which foster creative use of Specialized Mobile Radio (SMR) Service such as AVM. In one recently proposed rule (NPRM 93-144), the FCC proposed the consolidation of channel allocations for private land mobile radio stations in the 800 MHz band to metropolitan service areas (MSA) or even larger areas. In another proposed rule (NPRM

93-61), the FCC proposed guidelines for AVM service within the 902-928 MHz ISM bands.

While agreement among commenters can be found on many issues, spectrum sharing remains a significant point of contention. System developers that currently have licenses to commercially operate an AVM system have proclaimed that spectrum sharing is not possible between AVM system providers. System developers who do not currently have licenses have taken a more positive view towards spectrum sharing. In addition to interference between AVM systems, there exist concerns over potential interference with Part 15 devices, also operating in the 902-928 MHz ISM band.

Several studies have addressed portions of the interference problem. However, each of the studies to date has been primarily theoretical in nature. As a result, the studies do not reflect many of the important characteristics of the mobile communications channel at these frequency bands, such as multipath propagation and impulsive noise. Neither do these studies take into account the characteristics of real-world communication systems, including nonlinearities and intermodulation products. As a result, questions remain about the effects of interference between systems. The purpose of this study will be to determine the feasibility of spectrum sharing in AVM bands and to determine possible techniques to mitigate potential interference problems. We believe that this study will be useful to the FCC in formulating rules for the operation of AVM systems.

The remainder of this report is organized as follows. Section 3 discusses interference issues between spread-spectrum systems and the effect of this interference on system capacity, both for position location and communications applications. Section 4 discusses the effects of real-world channel models on the performance of CDMA systems operating at various speeds. Section 5 analyzes the potential for intermodulation products between CDMA systems. Section 6 presents an overview of various interference rejection techniques which may be employed for reducing interference between competing CDMA systems and narrowband systems. Taken as whole, this report reflects the growing progress in techniques which allow different spread-spectrum systems to share similar frequency bands.

**References**

[Qui86] "Introduction to Quiktrak - A tutorial," Appendix A - Quiktrak Operator User's Manual, October 6, 1986.

# 3 Effects of Interference on System Capacity

System capacity concerns are a key issue in selecting standards for AVM systems, and in allocating frequency spectrum among competing systems. Other wireless systems, such as cellular telephone services, have experienced explosive growth which has led to capacity shortages in urban markets. In this section, we consider the effects of bandwidth and interference on system capacity. AVM systems provide two functions: position location and communications services. Position location capacity in a given geographic location is a function of the available bandwidth. Communications capacity is a function of bandwidth and interference from other systems. Interference from systems with very different power levels can produce near-far effects which severely limit the communications capacity. In this section, we consider the effect of bandwidth and channelization on the position location capacity of AVM systems, and we also consider the effect of bandwidth and interference on the communications capacity of CDMA systems.

## 3.1 Position Location Capacity of AVM Systems

A key issue for determination of the optimum bandwidth for spread-spectrum AVM systems is how the capacity varies as a function of bandwidth. Pickholtz argues for Teletrac that the capacity of an AVM system is proportional to the *square* of the system bandwidth. Pickholtz bases this argument on the Cramer-Rao bound [Pick93,Tor84]:

$$\sigma_t^2 \geq \frac{T_c}{4\beta_r^2\left(\frac{S}{N}\right)T}, \tag{3.1}$$

where $\sigma_t^2$ is the variance of the error in the estimate of the arrival time of a pulse, $T_c$ is the chip duration, $\beta_r$ is one measure of system bandwidth, $(S/N)$ is the ratio of signal power to noise power, and $T$ is the time duration of the pulse. This result was derived by extending an earlier result for detection of the rising edge of a pulse to the case of a spread-spectrum signal. The conclusion which Pickholtz derives from this result is that a constant precision $\sigma_t^2$ can be maintained by doubling the bandwidth $\beta_r$ while reducing the time duration of the signal for position location $T$ by a factor of four. Because each position location operation requires one fourth of the time, the number of such operations in a given time period may presumably be increased.

Although this argument is essentially correct for the operation of edge detection, some confusion may result from the multiple operations performed by the AVM system. One can imagine two distinct definitions of capacity: the position location capacity of the system and the communications capacity of the system. The former measures the number of position fixes which may be generated in a fixed time and bandwidth, while the latter measures the amount of data which can be transmitted in a given time and bandwidth.

The shorter time required for a single position fix may result in a higher position location capacity for wider bandwidth systems (although the improvement will be less the

indicated above because the time required for other overhead operations and the guard time between successive position fixes remains unchanged). However, the information carrying capacity of any system only increases linearly with bandwidth. This result follows directly from information theory [Cov91]. As a result, there is no disadvantage from subdividing this bandwidth for different systems. While the position location operation may be slightly more efficient at higher bandwidth, there is no such relationship for the messaging capabilities of the system.

### 3.1.1 Effect of Channelization on Capacity

Other techniques exist for improving the position location capacity of a spread-spectrum system. A position location system can perform only one position fix simultaneously for each orthogonal channel. The Southwestern Bell Mobile Systems (SBMS) AVM system features a unique FDMA/CDMA system for transmission of the channel. The line spectra of the CDMA code is constrained so that 5 orthogonal FDMA channels are formed. Although this does not significantly increase the information-carrying capacity of the AVM messaging system, it does allow for up to 5 simultaneously orthogonal position location signals. As a result, for low loading levels, the position location capacity of the SBMS system is increased by a factor of five.

## 3.2 Communications Capacity of AVM Systems.

An AVM system provides a communications capability for messaging. The communications capacity of AVM systems is a function of both bandwidth and interference from other users and possibly from other systems. In this subsection, we illustrate these tradeoffs for a simple CDMA system model. We then draw some conclusions from these simple models about the effect of interference on CDMA communications.

We consider the problem of evaluating the probability of bit error, $P_e$, for a DS/SS AVM system and examine the effects of multiple access interference (MAI) on $P_e$ for this system. Our intention is to accurately model the effects of the MAI. For this purpose, we employ the improved Gaussian approximation technique explained below and developed fully in [Mor89]. We consider a simple CDMA model in which $P_e$ is calculated for a BPSK, direct sequence, spread spectrum system with the number of users, K, varying from $1 \leq k \leq 64$.

The following assumptions, from [Mor89], were made in evaluate the effects of the MAI for this simple CDMA system:

- Each user employs randomly generated spreading sequences.
- All users have equal received signal powers (this assumption will later be relaxed to investigate the near-far effects between two different systems).
- Without loss of generality, we evaluate the bit error probability for user one.
- The decision statistic for user one is normalized with respect to the chip duration.
- There are K-1 interferering signals.

- There are N chips per data bit, so $T=NT_c$ where $T_c$ is the chip duration.

### 3.2.1 System model

The system model and analysis follow the description given in [Mor89] and [Hol92]. A diagram of the model is shown in Figure 3.1, where A equals $\sqrt{2P}$. There are K users that vary in number from 1 to 64, and the modulation technique for the spread-spectrum signal is asynchronous BPSK DS/SSMA as seen in Equation (3.2). The transmitted signal from the kth user may be represented by

$$s_k(t-\tau_k)=\sqrt{2P}b_k(t-\tau_k)a_k(t-\tau_k)\cos(\omega_c t+\phi_k), \tag{3.2}$$

where the variables used to represent this signal are defined as follows:

- P is the power of the received signal and is normalized to 2.
- $b_k(t)$ is the data signal.
- $a_k(t)$ is the spreading signal
- $\tau_k$ is the propagation delay
- $\phi_k$ is the phase angle of the kth carrier
- $\omega_c$ is the carrier frequency

The received signal will be the sum of the K signals plus an additive white gaussian noise process (AWGN) with double-sided power spectral density of $\frac{N_o}{2}$.

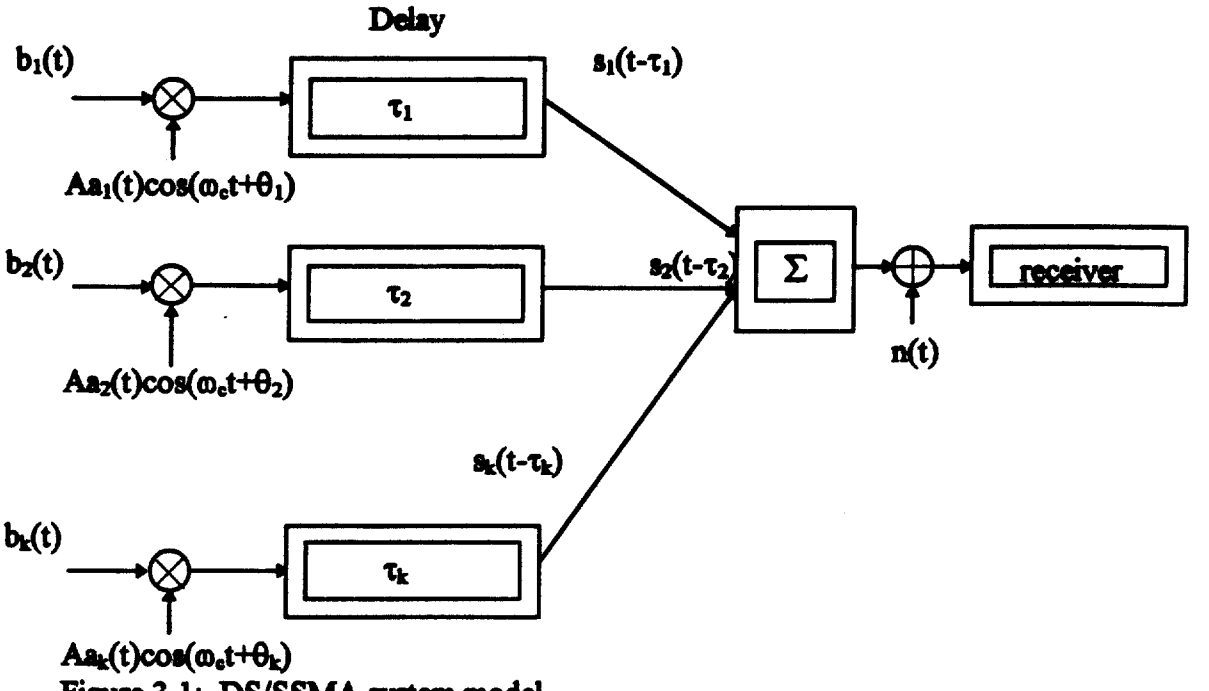

Figure 3.1: DS/SSMA system model.

The data signal is a sequence of rectangular pulses with period T, and has equal probability of being -1 or 1. The spreading signal is also a sequence of rectangular pulses, but with a period of $T_c$, and has equal probability of being -1 or 1. The data signal and spreading signal are both independent, identically distributed random sequences.

### 3.2.2 System analysis

The decision statistic for the received signal using a coherent receiver, normalized by dividing by $T\sqrt{\frac{P}{2}}$, is [Mor89]:

$$Z_1 = b_o^{(1)} + \frac{1}{T}\sum_{k=2}^{K} W_k \cos\Phi_k , \tag{3.3}$$

where $b_o^{(1)}$ is a data bit from user 1 at time 0, $\Phi_k$ is the carrier phase, and $W_k$ is the multiple access interference which may be expressed by

$$W_k = P_k S_k + Q_k(1-S_k) + X_k + Y_k(1-2S_k), \tag{3.4}$$

where $P_k$, $Q_k$, $X_k$, and $Y_k$ are all random variables used to describe the MAI. The incremental delay $S_k = \tau_k - \tau_1$ measures the time offset of the kth user relative to user one.

From Equation (3.3), it is seen that a bit error will occur when the sum of the interference has greater power than the data bit. Therefore an accurate evaluation of $P_e$ depends on a good approximation for the MAI. The Gaussian approximation [Pur77] and the improved Gaussian approximation [Mor89] are used to find an expression for the power of the MAI and for calculating $P_e$.

### 3.2.3 Gaussian approximation

As explained in [Pur77, Hol92], the Gaussian Approximation is used to calculate $P_e$ for a BPSK modulated signal and a coherent receiver. This approximation assumes that the MAI has a Gaussian distribution with zero mean and that $P_e$ can be calculated using the signal-to-noise ratio (SNR) as the argument of the Q-function, which is given by

$$Q[x] = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-\frac{u^2}{2}} du \tag{3.5}$$

The SNR of the desired signal is calculated by evaluating the variance of the MAI which is given by $\left(\frac{3N}{K-1}\right)^{\frac{1}{2}}$. An approximation for $P_e$, can now be calculated using Equation (3.6).

$$P_e = Q\left[\sqrt{\frac{3N}{K-1}}\right] \tag{3.6}$$

Equation (3.6) illustrates the key relationship that the error probability increases with bandwidth and decreases with interference. The basic result of this is that the system capacity of a CDMA communications system will increase linearly with bandwith [Cov91]. However, the assumption that the MAI is Gaussian is only valid only when K and N are relatively large. Unfortunately, the Gaussian approximation is optimistic when either K or N is small. The improved Gaussian approximation remedies this by providing a more accurate expression for the variance of the MAI, leading to an estimate of $P_e$ that is valid for all values of K and N.

### 3.2.4 Improved Gaussian approximation

This approximation assumes that the MAI is approximated as Gaussian when conditioned on the delays and phases of K-1 interfering signals and on a random variable B, defined below. For this approximation, we calculate the distribution of the variance of the MAI $\Psi$, evaluate the Q-function for each value of $\Psi$, and then calculate the average value of this distribution. The variable B is defined as the number of chip boundaries in the desired signal where a transition to a different value occurs, and B is calculated from the discrete aperiodic autocorrelation C of the spreading code according to [Mor89]:

$$B = \frac{N-1-C}{2}, \tag{3.7}$$

where

$$C = \sum_{j=0}^{N-2} a_j^{(1)} a_{j+1}^{(1)}, \tag{3.8}$$

and $a_j^{(k)}$ is the jth chip in the kth signal's signature sequence. The probability of bit error is now given by

$$P_e = E\left[Q\left[\frac{N}{\sqrt{\Psi + \frac{N_o}{2E_b}}}\right]\right] = \int_0^\infty Q\left[\frac{N}{\sqrt{\Psi + \frac{N_o}{2E_b}}}\right] f(\psi)d\psi \tag{3.9}$$

where $\Psi$=Var[MAI|S,$\Phi$,B] is the conditional variance of the multiple access interference, and the probability density function $f_\Psi(\psi)$ may be calculated from the distributions of C and B [Mor89]. Thus, the bit error rate may be evaluated from Equation (3.9) for all levels of MAI.

### 3.2.4 Numerical Results

Figures 3.2 and 3.3 show that the probability of bit error decreases as K decreases and as $E_b/N_o$ increases. Note, though, that there is only a small improvement when $E_b/N_o$ increases from 20 dB to 50 dB. Even when a detailed analysis of the interference distribution is considered, communications capacity is linearly proportional to the bandwidth.

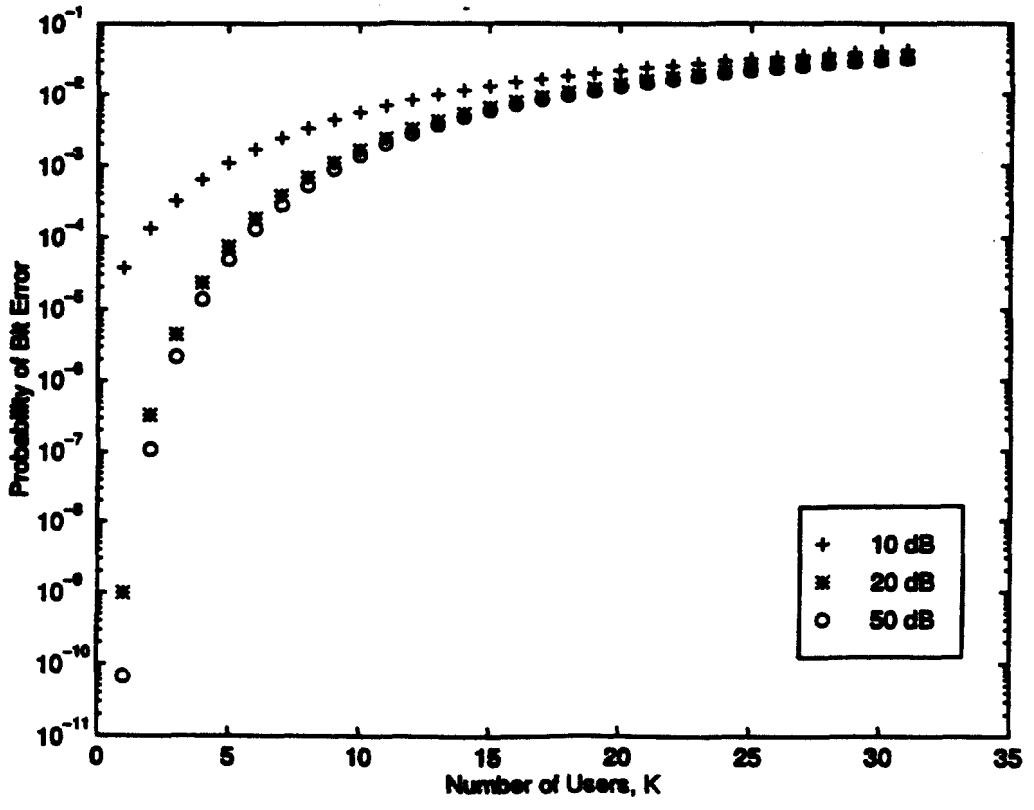


Figure 3.2: Probability of bit error versus K using the improved Gaussian approximation (N=32).

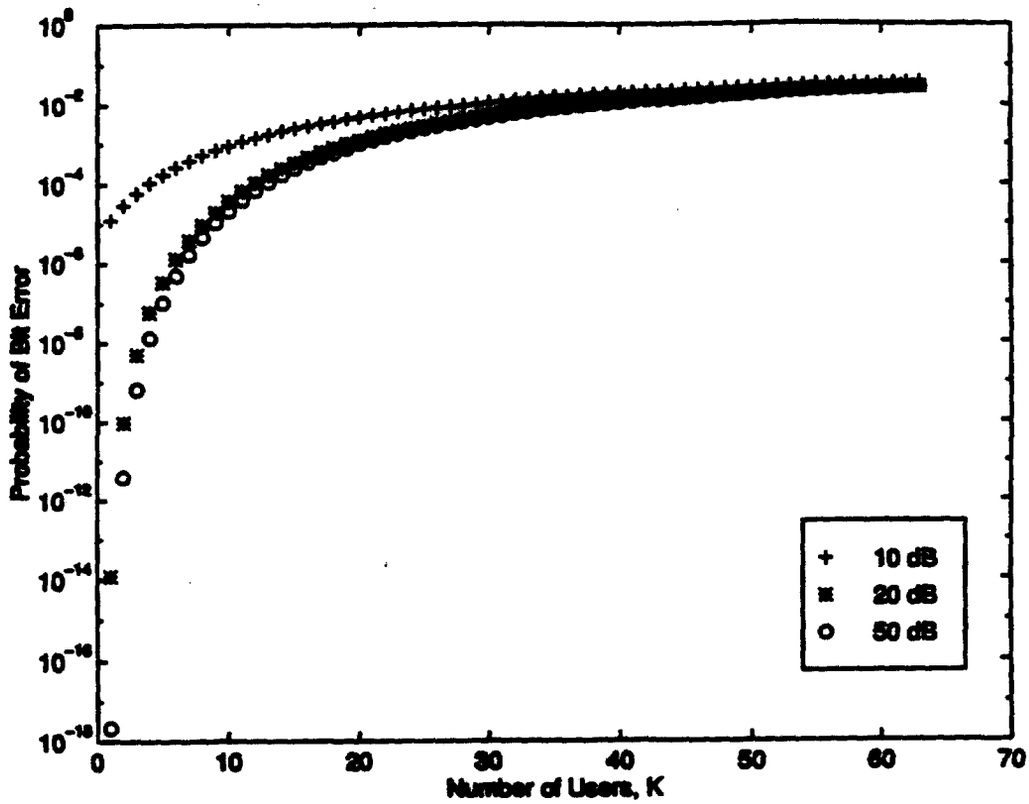


Figure 3.3: Probability of bit error versus K using the improved Gaussian approximation (N=64).

### 3.2.5 Near/Far Effects

Figures 3.4 and 3.5 have extended the peformance results of Equation (3.9) to the case of unequal signal powers for processing gains of N=32 and N=64 respectively. The method for accomplishing this extension is described in [Lib94]. The bit error rate $P_e$ is plotted as a function of the carrier to interference ratio C/I for a two user system for $E_b/N_o$=10 dB and $E_b/N_o$=20 dB. These results illustrate the well-known near-far problem. A weak interferer has relatively little effect on system performance; however, a strong interferer has a severe effect on the capacity of a CDMA system.

These results may be used to approximate the effects between high-power AVM systems and lower power Part 15 devices. The AVM systems considered here share the 902-928 MHz frequency band with low power devices which operate under Part 15 regulations. In order to comply with FCC regulations, these devices must use low power (<1W) spread-spectrum signaling, with a processing gain of at least 10. Under current FCC rules the Part 15 users must operate on a secondary basis to other licensed users such as AVM systems.

Although the potential exists for interference between AVM systems and Part 15 devices, isolation of the two systems will considerably reduce this interference. Since AVM systems operate at significantly higher power levels (5-10W) and have the advantage of siting base stations at favorable locations, it is likely that the interference from Part 15 devices will be small. Nonetheless, when a Part 15 device is operating much closer to a base station than an AVM mobile unit, the transmitted power is large enough to produce a significant near/far problem. However, Part 15 devices operating indoors and over short distances are unlikely to experience significant interference from AVM systems. Building walls and floors will attenuate AVM signals by as much as 20-30 dB [Sei92]. However, Part 15 devices designed for outdoor operation may experience significant interference. Several interference rejection techniques which are available to address narrowband interference from Part 15 devices will be discussed in Section 6.

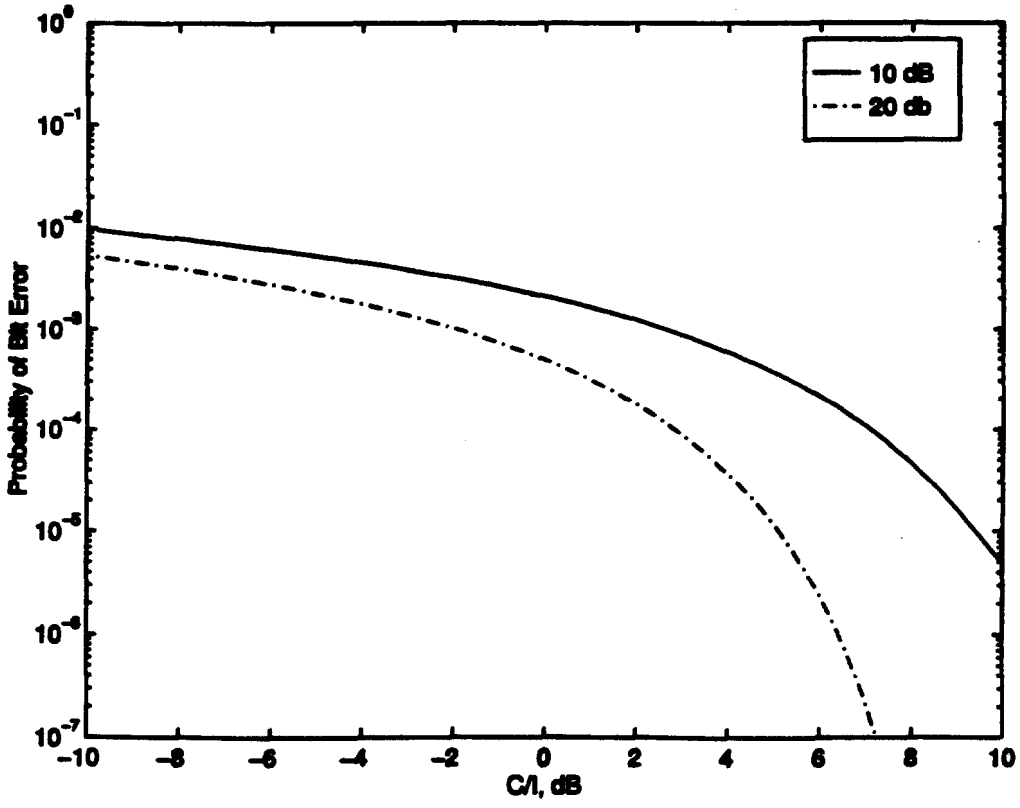


Figure 3.4: Probability of bit error versus C/I for a two user system with N=32.

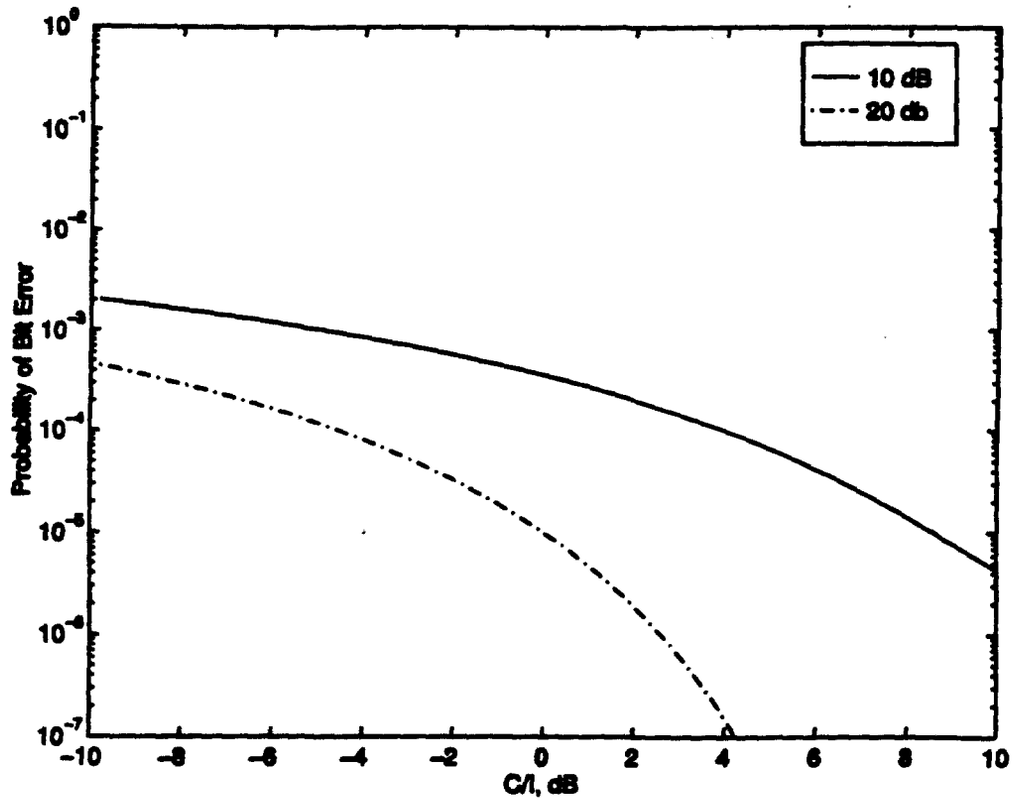


Figure 3.5: Probability of bit error for near-far situation.

### 3.3 Summary

We have examined both the position location capacity and the communications capacity of spread-spectrum systems as a function of interference and bandwidth. There appears to be some advantage in position location capacity for systems which employ a larger bandwidth. However, other techniques are available which also increase the position location capacity of systems, such as orthogonal channelization techniques.

The communications capacity of spread-spectrum systems increases only linearly as a function of bandwidth, even using detailed analysis for the effects of interference. The near-far problem severely limits the system capacity of the weaker CDMA system in situations where multiple signals have different power levels. In order to avoid near-far effects from AVM systems operating in the same spectrum as Part 15 devices, careful siting of AVM base stations should be employed. Furthermore, signal antenuation through building walls should be sufficient to alleviate interference from AVM systems to indoor Part 15 systems.

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# 4 Analysis of RF Propagation Effects

The Radio Frequency (RF) channel will have a significant effect on the performance of real-world AVM systems, and on the choice of bandwidth for AVM systems. Multipath transmission results from signal reflection off of large objects such as hillsides and buildings. Multipath can result in two significant sources of error for AVM systems. Detection of the wrong arriving multipath component can result in large timing errors and catastrophic failure of the position location attempt. Coherent combination of closely spaced multipath components can resulting in fading which reduces signal to noise ratio. Both effects can be minimized by resolving the multipath components as completely as possible which requires larger bandwidth.

This section presents an analysis of RF propagation characteristics and the effects of RF propagation on the performance of DS/SS AVM systems for both urban and suburban environments. The RF propagation effects of interest include multipath propagation and Doppler fading. It is well known that spread-spectrum signals are resistant to multipath interference, and in some instances even exploit multipath characteristics to improve system performance.

In order to evaluate the effects of RF propagation, realistic countermeasures such as error correction coding and interleaving must be considered. We have evaluated the performance of a candidate DS/SS AVM system with multipath distortion and Rayleigh fading and have investigated the effect of Doppler shift due to the motion of vehicles with speeds ranging from 10 km/hr to 80 km/hr. This candidate system is chosen to demonstrate the feasibility of a spread-spectrum system with relatively narrow bandwidth.

## 4.1 RF Propagation effects in urban and suburban areas

RF propagation characteristics generally can be divided into two main categories: long-term fading (large-scale fading) and short-term fading (small-scale fading). Long-term fading due to RF propagation loss and shadowing usually can be described by a distribution about the average PL (Path Loss) model for a specific location. On the other hand, short-term fading due to multipath propagation and Doppler shift can result in a the mobile channel with flat fading or frequency-selective fading characteristics, depending on the characteristics of signals. For example, narrowband signals usually can be characterized by a flat fading channel while wideband signals are characterized by a frequency-selective channel. Examples of these two kinds of channels are shown in Figure 4.1-4.2. Figure 4.1 illustrates the case of flat fading, in which the delay between multipath components is small in comparison with the duration of one symbol. As a result, multiple arriving components combine coherently to produce amplitude fading. Figure 4.1 illustrates the case of frequency selective fading in which distinct multipath components are resolvable. It is desirable for a DS/SS AVM system to operate with large enough processing gain to fall in the frequency selective case, thereby exploiting the diversity of

multiple arriving components. A summary of propagation characteristics is provided in Table 4.1.

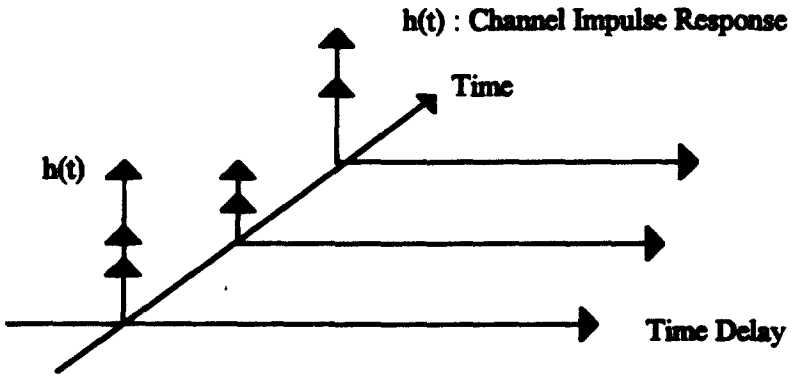



Figure 4.1 Flat fading channel

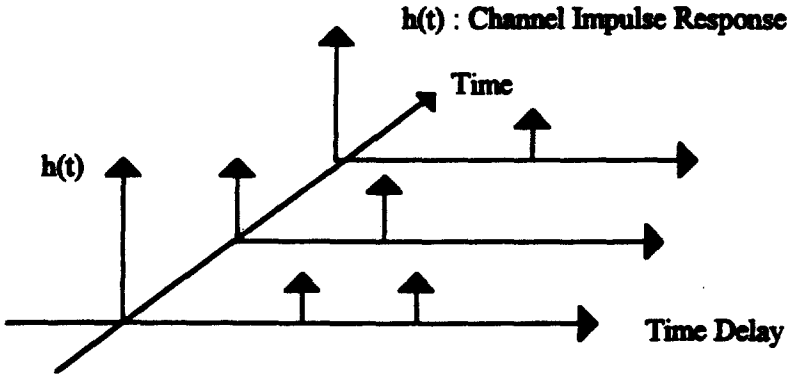
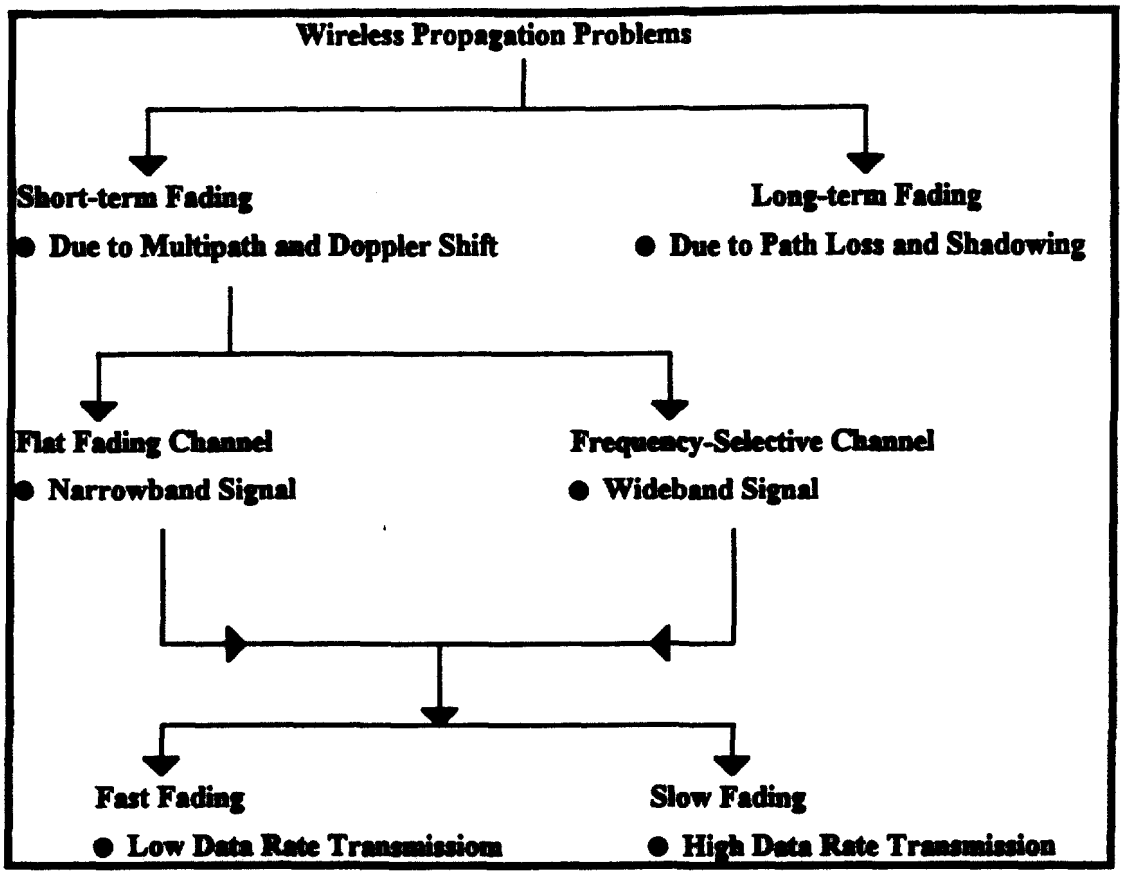



Figure 4.2 Frequency-selective fading channel

Table 4.1 Wireless Propagation Characteristics.




In this report, we only consider the effects of short-term fading (i.e., multipath fading and Doppler). The effects of large-scale fading are best modeled by the techniques for analyzing the near-far problem which were discussed in Section 3. In the next Section 4.2, we will discuss the effects of short-term fading on system performance.

## 4.2 Multipath fading and Doppler shift

In urban and suburban environments, mobile radio communications signals can propagate along more than one path due to reflections and scattering from buildings, trees, and other obstacles along the path. This is known as multipath propagation. Multipath propagation creates intersymbol interference for narrowband systems. However, in wideband systems (e.g., DS/SS system ), multipath can be used to improve system performance since multipath components can be resolved into individual components at the receiving end and coherently combined to produce a better estimate of transmitted data. Another propagation effect, Doppler shift, results in a frequency shift on the signal power spectral due to motion of the receiver. Fading induced by the Doppler shift can cause burst errors in mobile communications system

In the next subsection, we will investigate the impact on the system performance caused by multipath and Doppler shift.

### 4.3 Propagation models

Several propagation models have been suggested to explain the observed statistical characteristics of electromagnetic fields and the associated effect on the signal envelope and phase. The earliest models was due to Ossana [Oss64] who attempted an explanation based on the interference of incident and reflected waves from flat sides of randomly-located buildings. Although Ossana's model predicted power spectra that were in good agreement with measurements in suburban areas, it assumed the existence of a direct path between transmitter and receiver. It is therefore rather inflexible and inappropriate for urban areas where the direct path is almost always blocked by buildings or other obstacles.

A model based on scattering is generally more appropriate, and the most widely quoted and accepted model is that of Clarke [Cla68]. This model assumes that the field incident on the mobile antenna is composed of a number of plane waves with random phase. These plane waves are vertically polarized with horizontal angles of arrival and phase angles which are random and statistically independent. Furthermore, the phase angles are assumed to have a uniform probability density at $[0, 2\pi]$. A model such as this, based on scattered waves, allows the establishment of several important relationships describing the received signal, for example, the statistics of the signal envelope and the nature of the frequency spectrum.

If either the transmitter or receiver is in motion, each multipath component experiences a different Doppler shift as the component arrives at the receiver at a different angle. The Doppler shift of the i$^{th}$ component $f_i$ is related to the receiver speed as well as the angle $\alpha_i$ of the i$^{th}$ component, according to [Par89]

$$f_i = f_m \cos\alpha_i \tag{4.1}$$

where $f_m = v/\lambda$ is the Doppler frequency corresponding to a receiver speed $v$ and a carrier wavelength $\lambda$. Since the single carrier frequency signal generates multiple components at the receiver, each component has a shift in frequency about the carrier frequency. A Doppler power spectrum is shown in Figure 3.3. The expression for the received power spectrum for an omnidirectional antenna is given in [Cla68].

$$S(f) = \frac{E^2}{2\pi f_m \sqrt{1-\left(\frac{f}{f_m}\right)^2}}, \quad f \le f_m \tag{4.2}$$

$$= \quad 0 \quad , \text{otherwise,}$$

where $E$ is the rms value of signal envelope.

The results presented here can be used to create a complete multipath channel model in the next subsection.

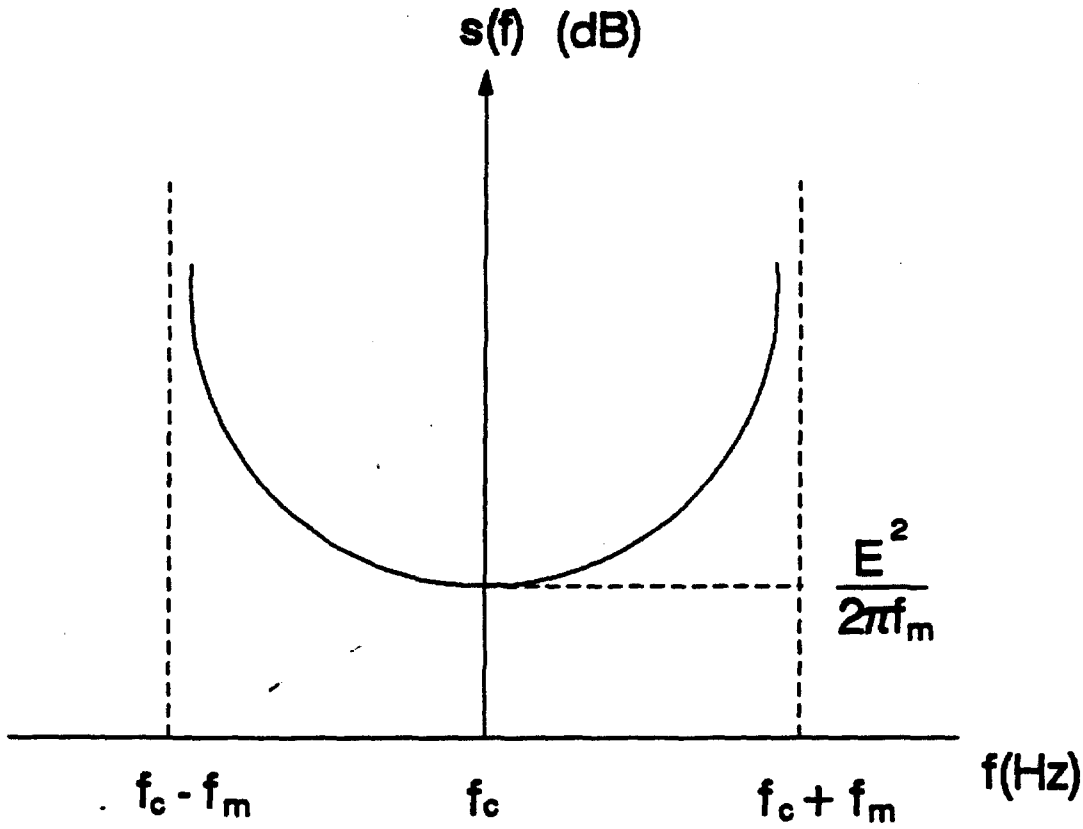



Figure 4.3 Theoretical power spectrum of Rayleigh fading.

### 4.4 Multipath channel model

A multipath channel in a mobile environment can be described as a discrete time-varying filter since the channels change rapidly with time due to the vehicle motion. The impulse response for multipath channel can be expressed as [Tur72]

$$h(t;\tau)=\sum_{i=1}^{M}\alpha_i e^{j\theta_i}\delta(t-\tau_i) \tag{4.3}$$

where $\tau_i$ = the arrival time of the i$^{th}$ observed component
$M$ = the number of multipath components
$\theta_i$ = the phase of the i$^{th}$ multipath component
$\alpha_i$ = the magnitude of the i$^{th}$ multipath component

For a wideband channel, the receiver is able to resolve individual multipath components in the time domain (i.e., $\tau_i \neq 0$). However, these components cannot be resolved for a narrowband channel (i.e., $\tau_i = 0$). Furthermore the wideband multipath channel can be grossly quantified by its mean excess delay $\tau_{avg}$ and root mean square delay spread $\tau_{rms}$. The mean excess delay is the first moment of the power delay profile and is defined as [Cox73]

$$\tau_{avg} = \frac{\sum_i \alpha_i^2 \tau_i}{\sum_i \alpha_i^2}. \tag{4.4}$$

The rms delay spread is the square root of the second central moment of the power delay profile and is defined to be

$$\tau_{rms} = \sqrt{\frac{\sum_i \left(\tau_i - \tau_{avg}\right)^2 P(\tau_i)}{\sum_i P(\tau_i)}}, \tag{4.5}$$

where the delays of each component are measured relative to the first arriving component at $\tau_1 = 0$.

In this research, a two-ray channel model is considered and used in the simulation. The generation of a two-ray channel impulse response is described in the following subsection.

### 4.5 Two-ray channel model

The two-ray model describing multipath propagation in the mobile channels uses a direct ray and a delayed ray. The impulse response of the wideband (frequency-selective) channel using a two-ray model corresponds to $M$=2 in Eq.(4.3). That is,

$$h(t;\tau) = \alpha_1 e^{j\theta_1}\delta(t) + \alpha_2 e^{j\theta_2}\delta(t-\tau) \tag{4.6}$$

where $\alpha_1$ and $\alpha_2$ are independent and Rayleigh distributed, $\theta_1$ and $\theta_2$ are independent and uniformly distributed over [0, $2\pi$], and $\tau$ is the time delay between the two rays. Generally, for a baseband simulation, the sum of $E\{\alpha_1^2\}$ and $E\{\alpha_2^2\}$ is set to unity so the channel will have an average unity gain. The ratio of $E\{\alpha_1^2\}$ and $E\{\alpha_2^2\}$ is the power ratio of the main ray to the delayed ray and is denoted as C/D. A flat fading channel also can be modeled by setting $\alpha_2$ to zero.

In the simulations which follow, the delay $\tau$ between two rays is used instead of $\tau_{rms}$. The relation between $\tau$ and $\tau_{rms}$ can be determined as follows.

$$\tau_{rms} = \sqrt{\frac{(\tau_1 - \tau_{avg})^2 P(\tau_1) + (\tau_1 - \tau_{avg})^2 P(\tau_2)}{P(\tau_1) + P(\tau_2)}} \tag{4.7}$$

$$\tau_{avg} = \frac{\tau_1 P(\tau_1) + \tau_2 P(\tau_2)}{P(\tau_1) + P(\tau_2)}, \tag{4.8}$$

where $\tau_1$ corresponds to the 1st ray and $\tau_2$ corresponds to the 2nd ray in a two-ray model. For convenience, $\tau_1$ is set to zero, and $\tau_2$ is set to $\tau$. Since $P(\tau_1)$ is the average power at a fixed delay $\tau_1$, then $P(\tau_1)$ and $P(\tau_2)$ can be expressed as

$$P(\tau_1) = E\{\alpha_1^2\} \tag{4.9}$$

$$P(\tau_2) = E\{\alpha_2^2\} \tag{4.10}$$

### 4.6 Generation of two-ray channel impulse response

A MATLAB two-ray Rayleigh fading simulator, *tworaygenerator.m*, based on [Sim75][Rap91] was written to generate the amplitude and phase of each ray in the two-ray model. For this channel simulator, the Gaussian distributed random variables (for the amplitudes of the Doppler shifted components) are first obtained using a Gaussian number generator and each random variable is used as a Fourier coefficient in the frequency domain at a particular frequency. Each coefficient is weighted by a shaping factor confined to the fading magnitude spectrum derived from Eq.(4.2). The shaped fading magnitude spectrum is represented by

$$G(f) = r_f \cdot \frac{1}{\sqrt{1-\left(\frac{f}{f_m}\right)^2}}, \quad 0 \le f \le f_m - \delta f \tag{4.11}$$

$$= r_f \cdot \sqrt{f_m \left[\frac{\pi}{2} - \tan^{-1}\left(\frac{f_m - \delta f}{\sqrt{2 f_m - \delta f}}\right)\right]}, \quad f = f_m$$

$$= 0 \qquad \text{, otherwise,}$$

where $r_f$ is a Gaussian distributed random variable and $1/\sqrt{1-\left(f/f_m\right)^2}$ is the magnitude spectrum which is the square root of the power spectrum given Eq.(4.2) and $\sqrt{f_m\left[\frac{\pi}{2} - \tan^{-1}\left(\frac{f_m - \delta f}{\sqrt{2 f_m - \delta f}}\right)\right]}$ is an estimate for the magnitude at $f_m$.