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Probing Techniques for Multiuser Channels with Power Control

A dissertation submitted in partial satisfaction of the

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by

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Dedication

To the memory of my father, David Hansen.

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ABSTRACT OF THE DISSERTATION

Probing Techniques for Multiuser Channels with Power Control

by

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This work investigates a set of probing techniques for multiuser radio systems. These techniques are designed to allow radio transmitter/receiver pairs to determine the characteristics of a communication channel they wish to use. It is assumed that the channel is shared by multiple users that employ power control to allow each pair to maintain a fixed signal-to-interference ratio and transmission rate. The goal is to allow a new user pair to determine the maximum feasible bit rate it can achieve and the information necessary to choose a signaling format that will yield the maximum rate.

Three particular channel models are examined: a high symbol rate indoor channel, a moderate symbol rate mobile radio channel, and a channel with adaptive antenna arrays in addition to power control. The probing techniques are tailored to give information that is appropriate for a system operating under each channel model. The indoor channel probing algorithm gives precise results for the

maximum feasible SIR level. The mobile radio probing algorithm quickly determines whether or not a particular channel can be used for communication at a fixed rate. Probing with adaptive antennas gives an estimate of the SIR that can be achieved at a target transmitter power.

The intended applications for channel probing are future wireless systems that are fully distributed. Until now, most distributed access algorithms have used ad hoc techniques. Channel probing puts distributed access on a solid foundation and allows distributed systems to employ sophisticated power and channel allocation techniques that have been developed for centralized systems.

Chapter 1

Introduction

This dissertation introduces new techniques for determining the characteristics of communication channels that are shared by multiple users. These techniques are grouped together under the name *channel probing*. As the name suggests, probing takes the form of a single user transmitting a signal on a channel and measuring a response, usually a measurement of both the received signal power and received interference power from other users. From the response, the user is able to determine the characteristics of the channel. This information is in turn used to determine the optimal modulation format and power level for communication.

1.1 Motivation for Channel Probing

Since the introduction of cellular telephone systems, researchers have been investigating methods for increasing the capacity, or number of users per unit of

bandwidth, that the systems can handle. This research is critical, because radio bandwidth is limited and the demand for wireless communication services is increasing. At the same time, new wireless communication services, such as two-way pagers, personal communication systems, navigation systems and many others are also being developed and competing for increasingly scarce radio spectrum. This trend is likely to continue for the foreseeable future.

The application of digital technology has brought new cellular standards, IS-54 TDMA (time division multiple access) and IS-95 CDMA (code division multiple access), with large capacity gains relative to present analog systems. However, the capacity increase has exacted its own cost: an enormous increase in complexity. This has already lead to problems in implementing new systems and in convincing the telecommunications community that they are viable solutions. For example, there are no IS-95 CDMA systems in operation in the United States as of November 1996, even though VLSI chip sets to implement the phones have been available since 1991. There are also very few operating TDMA systems.

The problem with these new systems is not the difficulty in implementing the radio modem. In fact, the sophisticated VLSI circuits work extremely well. Rather, the difficulty has been the implementation of complex control networks necessary to make the new systems work. Unless changes are made, future systems - which will be even more complicated - will also encounter complexity problems.

A potential solution to the complexity dilemma is to make complex multiuser

communication systems more distributed. With distributed systems, the choice of channel, signalling format, and power can be made by each user based on its own measurements of the multiuser channel. Recent developments [3][4][18] have demonstrated that power control can be made completely distributed with the same results as a centralized system. Distributed channel allocation, however, is a newer topic, and previous attempts have used a variety of ad-hoc techniques [13][66].

The purpose of probing is to allow each user to measure its own channel characteristics so it can apply the same type of power and channel allocation algorithm that a centralized controller would employ. With probing, users work together to find appropriate channel allocations that help to maximize capacity. Probing helps to formalize a method for dynamic channel allocation. Instead of relying on ad-hoc measures of channel congestion, the channel probe allows the user to precisely determine the maximum communication rate it can achieve.

1.2   Overview of Dissertation Topics

The dissertation covers several different probing algorithms that are appropriate for different types of multiuser channels. To begin, Chapter 2 presents background material on channel models, dynamic channel allocation, distributed power control, and capacity measures. Next, Chapter 3 discusses probing for channels where exact measurements are possible. Two specific examples are discussed: a slow frequency-hopped indoor wireless system and a multitone modulated wireline system. In each case, the channel varies slowly compared to the rate at which the distributed algorithms

will operate. This allows precise channel estimation and channel allocation to be performed.

Chapter 4 presents a probing algorithm for systems where the channel cannot be estimated precisely. The example is a wireless cellular system with mobility. Channels are partitioned into power controlled and fixed assignment. Users initially enter the system through a fixed assignment channel to guarantee access. They then probe for a power controlled channel and use power control whenever feasible. The goal is to balance capacity with the limits of time varying channels.

Chapter 5 explores probing for power control with adaptive antennas. The addition of adaptive antennas makes probing much more difficult. Power control and minimum mean square error (MMSE) adaptive antenna arrays are discussed.

Last, Chapter 6 presents concluding remarks on probing and its application to multiuser communication systems.

Chapter 2

Background

This chapter introduces background material to lay a technical foundation for the later chapters. It begins with an overview of wireless and wireline channels, including a discussion of current communications systems and the channel impairments they encounter. Next is a review of power control and dynamic channel allocation algorithms. These are new techniques that enhance the performance of multiuser communication systems. The last topic discussed in this chapter is capacity and how it is measured in practical systems.

2.1 Wireless Channels

The characteristics of wireless radio channels arise from the physics of radio propagation and vary with the operating environment. In recent years, the mobile radio (cellular telephone) and indoor environments have been studied extensively

[28][32][37][42][48][57]. This work has led to a common statistical model that can used to describe the nature of wireless channels.

2.1.1 Propagation Model

There are three components to the radio propagation model that correspond to three distinct physical mechanisms. The first, path attenuation, arises from the expansion of the electromagnetic wave front as the radio wave travels from the transmitting antenna to the receiving antenna. In free space, the power of the received antenna will be reduced by a factor proportional to the square of the distance between transmitter and receiver. In mobile radio and indoor channels the attenuation can increase at a faster rate, which is expressed as a distance exponent greater than 2. The attenuation slope is increased because the received signal is typically a combination of a direct path and a low angle reflection off the ground [37]. When these signals combine, the resulting signal attenuation is proportional to distance to the fourth power. This effect has been observed in practice, with experimentally determined attenuation exponents between 3 and 5 [32][42]. High attenuation exponents (greater than 4) tend to occur both in dense urban areas and in other areas when the separation between transmitter and receiver is more than 40 km. This additional attenuation is primarily due to signal scattering off objects blocking the signal path. The path attenuation does not vary significantly within the frequency band of a typical radio system.

The second propagation characteristic is shadowing, which includes signal attenuation caused by buildings, hills, wall partitions, or any other object that is very

large compared to the radio wavelength and blocks a line of sight path. Radio propagation can also be enhanced by atmospheric ducting [42], a condition where the atmosphere refracts radio waves towards the earth and improves propagation characteristics over the horizon. The signal path improvement or attenuation is modeled as a log-normal random variable whose variance depends on the environment. As users move, the shadowing varies because of the blocking effect of different objects. Like path attenuation, shadowing does not vary much over the ranges of frequencies employed in most communication systems.

The last propagation characteristic incorporated in the model is fading, a process caused by the combination of many different signal paths at the receiving antenna. The common name for this is multipath and it is modeled as either a Rayleigh or a Rician process. Rayleigh fading occurs when there are a very large number of roughly equal powered, independent signal paths. When the signals combine at the receiver the voltage has a complex Gaussian distribution, as a result of the central limit theorem [41]. The Rayleigh distribution is the amplitude of the complex Gaussian voltage. In terms of signal power, the square of voltage, Rayleigh fading has an exponential distribution.

Rician fading is Rayleigh fading with one large signal component added. This type of fading occurs when the received signal is a combination of a strong direct path and many weaker, scattered paths. The Rician model is more accurate for many situations, but the Rayleigh model is used more often for analysis because it is

mathematically simpler and it represents the worst case in signal fading.

Since Rayleigh and Rician fading result from the vector addition of multipath signals, they are a strong function of the phase angles of these signals. Consequently, small changes in frequency or distance vary the phase of the multipath signals and change the fading level. Fading also tends to change with time due to mobility of transmitters, receivers, or other objects in the neighborhood.

The three characteristics can be combined into one statistical expression for the received signal power:

$$r = P_t C \left(\frac{1}{d}\right)^n X_f X_s \tag{2.1}$$

where P_t is the transmitted power, C is a constant that incorporates antenna gains and other fixed factors, d is the distance from transmitter to receiver, n is the attenuation exponent (usually $n \approx 4$ for mobile radio systems), X_f is an exponentially distributed random variable corresponding to the Rayleigh fading, and X_S is the shadowing random variable:

$$X_s = 10^{\left(\frac{x}{10}\right)} \tag{2.2}$$

where x has a Gaussian distribution, typically with standard deviation $\sigma = 8$ decibels.

2.1.2 Cellular Systems

The cellular concept was developed at Bell Laboratories in the 1970s as part of the Advanced Mobile Phone System (AMPS). In this system, the coverage area is

divided into hexagonal cells and a base station is located at the center of each cell. Users in a given cell only communicate with that cell's base station, as shown in Figure 2-1. However, they also generate interference to nearby users that share the same channel. To mitigate interference, channels are assigned to each cell according to a re-use pattern. For example, a common pattern is K=7, in which channels are re-used every seven cells. This forces the closest interferer to be at least two cells away.

Figure 2-1   Cellular Concept with Re-use Factor 7
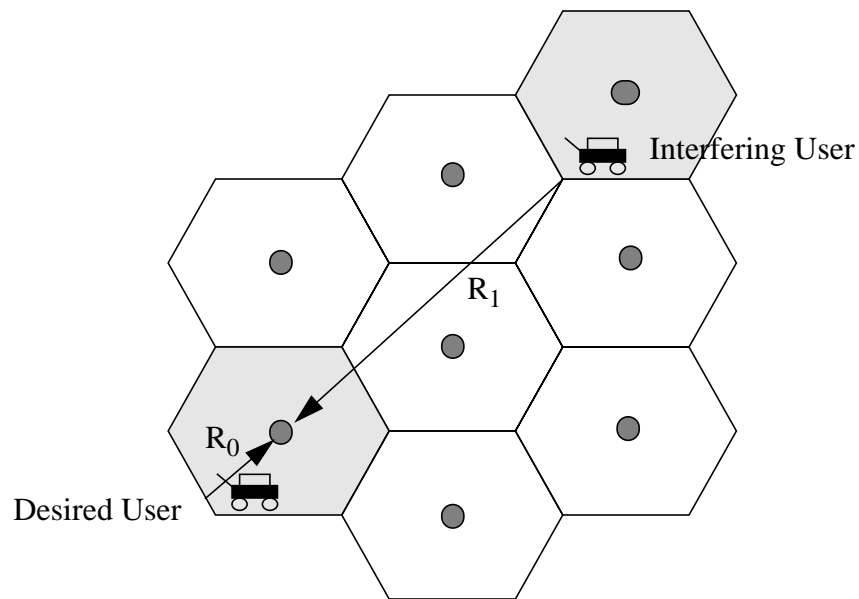
Under worst cast conditions, the signal-to-interference ratio (SIR) on the desired user's link will be fixed by the ratio of the distances R_0 and R_1, if shadowing and fading are neglected. The SIR, γ, is then lower bounded:

$$\gamma \geq \left(\frac{R_1}{R_0}\right)^n \qquad (2.3)$$

where n is the same propagation loss exponent given in Equation 2.1. Re-use factors and associated distance ratios are given in [37].

The SIR level on a channel is critical because it determines the transmission rate that can be achieved. More sophisticated channel access algorithms all work to maintain an SIR level that is high enough for each user to communicate, but no higher than necessary. The goal is to adapt to actual interference conditions rather that relying on worst case channel allocations. In this way, capacity can be increased by reducing the average re-use distance for channels.

2.2   Wireline Channels

Wireline systems have many physical forms including coaxial cable, waveguide, twisted pairs. In this work, twisted pairs in a cable bundle are studied because this is the medium for future multiuser wireline communication systems, such as the asymmetric digital subscriber line (ADSL) [55]. The ADSL system was developed to allow high speed digital communication to homes over traditional telephone wiring. The system employs very fast data rates, 6 megabits per second (Mbps) from the telephone company central office to the home and 768 kilobits per second (Kbps) in the reverse direction. Applications include cable television, internet access, and videophone service.

2.2.1 Twisted Pair Cable Characteristics

Twisted pair cables have three major channel impairments. These are

attenuation with distance, near end cross talk (NEXT), and far end cross talk (FEXT).

Each of these is frequency dependent and can be modelled as a frequency response. The

attenuation of the twisted pair channel, $G_0(f)$, is determined by the cable length and

by the presence of bridge taps at different points along its length. $G_0(f)$ can be

determined by an equivalent circuit model for transmission lines. For the results in the

dissertation, the frequency response models for Bellcore [5] standard loops are used.

The NEXT and FEXT terms are computed with a model based on [38]. NEXT

has a fixed frequency response:

$$G_{NEXT}(f) = \left(\frac{K_N}{10}\right)^{10}\left(\frac{f}{f_0}\right)^{3/2} \tag{2.4}$$

The cut-off frequency for NEXT, f_0, is 0.772 MHz. FEXT is also affected by the

frequency response of the disturbed twisted pair and the length of the cable, l:

$$G_{FEXT}(f) = \left(\frac{K_F}{10}\right)^{10}\left(\frac{f}{f_0}\right)^2\left(\frac{l}{l_0}\right)G_0(f) \tag{2.5}$$

In this equation, $f_0 = 3.15$ MHz and $l_0 = 1000$ feet. K_N and K_F are gamma

distributed random variables with mean and variance determined by the type of cable

[38]. The gamma distribution is similar to the Gaussian distribution in that it can be

completely determined by its mean and variance, however it has a different structure in

the tails. The gamma distribution is:

$$P[x \leq x_0] = \frac{\beta^\nu}{\Gamma(\nu)}\int_0^{x_0} x^{\nu-1}e^{-\beta x}dx \tag{2.6}$$

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with parameters ν and β derived from the mean and variance with the equations:

$$\nu = \left(\frac{m}{\sigma}\right)^2 \qquad \beta = \frac{m}{\sigma^2} \qquad (2.7)$$

and the gamma function is a generalized factorial based on Euler's integral:

$$\Gamma(\nu) = \int_0^\infty t^{\nu-1}e^{-t}dt \, , \, \nu > 0 \qquad (2.8)$$

2.2.2 Wireline Signaling Format

It is assumed that a multiple signal format such as that proposed in the ADSL standard is used on the wireline channel. The ADSL system uses discrete multitone transmission (DMT) [7][15]. This modulation format partitions the frequency spectrum into bins that are 4.3125 KHz wide with a discrete Fourier transform. The frequency partitioning allows each bin to be modulated separately with a constellation size that is appropriate for the signal-to-interference ratio that can be achieved on the bin. In the downstream link (from service provider to residence), there are 256 frequency bins. A plot of typical gain, NEXT, and FEXT, between twisted pairs in a PIC cable on the downstream path is given in Figure 2-2. Like the wireless channel, the ADSL wireline channel becomes interference limited when the cable bundle is shared by multiple user pairs.

Figure 2-2   Loop Gain with Typical NEXT and FEXT Response
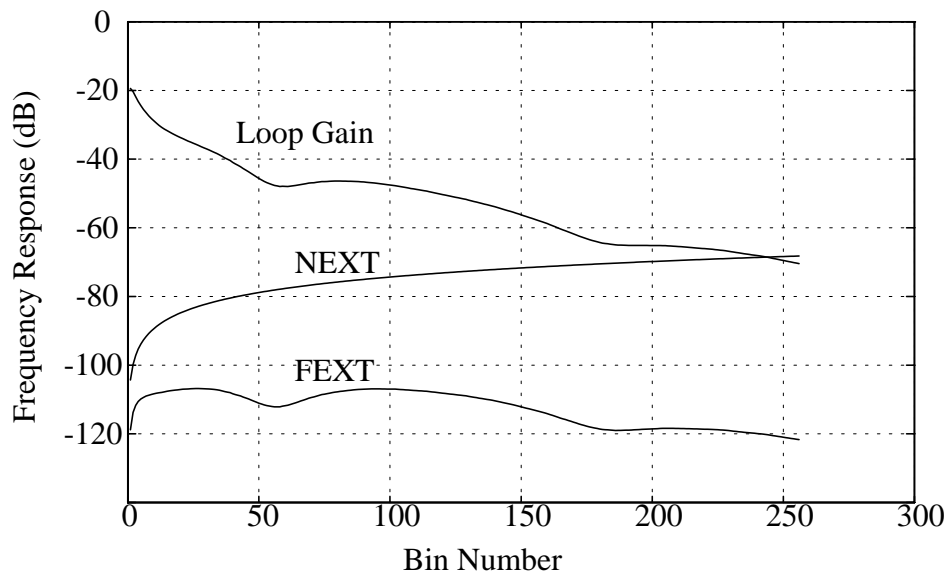
2.2.3 Wireline Channel Access

Current ADSL systems employ a multiple access technique that is analogous to fixed frequency re-use in the cellular wireless system. Each user enters the system at a fixed power level and allocates a QAM constellation for each frequency bin based on the received signal level. The interference level is assumed to be the 1% worst case for a congested cable [55]. In practice, however, the maximum SIR level will depend on the specific cable characteristics and the power levels of other users on the cable. System capacity, in terms of the average user transmission rate, can be improved by adapting to the actual interference conditions. Section 3.4 explores the capacity improvement that is possible with probing and dynamic power allocation.

2.3 Multiuser Channels

From a multiuser standpoint, wireline and wireless channels are fundamentally similar as shown in Figure 2-3 and Figure 2-4. Consequently, signalling techniques that have been applied to wireless systems can also be applied to wireline systems. Both systems are called multiuser because any user's transmission will cause interference to other users. To maximize performance, the transmitter signaling and power level must be coordinated between every user in the system.

Figure 2-3   Wireline Multiuser Channel
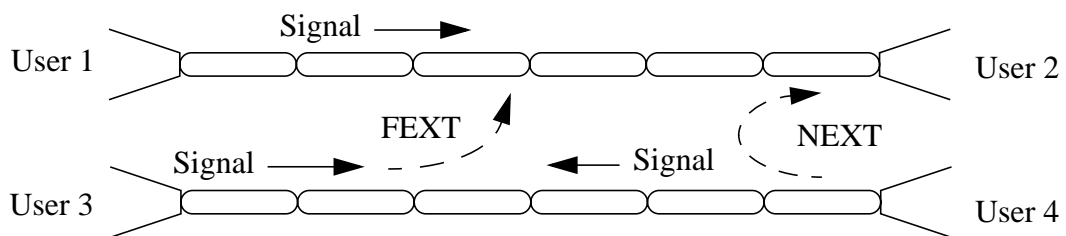
Figure 2-4   Wireless Multiuser Channel
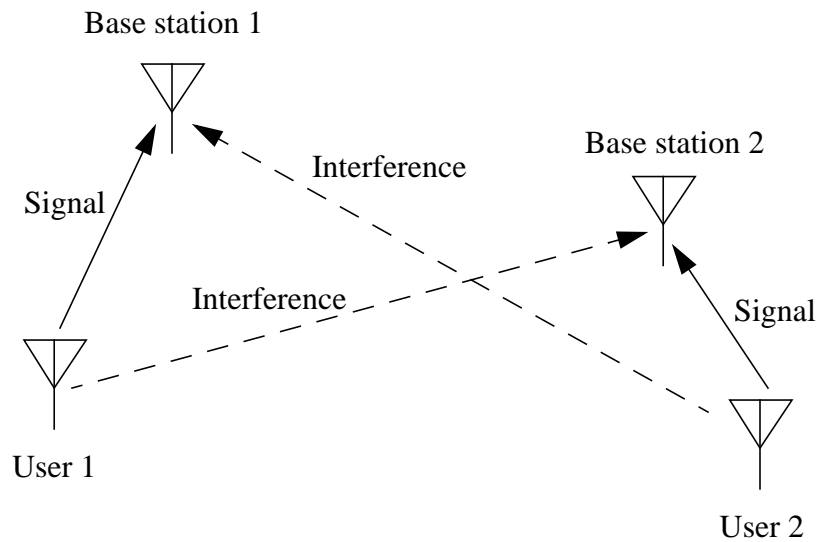
A general model for multiuser channels is the interference channel shown in Figure 2-5. The model consists of N coupled transmitter-receiver pairs. Each pair represents a link, such as user-to-base station for a cellular system, or user-to-user in a wireline twisted pair. Each link receives interference from every other link, and from thermal noise in the receiver. The ($N \times N$) link matrix, G, is defined by the power transfer functions between each transmitter and each receiver. As shown in Figure 2-5, element G_{ij} refers to the gain from the transmitter on link j to the receiver on link i.

Figure 2-5   Interference Channel Model
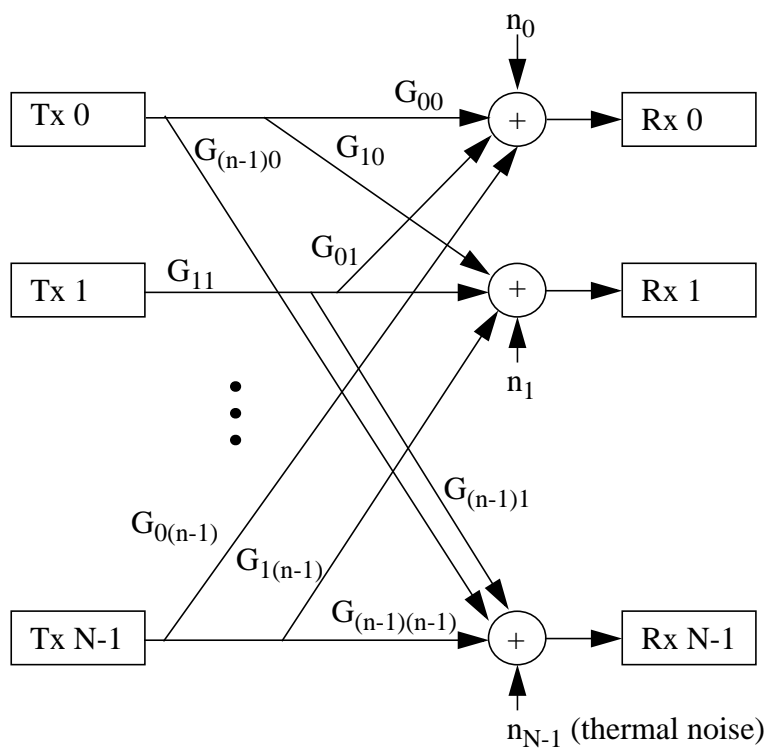
The links have signal-to-interference ratios:

$$i = \frac{P_i G_{ii}}{\displaystyle\sum_{j \neq i} P_j G_{ij} + N_i} \quad \text{for link } i = 0 \ldots N - 1 \tag{2.9}$$

where P_i is the power of the transmitter on link i and N_i is the power of the thermal noise.

In most systems, the interference channel will be divided into independent sub-channels or frequency bins. Each of these is considered to be a separate communications channel. A link may or may not see the same interferers on each sub-channel. The entire interference channel is characterized by a transfer function matrix and a noise vector for each sub-channel.

There are two major differences between wireless and wireline channels. First, the gain matrix, G, for wireless channels tend to vary much more quickly than wireline channels. Second, the amount of coupling between users, characterized by the off diagonal elements of G tend to be much smaller for wireline users. These difference affect both probing and bit allocation strategies.

2.4 Multiuser Channel Capacity

The concept of channel capacity was introduced by Shannon [50] as the definitive upper bound on the transmission rate over a communication channel. For Gaussian channels, it is easy to compute the capacity [17]:

$$C = W \log\left(1 + \frac{P}{N_0 W}\right) \tag{2.10}$$

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where P is the signal power, W is the bandwidth, and N_0 is the noise power per unit bandwidth. Recent developments in modulation and coding have demonstrated that it is possible to achieve rates that approach capacity on Gaussian channels. These methods are used in the telephone line modems we use every day.

The situation is more complicated for multiuser channels. First, for a multiuser channel there is not a capacity number, but rather a region of achievable rates with as many dimensions as users sharing the channel. Second, it is very difficult to compute the capacity of multiuser channels. In fact, the capacity of the interference channel (our system model) is unknown [17], although there has been significant progress in determining appropriate bounds [9][10][12][26]. At the present time, however, a direct evaluation of multiuser system performance with theoretical capacity is not possible.

2.4.1 Practical Restrictions on Signaling Format

The alternative to comparing a multiuser signaling algorithm to theoretical capacity is to compare new signaling algorithms to older ones. To make these comparisons fair, a set of practical capacity measures must be used that take into account the limitations of the signaling and detection methods used in real systems.

For wireless systems, it is assumed that some type of time and frequency division multiple access is employed. For frequency division multiple access (FDMA), the spectrum is divided up into orthogonal sub-channels on different frequencies. Each of these sub-channels is an independent interference channel. Since different sub-channels may have different propagation characteristics, there is often a benefit in

allowing each user to use each channel. This is accomplished with slow frequency hopping [51].

For ADSL wireline systems, it is assumed that discrete multitone transmission (DMT) is used. DMT divides the channel into 256 sub-channels on the downstream path (service provider to user) and 32 sub-channels on the upstream path (user to service provider). Every user shares every sub-channel and no time division is used.

Quadrature Amplitude Modulation (QAM) is the standard modulation format, and the maximum number of bits per symbol is:

$$b = \log\left(1 + \frac{\gamma}{\Gamma_{gap}}\right) \tag{2.11}$$

where γ is the signal-to-interference (SIR) level and Γ_{gap} is the gap between the system performance (required SIR for a desired bit rate) and the theoretical minimum SIR. In all cases it is assumed that a single user detector is employed and that the interference appears as Gaussian noise.

2.4.2 Practical Capacity of Interference Channels

For wireless cellular systems, one performance measure is the user capacity, which is defined as the offered load (in Erlangs) per cell that will yield a blocking probability of 1%. The assumptions are that user arrivals are random, independent, and uniformly distributed in space across the system. The arrival process is Poisson and the user hold times are exponentially distributed. Comparisons between systems assume that the number of channels (system bandwidth) is the same.

For wireline systems, capacity is measured with a revenue function for the system and algorithms are compared in terms of revenue. A typical revenue function has the form:

$$a = \frac{1}{N}\sum_i N_i R_i - \alpha N_d \qquad (2.12)$$

where N is the total number of users admitted to the system, N_i is the number of users admitted at rate class i with corresponding revenue R_i. N_d is the number of users dropped (forced out of the system by new users) and α is the weighting factor for dropping.

2.5 Dynamic Channel Allocation

Since the modulation and detection methods are fixed, wireless system capacity will be determined by the allocation of channels and power to users. A baseline system is the cellular system with fixed frequency re-use. Here channels are allocated by fixed patterns according to worst case interference conditions. Capacity can be increased by allocating channels and power to users in a more efficient manner. This process is called dynamic channel allocation (DCA) because channels are allocated to users as they need them.

In the fixed re-use cellular system, channel access is determined at the cell level and can be easily determined by the base station. If the channel is not currently in use, then it can be allocated to a user. With DCA, the assignment of channels to cells (and to users) is no longer fixed. The advantage of DCA is that it can employ an adaptive re-

use distance for each channel. Since most users are not operating under worst case conditions they can often tolerate a smaller re-use distance. Over the set of all users, the average re-use distance is reduced. This increases the number of users per channel, a common and important measure of system capacity.

The disadvantage of DCA is an increase in system complexity. Since channels are not directly allocated to cells, channel access can no longer be determined at the cell level. Sophisticated allocation techniques require a new user to be able to determine whether or not it is feasible to access a channel. Channel probing provides this information and consequently, DCA and probing must work together. In general, the probing algorithm is first applied to determine the channel characteristics. Next, a choice of channel allocation is made based on which channel (or group of channels) can best carry the required allocation of bits. Power control is then used to allocate the proper transmitter power to each user so that every SIR constraint can be met at all times.

2.6 Power Control

2.6.1 Fundamental Concepts

The objective of power control is to compute a power level for every user in order to meet a set of SIR constraints. This problem has been explored in [69]. In the general problem, individual users will have users different SIR constraints. In an N user

system the vector of SIR constraints for the users is $\gamma = \{\gamma_0, \gamma_1, ..., \gamma_{N-1}\}$ and the

vector of user transmitter powers is $p = \{p_0, p_1, ..., p_{N-1}\}$. Define a matrix H with

off-diagonal elements $(i \neq j)$ $h_{ij} = -\dfrac{\gamma_i G_{ij}}{G_{ii}}$ and diagonal elements $(i = j)$ equal to 1.

Also, define a noise vector n with elements $n_i = \dfrac{\gamma_i N_0}{G_{ii}}$. This term represents the

AWGN in the receiver scaled by the gain on the desired path and the SIR constraint.

The set of feasible solutions has the constraint:

$$Hp \geq n \qquad (2.13)$$

and the optimal solution (in terms of minimum power) is found when equality holds.

For a given gain matrix G and SIR requirement set γ, a feasible solution exists when:

$$det(H) > 0 \qquad (2.14)$$

and all principal minors of H are greater than zero. Under this condition, the all positive

optimal power vector is:

$$p^* = H^{-1}n \qquad (2.15)$$

2.6.2 Distributed Power Control

In a large system it is desirable to compute p^* in a distributed fashion. This has

been explored in [3][4][18]. In [4], the set of users is partitioned into an active group

that maintain their SIRs by a power update and a new-user group that increase their

powers in fixed steps until they either achieve the desired SIR level or give up. The power update equation for active users is:

$$p_i(n+1) = \frac{p_i(n)\delta\gamma_i}{r_i(n)} \qquad (2.16)$$

where $r_i(n)$ is the SIR measured by user i at time n, γ_i is the target SIR level and δ is a small constant greater than 1. New users initiate transmission at a very low power level and increase their powers in fixed steps:

$$p_i(n+1) = \delta p_i(n) \qquad (2.17)$$

Under this distributed algorithm, the SIRs of active users will be maintained between γ and $\delta\gamma$ and new user SIR levels will converge to a maximum feasible SIR level as n becomes large.

2.7 Summary

Future multiuser systems will incorporate both DCA and power control to help maximize capacity. (The acronym DPCA is often used for the combination of power control and dynamic channel allocation.) Recent work [65] in DPCA algorithms has yielded very high capacity algorithms that offer significant improvements over fixed allocation techniques. However, these algorithms require precise knowledge of the achievable SIR level for each user. They also require precise power control to insure that every user can maintain its SIR level. In a complex communication system, such as a cellular or a PCS network, it would be difficult for a central controller to measure and

maintain all the information necessary to implement the next generation of DPCA algorithms. The fact that these algorithms work best when each user employs frequency hopping (or another method to access multiple channels) makes the implementation problem even more difficult.

The solution to the complexity problem lies in distributed algorithms. The distributed power control algorithm mentioned above is well understood and can achieve virtually the same accuracy as centralized power control in a wide variety of environments. The next step is to make the entire channel allocation and user admission process distributed and yet retain the capacity of the new DPCA algorithms. This can be achieved with channel probing.

Channel probing assumes that each active user in a multiuser system will employ distributed power control to maintain its SIR level. New users probe each channel at low power to determine the maximum feasible SIR level that they can achieve without disturbing the active users. This information is then applied to a DPCA algorithm. Once a channel (or set of channels) is selected, the new user admits itself directly to the network. No centralized control is needed.

Research in channel probing consists of developing algorithms and exploring how well they work. The algorithms discussed in the next three chapters have been tailored for different wireless and wireline systems. In some systems it is possible to accurately measure signal and interference power levels while in others it is not. This influences both the channel allocation algorithm and also the probing method. When it

is possible to precisely measure the channel it is also possible to probe very accurately and achieve a very well engineered system. When accurate measurements are not possible, the probing algorithm will use a heuristic that tries to balance the goals of rapid response and good admission decisions.

Chapter 3

Probing Power Controlled Channels

This chapter explores the fundamental algorithm for channel probing and the limitations on its accuracy. The emphasis is on communication systems where the channel is very stable relative to the symbol rate. In these systems, the gain matrix, G, will remain constant long enough for users to estimate the important parameters and choose a channel and power allocation. Stable channels include indoor wireless channels and ADSL wireline channels. For these channels, it is possible to perform precise bit allocation using the channel probing information.

3.1 Probing for Maximum Feasible SIR

In Section 2.6 the concept of a feasible set of SIR constraints was introduced. For distributed power control to operate properly, each user must pursue an SIR constraint, γ_i, that is feasible. To simplify the choice of SIR level, each user is forced

to select a level at admission time. It is assumed that the channel is currently occupied by other users that are operating with distributed power control. When a user enters the system it is only allowed to select an SIR level that is less than the maximum feasible level, given the other user SIR constraints. This way the active users on the channel are always driving the distributed power control to a feasible solution.

The maximum feasible SIR level that a new user can obtain on a power controlled channel is:

$$\gamma_{max} = \frac{G_{ii}(p_1 - p_0)}{q(p_1) - q(p_0)} \qquad (3.1)$$

where p_1 and p_0 are two different transmitter powers, $p_1 > p_0$, G_{ii} is the gain on the signal path, and $q(p_1)$ and $q(p_0)$ are interference measurements made while transmitter power levels p_1 and p_0. This result was first approximated in [27] and later shown to be exactly true in [65].

The initial power level, p_0, can be set to zero and the probing result still holds. In fact, with this information, the new user can also compute $r(p)$, its SIR level at transmitter power p:

$$r(p) = \frac{p G_{ii} \gamma_{max}}{q(0)\gamma_{max} + p G_{ii}} \qquad (3.2)$$

The probing solution for $r(p)$ is identical to what the new user would achieve by increasing its power according to equation (2.17) to p and then waiting for the

distributed power control algorithm to converge completely. However, the probing solution offers several advantages. First, probing can be performed much more quickly. This is important if several channels must be probed to determine which is the best for bit allocation. Second, the probing can be performed at a very low power. This prevents excessive interference to active users if the channel turns out to be very congested.

3.2 Probing Accuracy

The accuracy of channel probing is critical because it places a fundamental limit on the performance of any DPCA algorithm that uses the probing results. When the probing result is in error, the DPCA algorithm may choose the wrong channel or allocate the wrong constellation size to a channel. This results in a loss in capacity relative to a system where perfect measurements are possible. In a dynamic environment, probing errors are inevitable even if the measurement technique is optimal. This section explores the sources of probing errors and discusses ways to limit them in practice.

Channel probing depends on both the accuracy of signal and interference measurements and on the accuracy of the underlying channel model. It is assumed that the channel varies extremely slowly relative to the symbol rate of the system. This assumption is necessary in order to measure received power, received interference, and the channel gain. If the channel varies on the order of the symbol rate, such as in a low data rate mobile system with rapid Rayleigh fading, distributed power control is only possible with averaging over the fading. In this case a different power control strategy

is needed and precise channel probing is not feasible.

It is also assumed that the channel gains vary slowly with respect to the power control update rate of the system. This assumption is necessary to insure convergence of the distributed power control. The results in Section 3.2.1 and Section 3.2.2 depend on exact convergence. In mobile radio systems, however, shadowing and other effects can limit the ability of the power control to track the channel. When this occurs the effectiveness of channel probing becomes limited and a different strategy must be employed. A method for implementing DPCA under these conditions is discussed in Chapter 4.

3.2.1 Estimation With Coherent Detection

A coherent receiver allows the probing user to make accurate measurements of the maximum feasible SIR on the power controlled channel. The system model in Figure 3-1 is assumed.

Automatic gain control (AGC) is employed to compensate for the transfer function of the channel. A known probing sequence is transmitted to the receiver or, if the SIR is high enough, a decision based loop is used to adjust the AGC. In either case, it is assumed that the knowledge of the channel gain is perfect and gain errors will not be introduced into the estimate of the interference power. To compute the estimate of γ_{max}, the transmitter sends a probing signal at the initial power level. The receiver waits until the interference power on the channel has settled and then begins the measurement

of its first interference power estimate, $\hat{q}_1$. The interference power is averaged over a

frame of length N and stored.

Figure 3-1   Interference Power Estimation
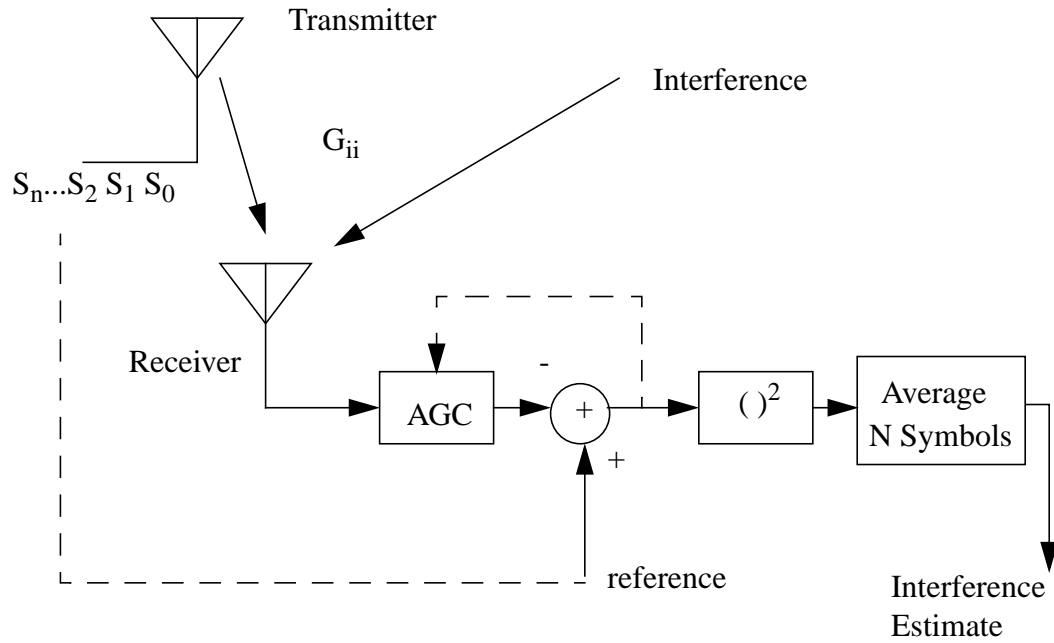
The transmitter then increases its power by a factor δ. Once again the receiver

waits until the interference power on the channel has settled and then it measures the

second estimate, $\hat{q}_2$. The received signal powers are computed from the AGC settings,

yielding s_1 and s_2. The maximum feasible SIR estimate is computed with:

$$\hat{\gamma}_{max} = \frac{s_2 - s_1}{\hat{q}_2 - \hat{q}_1}$$

(3.3)

To simplify the error analysis, the inverse of $\hat{\gamma}_{max}$ is used. Let $B = \gamma_{max}^{-1}$ and let $\hat{B}$ be

the estimate of B. Then,

$$\hat{B} = \left(\frac{1}{(\delta - 1)s_1}\right)(\hat{q}_2 - \hat{q}_1) \tag{3.4}$$

If the interference seen at the receiver is Gaussian, then the interference estimates and $\hat{B}$ will be chi-square distributed [45]. Using this fact:

$$E[\hat{B}] = B \tag{3.5}$$

$$Var[\hat{B}] = \frac{2B^2}{N}\left[1 + \frac{2q_2 q_1}{(q_2 - q_1)^2}\right] \tag{3.6}$$

Therefore, the estimate of B is unbiased and depends on the frame length used for the estimates and the change in interference level between the two estimates. Since the estimate is unbiased, the variance is the same as the mean-square error (MSE). Making the substitution, $q_2 = (1 + \varepsilon)q_1$ the normalized root-mean square (RMS) error is:

$$Error = \sqrt{\frac{2}{N}\left(1 + 2\frac{(1 + \varepsilon)}{\varepsilon^2}\right)} \tag{3.7}$$

The error in the estimate of the maximum feasible SIR is due to the size of the frame used to make the estimate and the gap in interference level between two measurements. This fact can be exploited to allow new users to know how accurate their estimates of γ_{max} will be. After making an initial measurement of the interference power, the new user can increase its transmitter power until it measures a change in interference that is large enough for an accurate estimate. If, after increasing the probing power by several decibels, the interference does not increase, the new user will

know that any practical SIR level will be feasible.

3.2.2 Estimation Without Detection

Sometimes it is desirable to probe the channel at a very low SIR level. For a low

power probe, it might be impossible to provide carrier synchronization, symbol

synchronization, or accurate decisions. However, it is still possible to probe the channel

with a series of power measurements. It is assumed that a square law detector is used to

measure power, and the results are averaged over multiple symbols to improve the

accuracy. Since there is no symbol detector to separate the received signal from the

interference, it is necessary to provide a way for the receiver to make several different

measurements. It is also assumed that the system will allow the probing user to measure

the receiver noise, desired signal plus receiver noise, and the interfering signal plus

receiver noise on separate channels or segments. This is possible if synchronization

information is made available on a setup channel.

The receiver noise is averaged over N_1 symbols and stored in r_1. The

transmitter turns on its higher power setting and the receiver averages N_1 symbols and

stores the result in r_2. As before, the new user measures interference levels $\hat{q}_1$ and $\hat{q}_2$

by averaging over N_2 symbols. The received signal power is estimated with:

$$\hat{s}_2 = r_2 - r_1 \tag{3.8}$$

and the inverse of the maximum signal to interference ratio is:

$$\hat{B} = \left(\frac{\delta}{(\delta-1)\hat{s}_2}\right)(\hat{q}_2 - \hat{q}_1) \tag{3.9}$$

This is the same as equation (3.4), except that the larger signal power measurement is used because it will have a smaller error. The estimate of the signal power is unbiased ($E[\hat{s}_2] = s_2$) and its variance is a function of the receiver noise power, σ_n^2, and the number of symbols used in the estimate:

$$Var[\hat{s}_2] = \frac{4}{N_1}s_2\sigma_n^2 + \frac{4}{N_1}\sigma_n^4 \tag{3.10}$$

This holds true for any zero mean signal that is not correlated with the receiver noise. To compute the statistics of the estimate $\hat{B}$ the approximation from [41] is employed:

$$E[g(x)] \cong g(\eta_x) + g''(\eta_x)\frac{\sigma_x^2}{2} \tag{3.11}$$

where η_x and σ_x^2 are the mean and variance of x. The expected value of the probing estimate is:

$$E[\hat{B}] \cong B\left(1 + \frac{4\sigma_n^2}{s_2 N_1} + \frac{4\sigma_n^4}{s_2^2 N_1}\right) \tag{3.12}$$

which shows that the estimate is asymptotically unbiased. An approximation of the RMS error is:

$$rror \cong \sqrt{\frac{2J}{N_2} + \frac{4\sigma_n^2}{s_2 N_1} + \frac{4\sigma_n^4}{s_2^2 N_1^2} + \frac{24J\sigma_n^2}{s_2 N_1 N_2} + \frac{24J\sigma_n^4}{s_2^2 N_1^2 N_2}} \tag{3.13}$$

where $J = 1 + 2\dfrac{(1 + \varepsilon)}{\varepsilon^2}$ and $\varepsilon = \dfrac{q_2}{q_1} - 1$ as in the error estimate for the coherent

detection.

To compare the two probing methods, assume that a probing segment is used at

the beginning of each frame and it occupies 10% of the frame length. Also assume that

the signal to noise ratio (SNR) for the signal is 0 dB. Substituting $N_2 = 0.9N$,

$N_1 = 0.1N$, and $\dfrac{\sigma_n^2}{s_2} = 1$ into equation (3.13) yields:

$$rror = \sqrt{\frac{2.222J + 40}{N} + \frac{266.7J + 400}{N^2} + \frac{2667J}{N^3}} \qquad (3.14)$$

A plot of the estimation error in dB for the two probing techniques is given in

Figure 3-2. The top two curves show the error for a change in interference level of 0.25

dB and the lower two curves show the error for a change in interference level of 2.0 dB.

From these curves it can be seen that for $N > 100$ the difference between the two

probing techniques becomes small compared to the error. This implies that estimating

the channel gain without symbol detection does not introduce a significant error if N

can be made sufficiently large. For $N = 10^4$ it is possible to estimate the maximum

feasible SIR within 1.5 dB. Thus, for stable channels it is possible to probe the power

controlled channel very accurately.

Figure 3-2   Probing Error Due to Interference Estimation
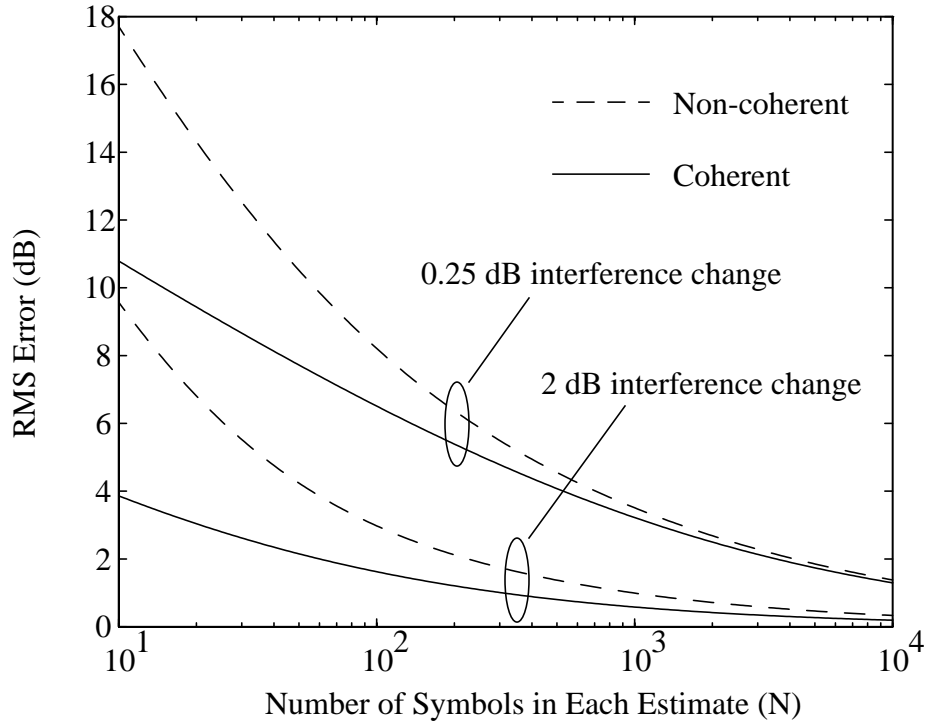
3.2.3 Effect of Distributed Power Control

Another source of error for channel probing is the convergence of distributed power control. Channel probing requires precise measurements of interference from the active users. If the interference levels are changing because of the distributed power control algorithm, this will lead to errors in the estimate of γ_{max}. To completely avoid these errors, the probing user must wait for the interference level to converge completely. Since this may not be practical, a bound on the error due to power control convergence is derived.

From [4] we know that the distributed power control will converge whenever

there exists a feasible solution for equation (2.13). However, the rate of convergence depends on matrix H. The distributed power control algorithm is equivalent to a matrix update equation for the power vector:

$$p(k+1) = Fp(k) + n \qquad (3.15)$$

where

$$F = I - H \qquad (3.16)$$

and I is the $N \times N$ identity matrix. When a new user probes the channel the active users see a change in the background interference level and adjust their powers upward to compensate. The interference seen by the new user is the inner product of $p(k)$ and a vector of transfer functions from the active users to the new receiver, $g_n = [g_{n0}, g_{n1}, ..., g_{n(N-1)}]^T$. Consequently, the interference level follows the convergence rate of the current set of active users. When probing we may assume that the active users have converged completely for the first interference measurement. The new user then turns on its transmitter power and waits m steps before measuring the second interference level. The difference in the interference measurements is:

$$q_2(m) - q_1 = g_n^T[I - F^m](p_2 - p_1) \qquad (3.17)$$

and as m becomes large, $F^m \to 0$ and the difference will increase uniformly to the desired result:

$$g_n^T(p_2 - p_1) \qquad (3.18)$$

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Using the Holder inequality [30], the absolute error at step m can be bounded by:

$$rror \leq \|g_n\|_\infty \|F\|_1^m \|p_2 - p_1\|_1 \tag{3.19}$$

In many systems, the change in interference will be dominated by the change in power of the strongest interferer. We can then make the substitution:

$$\|g_n\|_\infty \|p_2 - p_1\|_1 \;=\; C g_n^T (p_2 - p_1) \tag{3.20}$$

where C is a small constant greater than 1. Then, the normalized error is bounded by $C\|F\|_1^m$. As m becomes large, the error can also be bounded by the spectral radius (largest eigenvalue) of F, however this result is less useful for probing since the goal is to keep m as small as possible.

The error result has several implications. Unlike the errors due to estimation of interference power levels, the error due to power control convergence cannot be reduced by increasing the difference in transmitter power between each probing step. Also, as active users choose their SIR targets closer to the maximum feasible, the norm of F will increase, convergence will slow down, and accurate probing will take longer.

To measure the probing error in due to convergence, a 19 cell wireless system with multiple channels and slow frequency hopping was simulated. We assumed that interference measurements are averaged over frames long enough to make the measurement error insignificant. Consequently, any errors due to interference estimation are ignored. Distributed power control is used and probing users wait from 2 to 6 steps for the power control to converge before making measurements.

The measurement procedure is as follows. A new user enters the system and probes 23 channels at low power. It then stores those results and slowly increases its power according to equation (2.17) for 75 steps. It then compares its current SIR level on each channel with the probing estimates. The results are given in Figure 3-3.

Figure 3-3   Probing Error from Power Control Convergence
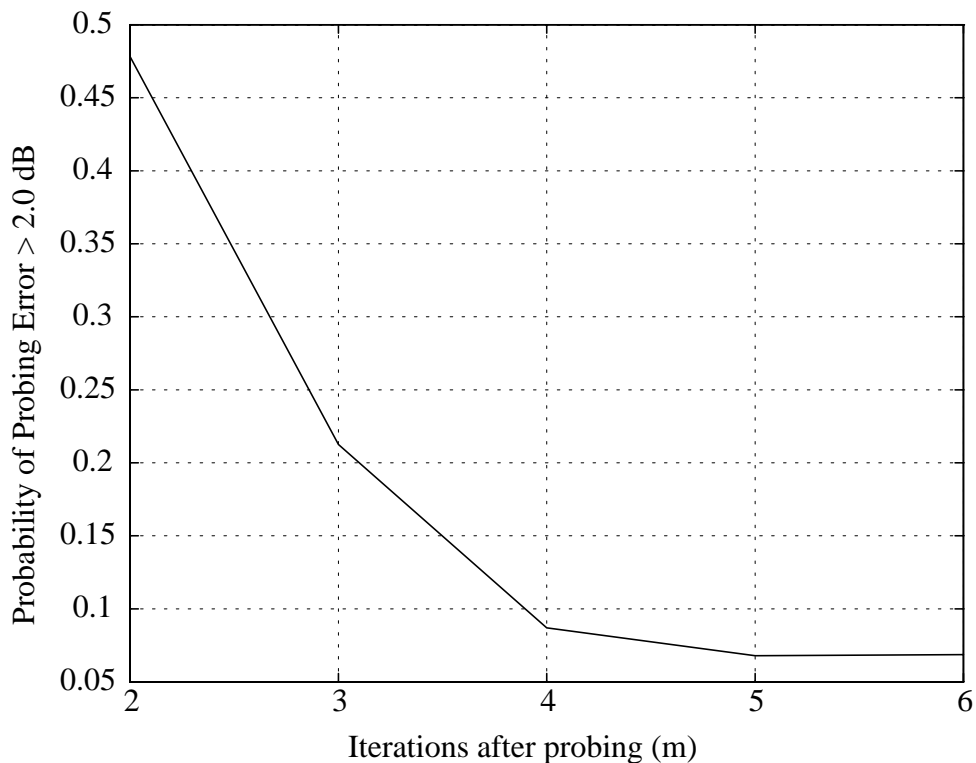
The probability of a probing error greater than 2 dB is plotted as a function of the number of steps, m. For $m > 5$ the error rate no longer decreases, indicating that additional convergence time does not improve the probing estimate significantly. Since error due to power control convergence must decrease with increasing iterations, the residual error is not due to power control convergence. Therefore, we conclude that the

convergence error is negligible for $m > 5$.

3.2.4 Effect of User Dynamics

The last probing error we investigate is the effect of user dynamics, the entry and exit of users from the system during probing. There are several specific errors that fall into this category. For example, two or more users may probe the channel at the same time causing inaccurate estimates of γ_{max}, or, a user might exit the system while a new user is making interference measurements. In the latter case, the interference may actually drop during probing which leads to a completely erroneous result. In general, errors of this type can be reduced or eliminated if probing can be done quickly relative to the dynamics of the system. Of course, any probing result will be out of date once an active user leaves the system. However, if probing is used as part of an admission control procedure, active users will be able to maintain the SIR levels and bit allocations they determine from probing.

To measure the probing error due to user dynamics, the simulation program described in Section 3.2.3 is used. The new user waits $m = 5$ iterations after probing to eliminate convergence errors. The resulting probing error is then assumed to be entirely due to user dynamics. The new user stores the probing results and slowly increases its power according to equation (2.17) for 75 steps. It then compares its current SIR level on each channel with the probing estimates.

The entire interval from initial probing to final SIR measurement is called the

probing interval. After the probing interval, the new user is admitted to the system as an active user, where it maintains target SIR levels on a subset of the channels with distributed power control. The active time in the network is an exponentially distributed random variable. The average active time was varied over several simulation runs to evaluate the effects of user dynamics. Figure 3-4 presents a plot of the simulation results.

Figure 3-4   Channel Probing Performance
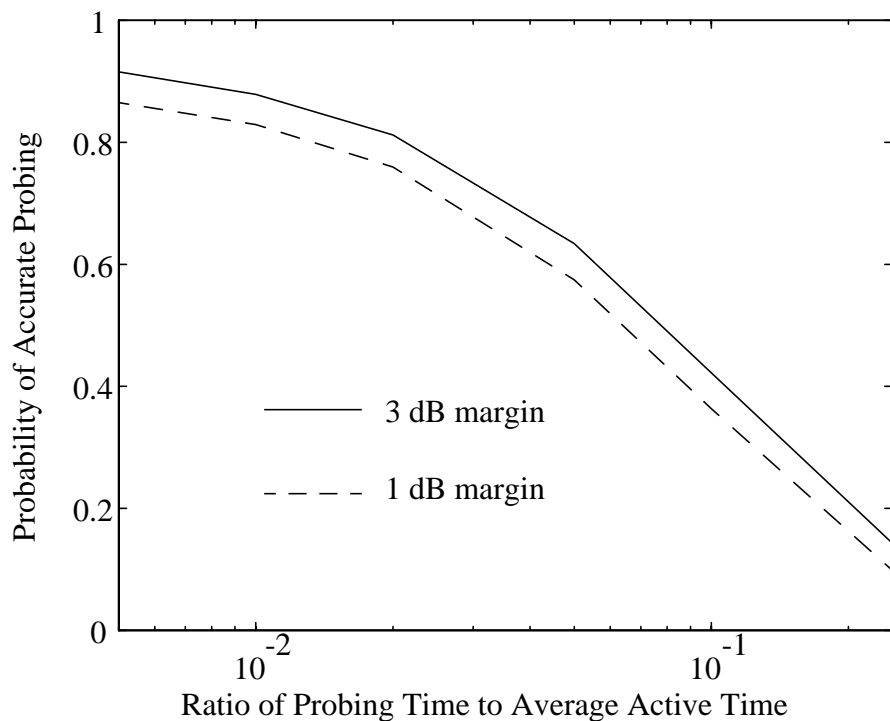
As the ratio of probing time to active time approaches 1%, the user will be able to probe within 3 dB of the correct SIR level about 85% of the time and within 1 dB about 80% of the time. An error of 3 dB is significant, because that corresponds to the

power change to allocate an additional bit for systems that employ multiple constellation sizes. When the probing errors are below this amount we know the system is accurate enough to make bit allocation decisions as part of an admission algorithm.

3.3 Application of Probing to Indoor Wireless Systems

Sophisticated DPCA algorithms for indoor wireless applications have been developed based on adaptive bit allocation [65]. Of these algorithms, the best performing is a minimum hop interference avoidance strategy. With this strategy, each user must allocate a set of M bits over a group of N frequency hops with the minimum number of hops possible. If a feasible allocation cannot be found, the user is blocked.

The minimum hop strategy achieves high capacity by allowing users to adapt to the actual interference conditions. Users near the base station can use a few slots at high SIR levels and achieve very high re-use factors. At the same time, users at the cell edge. can use more channels at a lower SIR level. Power control limits the power of each user to the minimum necessary for communication.

3.3.1 Simulation of System with Probing

The results in [65] were based on a centralized implementation of the interference avoidance DPCA algorithm. We present new results to demonstrate that this algorithm can be implemented in distributed fashion with channel probing. The capacity loss in the distributed version of the algorithm is caused by probing errors and

power control inefficiencies that occur with distributed power control (DPC). The simulation helps to quantify this capacity loss. The specifications of the system we simulated are given in Table 3-1.

Table 3-1: Frequency Hopped System with Probing

Channels	23
Constellation sizes	0, 2, 3, 4, 5, or 6 bits/ symbol
Γ (SIR gap)	4 dB
Average bits/symbol	2.17 (50 bits / 23 hops)
Propagation Loss	R^{-3}
Shadowing	10 dB standard deviation
Number of Cells Simulated	19

The frequency hopping patterns for each user are determined by a group coincidence system [65] in which a user sees interference from the same set of users in each hop. Interference is avoided by the choice of channels that each user makes at admission time. New users admit themselves with the following algorithm:

1. If no hopping pattern is available, block user. Otherwise continue.

2. Select a hopping pattern that is free and has not been probed previously.

3. Probe all hops to determine γ_i and b_i terms.

4. If total number of bits < 60 (50 + 10 bit safety margin) mark this hopping

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pattern as unusable and go back to step 1. Otherwise continue.

5. Allocate bits to channels starting from highest to lowest γ_i.

6. Follow power update equation (2.17) for each channel until SIR level is achieved.

7. Admit user to the system and use DPC equation (2.16) to maintain SIR level.

3.3.2 Simulation Results

Figure 3-5 is a plot of the blocking probability of the distributed DPCA system with channel probing as a function of Erlang load. Two different simulation runs are included. The fast run has probing times 1% of the user active time and the slow run has probing times of 0.06% of the user active times. These correspond to the operation when probing is very accurate. For comparison, the performance of the centralized algorithm is included in the plot. The fast run has 84% of the Erlang capacity of the centralized system while the slow run has 91%.

The capacity of the distributed system is less than the centralized system because errors force the distributed system to test for more bits (the safety margin) than necessary to insure that it can be admitted to the system. However, this loss is small compared to the gains from dynamic channel allocation and power control. A fixed channel system (without frequency hopping) with the same bit load and number of channels would have about 1/5 the Erlang capacity of the distributed system.

Figure 3-5   Performance of Indoor Wireless Systems
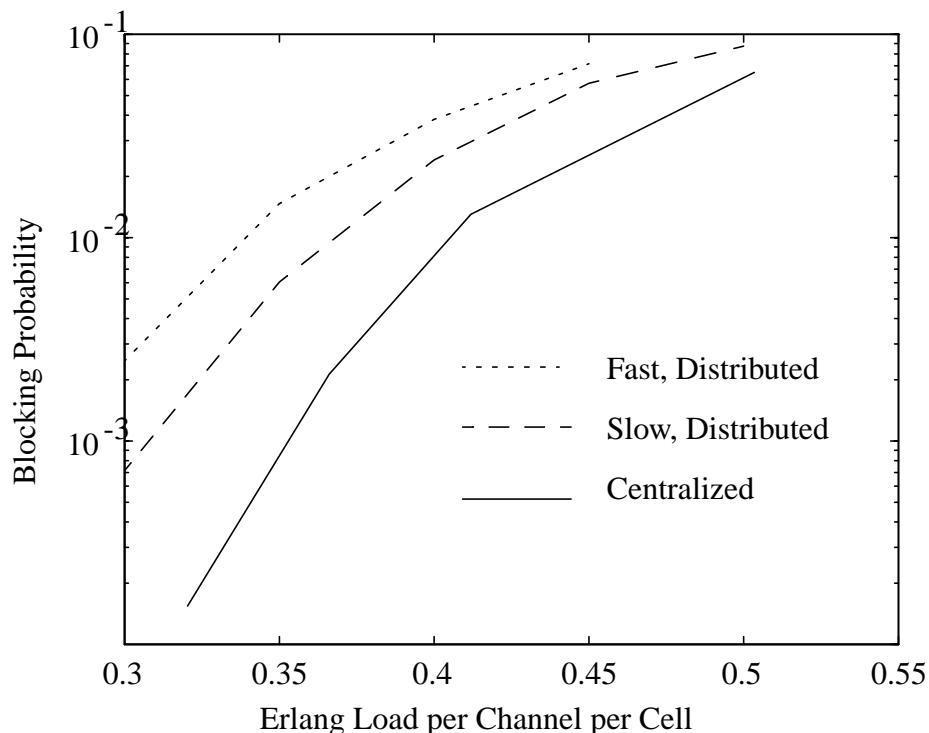
3.4   Application of Probing to ADSL Wireline Systems

In the indoor wireless system explored in Section 3.3 the goal of the access

algorithm was to admit as many users as possible, with each user sending data at the

same rate. For the ADSL system, however, the goal is to maximize the average bit rate

or a cost (revenue) function over bit rates of users that occupy the channel. The number

of links that can be supported is fixed by the number of twisted pairs in the cable bundle.

However, users can be offered different bit rates depending on the transmission

characteristics of the channel.

3.4.1 Distributed Access for Wireline Systems

The distributed access method for the wireline system is very similar to its wireless counterpart. A new user first probes the channel for the maximum possible SIR level and bit rate on each frequency bin. Next, it determines the maximum rate class that it can achieve from the total number of bits it can allocate. It then chooses a bit allocation that will achieve that rate class, increases the transmitter power on each bin to the necessary level and initiates data transmission. Once active, it maintains the SIR levels on each frequency bin through distributed power control. The different rates are shown in Table 3-2. Rates 1 through 4 are defined in the ADSL standard [55] and rates 5 through 7 were added for cases where significant improvement is possible with probing.

Table 3-2: ADSL Rate Table

Class	Upstream Rate (Kbps)	Downstream Rate (Kbps)
1	192	1536
2	384	3072
3	576	4608
4	768	6144
5	960	7680
6	1152	9216
7	1344	10752

With probing and power control, active users always maintain their SIR levels and consequently dropping does not occur. Therefore, the system revenue can be

simplified from equation (2.12) to:

$$R_a = \frac{1}{N}\sum_i N_i R_i \qquad (3.21)$$

where N is the total number of users, N_i is the number of users admitted at rate class i with corresponding revenue R_i. Revenue can be set to equal the bit rate of the class. Revenue is maximized by allowing each user to transmit data at the highest rate possible, subject to the constraints of interference at admission time. Like the bit allocation problems explored in [65], an optimal revenue maximizing algorithm would require an exhaustive search over the space of feasible bit allocations. Since a search of this type is not practical, the admissions based algorithm seeks to maximize the aggregate revenue by each user maximizing its own bit rate, subject to the current channel constraints.

3.4.2 ADSL Simulation

A simulation program was developed to compare the performance of the probing system against the present ADSL system. As mentioned in Section 2.2.3, the present ADSL system uses a form of fixed allocation. Users allocate a constellation size to each bin according to the received signal level on that bin and an assumed fixed interference level. The interference level represents the 1% worst case cross talk level based on measurements of real cables [38].

The probing algorithm used in the ADSL simulation is the same as for the wireless simulation. The bit allocation algorithm is slightly different, however. In the

wireless system, the goal was to minimize the total number of channels that were used for the bit allocation. For the wireline system, it is assumed that every user will allocate bits on every available channel. Therefore, the goal is to minimize the excess interference on each channel. The bit allocation starts by allocating as many bits as possible and then removes bits starting with the channel with the least SIR margin until the target number of bits has been reached. The complete algorithm is:

1. Probe all frequency bins to determine γ_i and b_i terms.

2. Total the b_i terms to compute the maximum feasible rate class.

3. Sort frequency bins according to excess SIR over that needed for allocated constellations.

4. Repeat step 5 until the total number of allocated bits equals that necessary for the rate class in Step 2.

5. Decrease the bit allocation in the frequency bin with the smallest excess SIR by one bit.

6. Follow power update equation (2.17) for each bin until SIR level is achieved.

7. Admit user to the system and use DPC equation (2.16) to maintain SIR level.

The simulation system parameters follow the ADSL standard as closely as possible. A complete listing of the system parameters is given in Table 3-3.

Table 3-3: Simulation Parameters

Duplexing method:	Frequency division
Upstream bins allocated:	7 through 31
Downstream bins allocated:	32 through 255

Bits allocated per bin:	2-15, or zero
Bit allocation SIR margin:	12 dB (8 dB + 4dB coding gain)
	6 dB (2 dB + 4dB coding gain)
P_0 (initial probe power)	-60 dBm/Hz (bins 1-50)
	-54 dBm/Hz (bins 51-255)
N (probing steps)	14
δ (distributed power control margin)	2 dB
Maximum Power	-40 dBm/Hz (bins 1-50)
	-34 dBm/Hz (bins 51-255)
K_F mean	-78.1 dB
K_F standard deviation	11.17 dB
FEXT power sum K	-45.0 dB

The simulation program generates an interference channel model of 48 twisted pairs using the FEXT model in equation (2.5). NEXT is not included in the simulation because the upstream and downstream paths use frequency division duplexing and therefore will not see any NEXT. The frequency response of each twisted pair is a Bellcore standard loop [5] and the coupling is determined by the gamma distributed FEXT interference. Gamma distributed random numbers are generated with an algorithm derived from [35].

As with the wireless system, user arrivals to the network are Poisson distributed and the hold times are exponentially distributed. For each simulation run the load was set to 36 Erlangs, yielding a blocking probability of 1% and an average load of about

36 simultaneous user pairs.

3.4.3 Simulation Results

The simulation program was run for Bellcore standard loops number 1, 7, and 8. These are representative of the worst case conditions which an ADSL system would see in practice. The fixed allocation system is compared with two probing systems, one with a 12 dB SIR margin and the other with a 6 dB SIR margin. The fixed allocation system operates with a 12 dB margin because sometimes the interference level will be worse than the target used for bit allocation. This will not occur with the probing algorithm, however, because power control will maintain every user SIR at the level determined at admission time. Consequently it is possible to reduce the SIR margin without risk of an unacceptable low SIR level due to future users on the same cable.

The results are plotted in Figure 3-6 and summarized in Table 3-4. Even with a 12 dB safety margin, the probing system could out-perform the fixed allocation system in most cases. This demonstrates the effectiveness of probing and adaptive bit allocation for the ADSL wireline system.

Table 3-4: ADSL Revenue Summary

Loop	Fixed Allocation Revenue	Probing with 12 dB Margin Revenue	Probing with 6 dB Margin Revenue
1	4608	6091.2	7664.1
7	4608	4609.6	6142.1
8	4608	4590.2	6129.5

Figure 3-6   ADSL Simulation Results

6dB SIR Margin

12 dB SIR Margin
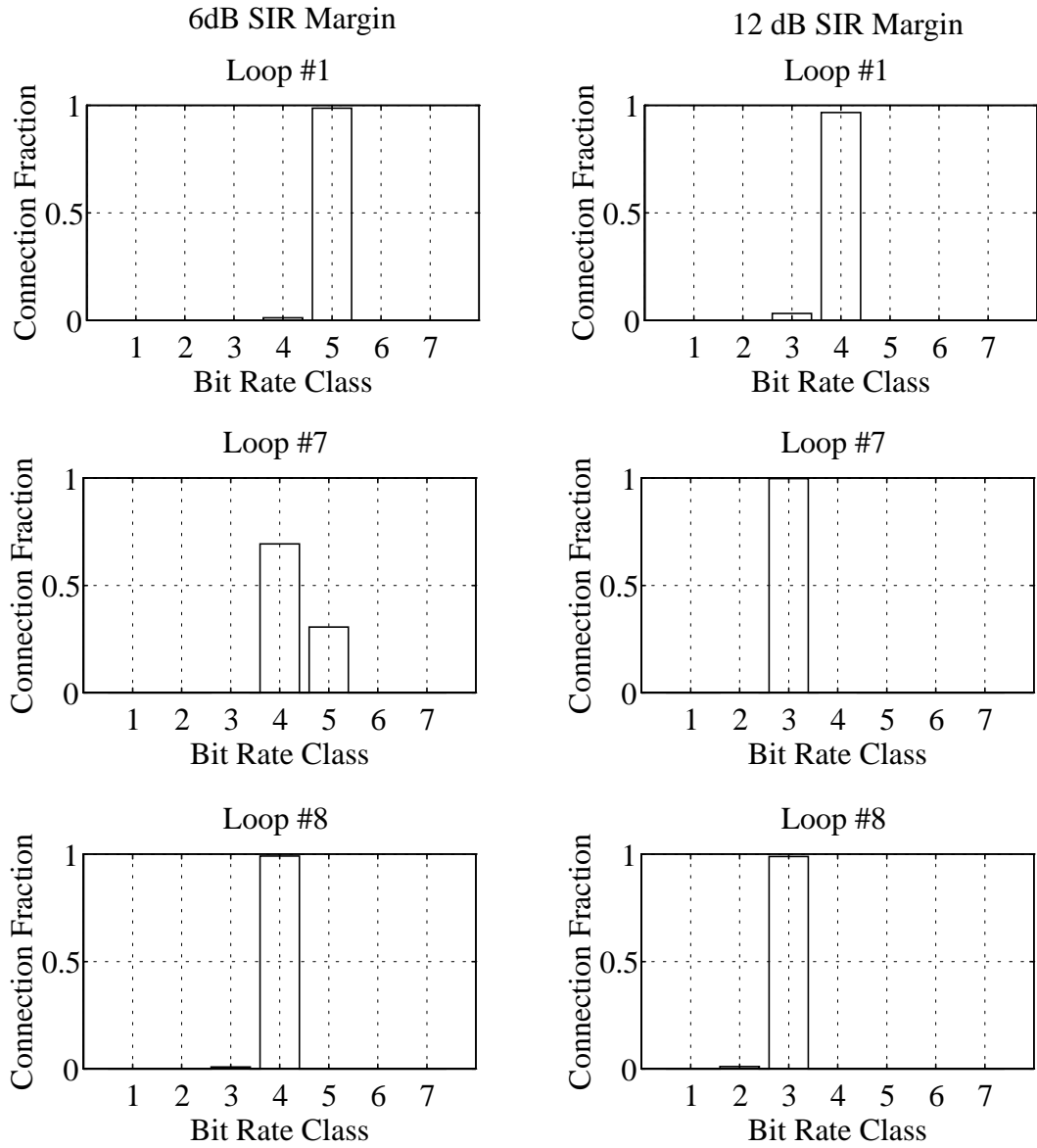
In general, the power controlled ADSL system with probing allowed each user

to increase its data rate by slightly more than one rate class, or roughly 1.5 Mbps. This

is equivalent to increasing the average constellation size by 1.5 bits on each bin. For

comparison, the gain achieved by channel coding is 6 dB, or 2 bits per symbol per

frequency bin. While significant, this performance gain is not as dramatic as that achieved with the addition of probing and DPCA to the wireless system.

The primary benefit of probing and distributed access for wireline systems is that, like coding, they can provide an increase in bit rate (and revenue) without an increase in system complexity. Power control and bit allocation functions can be encapsulated in the ADSL modem hardware. Since each user makes its own probing and allocation decisions independently, there are no changes required in system software.

3.5 Summary

Channel probing can be successfully applied to multiuser systems when it is possible to make very accurate signal and interference measurements. Accurate measurements are possible when three conditions are met: the system symbol rate is rapid compared to the rate at which channel gains vary (either due to fading or mobility), adequate time is allowed for distributed power control to converge completely, and user dynamics are slow enough for probing information to be up to date by the time it is applied. These conditions are met for both high bit rate indoor wireless systems and the DMT ADSL wireline system.

Power control and dynamic channel allocation provide the most benefit in systems that are strongly interference limited with users sharing multiple channels. This fact was demonstrated in [65] and has been verified by the results in this chapter. Wireline systems such as ADSL are limited by maximum constellation sizes and power

limits in addition to interference, so they will not benefit as much from dynamic channel allocation and power control as wireless systems. For congested systems, however, the addition of probing, power control, and distributed access can provide higher bit rates and higher revenue for system providers.

Chapter 4

Probing Time Varying Channels

The goal of the previous chapter was to make probing as accurate as possible so individual users could make precise bit allocation decisions. This allowed a system with distributed, dynamic channel allocation to approach the capacity of a centralized system. Unfortunately, this approach will not work when the channel varies faster that it can be estimated. Power control becomes less precise and probing will not be accurate enough to provide bit allocation information. A new algorithm that can produce quick results is required. This chapter explores a faster alternative to precise probing that is more suited to systems with channels that vary. Fast probing is applicable to mobile radio (cellular telephone) and other systems where the radio transceivers are assumed to be moving.

In a power controlled cellular system, the users near cell boundaries transmit the highest power and contribute the greatest amount of interference to users in other cells.

This causes a coupling effect in the network where changes in the interference level in one cell can affect the interference level in other cells that are far away. Coupling can be expressed quantitatively as $\|F\|$, the magnitude of the power control matrix update in equation (3.15). High coupling corresponds to large off-axis terms in F that tend to raise the magnitude [25]. High coupling is undesirable because it will slow the convergence of the power control algorithm and limit its ability to track changes in the channel characteristics. However, since users on the cell boundary experience the largest propagation losses to their base stations, they are forced to operate at or near their maximum power level. Consequently, they do not benefit from power control. These "worst case" users can be moved to fixed assignment channels to reduce the coupling effect. Meanwhile, other users can operate in power controlled channels to yield the capacity advantages of dynamic power and channel allocation. The technique of using two different channel types is called channel partitioning.

Since the channel is varying relatively quickly, it is natural to assume that users will not be able to assign different constellation sizes based on the instantaneous SIR. Rather, they will choose either to use the channel or not, based on whether a fixed minimum SIR level is feasible. The probing problem is then transformed into a problem of finding the best channel to use as quickly as possible. In the worst case, if no power controlled channel can be found, the user can remain in a fixed assignment channel.

The partitioned channel system is especially useful for a cellular mobile system with hand-off. Fixed assignment channels speed the hand-off process, since users do

not need to find a power controlled channel immediately when entering a new cell. Also, since new users enter the cell at the boundary, a fixed channel is the appropriate choice. As the user moves away from the boundary, it switches to a power controlled channel to minimize interference.

4.1 Channel Partitioning for Mobile Radio

4.1.1 Channel Partitioning Concept

The cellular system channels are partitioned into two sets, reserved and regular. Reserved channels are assigned to base stations with fixed re-use patterns as described in Section 2.1.2. Regular channels are assigned to every base station and allocated to users by a distributed access algorithm. New users and active users that require large re-use distances occupy reserved channels. All other users occupy regular channels.

There are two operating states for users, probing and active. In the probing state, a user transmits data on a reserved channel while probing a regular channel. In the active state, a user transmits data on a regular channel while applying distributed power control to maintain its SIR. New users enter the network in the probing state and migrate to the active state while transmitting data continuously. Probing is performed in a short segment of each transmission frame so that it will not interfere with data transmission, as illustrated in Figure 4-1. The segmented approach also allows operation with one transmitter and one receiver, minimizing the complexity of the mobile transceiver.

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The purpose of channel partitioning is to provide continuous user access while achieving a high level of frequency re-use due to power control. It has higher capacity than fixed re-use systems since most users operate in power controlled channels. The reserved channels allow new users to instantly transmit data instead of waiting for the power control algorithm to find a solution, as is necessary with the algorithms described in Chapter 3. While transmitting on a reserved channel, the new user probes regular channels until it finds one where it can achieve the necessary SIR. If the pool of available reserved channels is full, a new user is blocked. This can be determined instantly, and the user can then make the choice to try again or give up.

Figure 4-1   Signal Frame Format

Probing State

Regular Channel	Reserved Channel

Active State

Regular Channel	Regular Channel

Probing Segment	Transmission Segment

The channel partitioning system also provides a mechanism for hand-off with power control. When a hand-off becomes necessary, the user moves from a power controlled channel in the old cell to a reserved channel in the new cell. The user then probes for a power controlled channel as if it were a new user. In a similar fashion, a

user will hand-off within a cell if a power controlled channel becomes too congested. The ratio of reserved channels to power-controlled channels is selected to maximize the frequency re-use or effective Erlang capacity for a given number of channels. Erlang capacity is maximized when worst case users are forced to remain in the reserved channels while other users occupy power controlled channels. This helps to mitigate the coupling effect and reduces the effect of mobility on network capacity.

Another advantage of the channel partitioning system is backward compatibility with existing fixed channel assignment systems. Since existing cellular radio systems (AMPS and IS-54 TDMA) use fixed assignment, it may be desirable to migrate them to DPCA in the future to increase capacity. Initially, mobile users would use older hardware that would not allow distributed power control. These users would occupy reserved channels only. New mobiles that use both reserved and regular channels would be then be introduced. As users upgrade to newer hardware, reserved channels could be converted to regular channels, increasing system capacity.

The access algorithm is:

1. Create a sorted list of accessible base stations with at least one free reserved channel.

2. If there are no base stations on the list, block the new user.

3. Initiate data transmission on a reserved channel assigned to the nearest base

station.

4. Initiate probing on the free regular channel with the lowest interference level.

5. If the interference change is greater than the threshold, release the regular channel, hand-off if necessary, and return to step 4.

6. Otherwise, wait N steps for active users to adapt their power.

7. If the SIR level is greater than required, switch to normal state and release the reserved channel.

8. Otherwise, release the regular channel and return to step 4.

The power control algorithm is a modification of a distributed algorithm given in Section 2.6.2. The objective is to allow new users to access power controlled channels with less time delay. This reduces the load on reserved channels. The power control update for active users is:

$$p_i(k+1) \ = \ \mu_i(k)p_i(k) \tag{4.1}$$

where the update factor, $\mu_i(k)$, is computed from the ratio of the desired SIR to the measured SIR and upper bounded:

$$\mu_i(k) \ = \ min\left(\frac{\delta\gamma}{r_i(k)}, \mu_{max}\right) \tag{4.2}$$

Here γ is the desired SIR, $r_i(k)$ is the SIR measured during frame k in the probing segment, and δ is the safety-margin. In the steady-state, the SIR of an active user will be maintained at $\delta\gamma$. When no users are probing, the interference measured in the probing segment will be entirely due to other active users. In this case, the power

control compensates for changes in signal and interference levels caused by user mobility. The safety margin is determined by the change in the channel gain a user will encounter from frame to frame. If the frame rate is relatively rapid compared to the rate at which the channel changes, δ may be small.

Unlike equation (2.17), where new users initially transmit a small power that is increased in fixed steps, the rapid probing algorithm requires users to estimate the power they will require on a power controlled channel. New users attempt access to a power controlled channel by transmitting a fixed power in the probing segment of:

$$p_i(0) = \frac{\delta\delta_{probe}\gamma}{G_{ii}N} \qquad (4.3)$$

where N is the receiver noise power, G_{ii} is the gain to the base station, and δ_{probe} is a probing margin factor. The probing margin is used to offset the difference between the received noise power and the eventual interference level if a feasible admission solution is found by the other users. A new user transmits the probing signal for a fixed number of frames and measures the change in interference level in the probing segment. If the change in interference is less than δ, it will continue to probe the channel for several steps until the transmitter powers of the active users converge. If the new user achieves the desired SIR, it is admitted to the regular channel. If not, then it tries to probe another channel.

In the distributed power control algorithm with active link protection (described in Section 2.6.2) power updates are always bounded by δ. A new users increments its

power in steps of δ and active users never need to increase their power by more than δ since their SIRs are already greater than or equal to γ. With fixed power probing the situation is different. When a new user probes a channel, it will not directly interfere with active users. However, active users will see increased interference from the power updates of other active users. This occurs because each user updates its power according to the interference seen on the probing segment. If the increase in interference between two frames is greater than the safety margin, an active user's SIR will drop below the desired level. Also, since the transmit power is limited, an active user will sometimes need more power than is possible to maintain its SIR. In either case, if a user cannot maintain its SIR it will switch from the active state to the probing state and probe a new regular channel.

The maximum change in a power update is bounded by μ_{max}. The choice of $\mu_{max} = \delta$ is the most conservative. This will prevent new users from disturbing active users, assuming the active users do not reach their maximum power level. However, it is often better to select a higher level for μ_{max}. This allows the active users to adapt to new users more quickly, yielding a smaller probing time. Reduced probing time reduces the load on reserved channels, increasing potential capacity. Active users that fail to maintain their SIRs can re-probe and find new power-controlled channels.

The goal is to maintain a balance between new user access, rapid probing, and active user dropping. In the partitioned channel system, the strategy is to use very rapid

probing for power controlled channel access. This strategy arises from the fact that accurate probing measurement are slow, both because of fading in signals and because of the time required for the power control algorithm to converge. User mobility also limits the accuracy of measurements because channel characteristics will change before they can be measured. Rapid probing places less of a load on the reserved channels than slow probing. The reserved channels then have extra capacity which is used to accommodate active users that are forced out of power controlled channels by imperfect probing. The rapid probing algorithm can allow a user access to a regular channel in 4 to 7 power iterations.

4.1.2 Partitioned System Model

Channel access is evaluated by the load that the system can tolerate at a given blocking probability. Users are assumed to have Poisson arrivals, uniformly distributed over the service area, and exponential hold times. Even under these conditions the blocking probability for the partitioned system is very difficult to compute because the load on the channels cannot be modeled by a simple process with Poisson arrivals. Figure 4-2 presents a schematic model of the system. A new user enters the system and is served by a reserved channel in the nearest base station. The user then moves into a regular channel when it finds one that will allow it to meet the SIR requirement. After time, however, the user may no longer be able to maintain its SIR requirement in the regular channel and it moves back to a reserved channel in the same cell (a re-probe) or a neighboring cell (a hand-off). This occurs because of imperfect probing, finite

transmitter dynamic range, and mobility.

Figure 4-2   Network Model
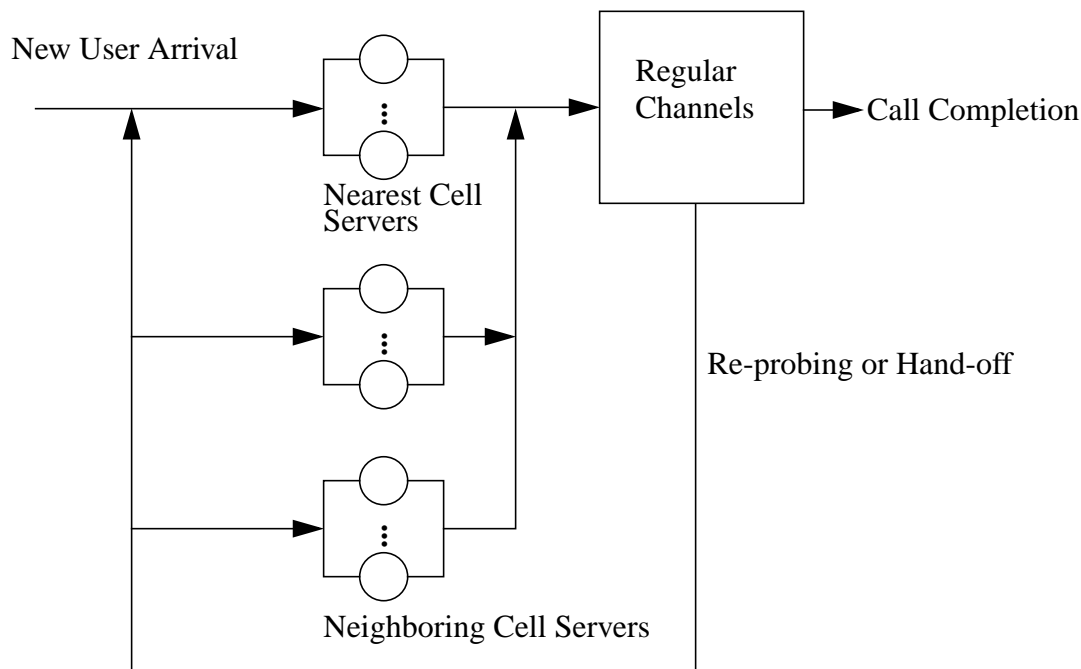
In the system model a new user is blocked when there are no available reserved channels at the closest base station. Preference is given to users that are already in the system by allowing them to access reserved channels in neighboring base stations. An active user will temporarily hand-off to a neighboring cell, if it can achieve the required SIR with that cell's base station. The preference system provides additional reserved channel servers for active users and helps prevent active calls from dropping.

Since reserved channels are used primarily for probing, the hold time will be a multiple of the time required to probe a regular channel. The multiple is equal to the number of attempts it takes to find a suitable regular channel. Users nearer to the base

station will probe fewer regular channels and also have the lowest probability of a re-probing event because they will not run out of dynamic range while holding a regular channel. These users will place very little load on the reserved channels. Users near the cell edge, however, will require a longer time to probe for regular channels and tend to re-probe often. These users place the largest load on the reserved channels and will be the primary cause of new user blocking.

The system blocking probability will be a function of the net load on the reserved channels. Roughly speaking, this will be the product of the net arrival rate (new arrivals and re-probes) and the average hold time. If the re-probing rate is low, the input to the reserved channels will be dominated by new arrivals. In this case, the blocking probability can be approximated with the Erlang-B formula [6]. However, as the re-probing rate increases, the arrivals at the reserved channels will no longer be Poisson and this method is not accurate. This occurs because re-probing is a function of the history of the system and the physical location of previous arrivals. Re-probing tends to occur in groups, as regions become congested and the regular channels are no longer able to support their users. Several users will then need to re-probe at the same time. To evaluate the performance under these conditions, it is necessary to use a simulation program.

4.1.3 Trade-offs in System Design

Given the network model, it is possible to examine the trade-offs that determine the user capacity for a given number of channels. In general, the more users that are

operating in regular channels, the higher the capacity, since regular channels can accommodate more users. However, enough reserved channels must be set aside to allow new users to probe and active users to re-probe when necessary. A simulation program is used to evaluate the performance of different configurations of channels.

The simulation program evaluates the performance of a network of 19 hexagonal cells, each roughly 7 km in diameter. The radio channel contains an attenuation factor of R^{-4} and log-normal shadowing with $\sigma = 8$ dB. Shadowing values are computed on a grid with 100 meter spacing. Actual shadowing values are computed by a 2-dimensional linear interpolation of the shadowing value in decibels.

The total number of channels in the system is 84. Each base station is allocated n reserved channels in a fixed re-use pattern of 7. The remaining 84-7n channels are regular channels that use DPCA. The SIR requirement in regular channels is 18 dB.

New users arrivals are Poisson distributed in time and uniformly distributed in space over the network. Hold times are exponentially distributed, with a mean of 4000 steps. The steps correspond to the power update step in equation (4.1). New users follow the algorithm in Figure 7 for admission, with a waiting time of $N=10$ steps. Active users in regular channels follow the power update in equation (4.1) with a margin of $\delta = 1.5$ dB and a maximum power update of $\mu = 2.0$ dB. Transmitter dynamic range for all users is limited to 66 dB. Users do not move in this first simulation, but they are allowed to temporarily hand-off to a neighboring base station during a re-probe. This gives re-probing active users an access edge over new users and

helps to prevent dropping.

The first simulation run was designed to find the optimal number of reserved channels per cell in an 84 channel system. Five groups of simulations were run with between 1 and 5 reserved channels per cell. For each simulation group, the arrival rate was varied until a blocking probability of 1% was achieved. The results are plotted in Figure 4. The largest user capacity (13.6 Erlangs per cell) was achieved with 2 reserved channels per cell. For the same number of channels, a fixed channel system can provide 12 channels per cell and a user capacity of 5.9 Erlangs per cell. In this case, the partitioned channel system provides a capacity gain of 2.3.

Figure 4-3   User Capacity Optimization
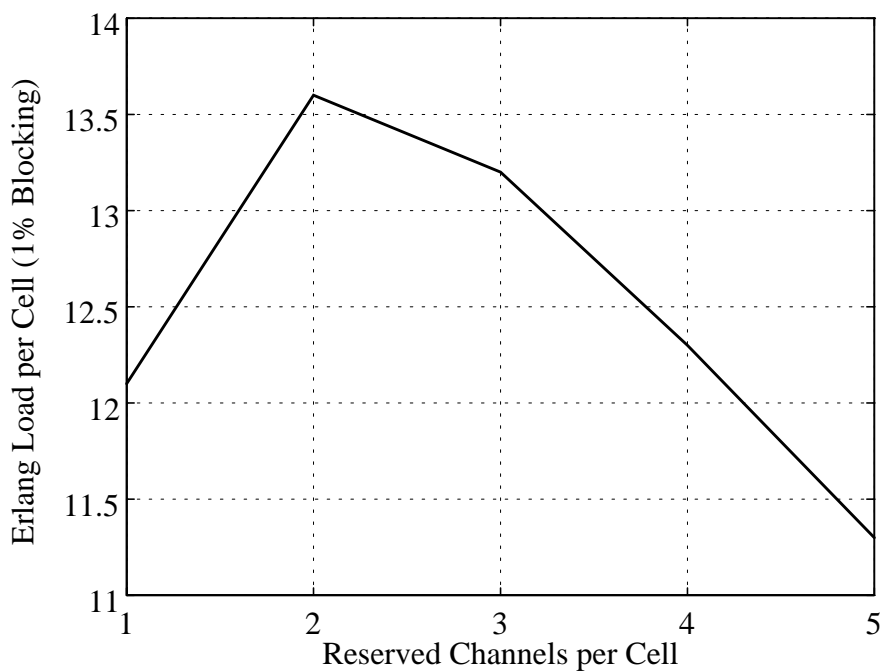
4.2 Mobility and Hand-off

The effects of mobility in fixed re-use systems is analyzed in [19]. In this analysis, the probability of a call failure (blocking during initial access or dropping during hand-off) is shown to be a function of the number of channels, the call load, and the average number of cells visited by a mobile during a call. To maintain a given call failure probability, the number of channels must be increased as either the mobile velocity is increased or the cell size is decreased. The same principle applies to the partitioned channel system. More reserved channels are required to handle hand-offs and probing for new regular channels as the level of mobility increases.

In addition to the problem of hand-off, mobility also introduces complications for the power control and channel access algorithms. As a user moves, its gain terms to the base stations will vary due to propagation distance changes and shadowing effects. As the gains change, new transmit power levels must be computed to maintain the SIR for each user. Eventually, some regular channels will no longer be able to support all of their users and re-probing will occur. This places additional load on the reserved channels and decreases the effectiveness of regular channels to provide capacity gain through power control.

When a user hands-off from one cell to another, there is a chance that a reserved channel will not be available. If this occurs, the user must either be queued (i.e. wait) until a reserved channels is available or forced out of the system (dropped). Dropping users is undesirable, so we choose to queue the active user until a reserved channel is

available. The user remains in the old cell on either a reserved channel or a regular channel, if feasible. Hand-off occurs when the new cell has a free reserved channel. The hand-off algorithm is:

1. Create a sorted list of accessible base stations.

2. If $G_{MAX} \leq G_C + 3$ dB then do not hand off.

3. If the condition in Step 2 is not true for M iterations then continue, otherwise cancel the hand off.

4. If there is a free reserved channel in the new cell then hand-off.

5. Otherwise, wait for 1 power iteration and go back to step 4.

A user starts executing the algorithm when the gain to the current base station, G_C, is 3dB less than G_{MAX}, the maximum gain of all the neighboring base stations. If G_{MAX} remains at least 3dB greater than G_C for M iterations, the user hands-off to the maximum gain base station. The algorithm provides a hysteresis effect in the hand-off decision to compensate for the effects of shadowing on the cell boundary. Since shadowing makes the cell boundary less distinct, it is desirable to limit unnecessary hand-offs in the boundary region with hysteresis. The threshold value of 3 dB is large enough to avoid the measurement errors that could occur in a practical system. With $M = 10$ the number of hand-offs in the simulation runs was consistent with the expected number of hand-offs from mobility, indicating proper operation of the algorithm.

The partitioned system assumes a fixed channel re-use factor of K=7 and a

corresponding SIR requirement of 18 dB. This is typical for the AMPS and IS-54 TDMA systems. A total of 84 channels are available with 28 set aside as reserved channels (4 per cell) while the remaining 58 are regular channels. Users in regular channels maintain an SIR of 18 dB. In this simulation, users have 66 dB of dynamic range in their transmitters.

To test the performance of the hand-off algorithm, several sets of simulations have been run. The results are plotted in Figure 4-4.

Figure 4-4   Blocking Probability with Mobility
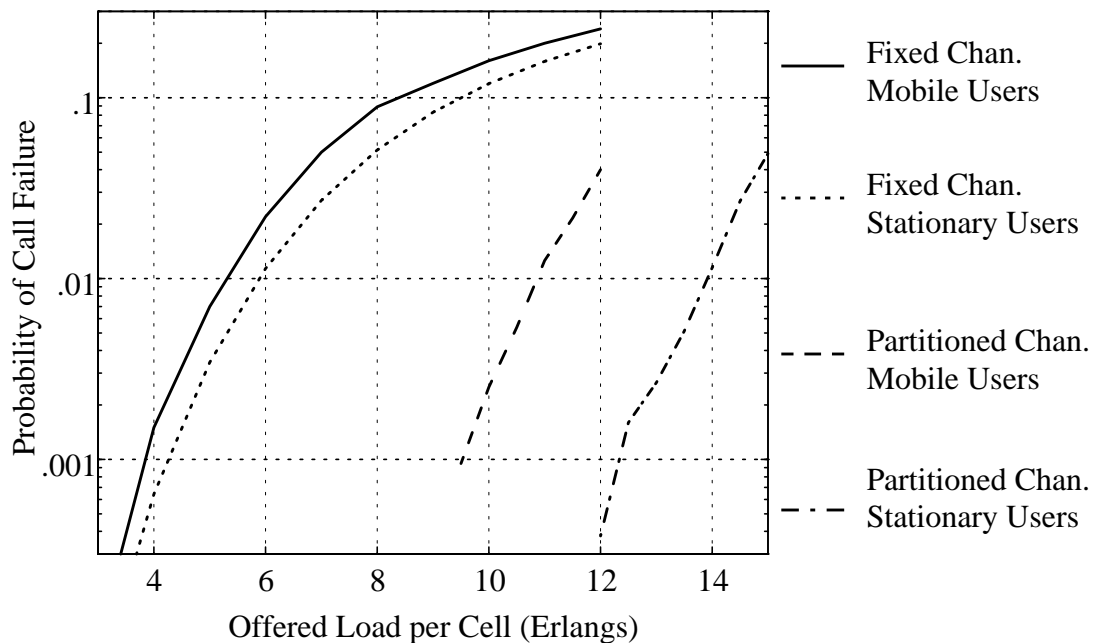
For comparison, fixed channel results from [19] have been included. These results are for a system with 12 channels per cell. Mobility is characterized by the mobility factor, θ, which is the probability that when a user exits a cell it is handing off to another cell.

Both the fixed channel results and the partitioned channel simulation have a mobility factor of θ = 0.5. This mobility factor would be considered high for a traditional cellular system, and is designed to demonstrate the performance of the partitioned channel system under stressful conditions. Even under these conditions, the partitioned channel system provides a factor of 2 increase in the user capacity without a reduction in the required SIR level for users.

A pure DPCA system (no fixed re-use channels) would not work well under these high mobility conditions because of the rapid rate at which power controlled channels become infeasible. As channels become infeasible, users must re-probe often. Without a pool of reserved channels, this would require some type of service interruption for every hand-off or re-probe. The length of time to find a new power controlled channel is indeterminate and it is impossible to predict the number and length of the service interruptions that would occur.

4.3 Channel Partitioning with Power Level Constraints

In a practical system, the transmitter power level will be selected from a discrete set:

$$P_k \in \{A_0, A_1, ..., A_{N-1}\} \tag{4.4}$$

The levels will usually be in fixed decibel increments. In absolute terms:

$$A_i = \alpha A_{i-1} \qquad (4.5)$$

where α is the increment value. For example, in IS-54 TDMA, $A_0 = 0$ dBm, $N = 8$, and $\alpha = 4$ dB.

With distributed power control, it is necessary to round-up to the next highest discrete power level after the required transmitter power is computed. From equation (4.1), the modified power update is formed:

$$p_i(k+1) = \min A_i \text{ s.t. } A_i \geq \mu_i(k)p_i(k) \qquad (4.6)$$

A further restriction we can add is to limit the change in power from time k to $k+1$ to one power step:

$$\mu_k \in \{\alpha^{-1}, 1, \alpha\} \qquad (4.7)$$

This is useful if the step size is relatively large and more than one step at a time could cause users to be dropped. Another benefit is that only two bits of power control information need to be sent from the base station to the mobile with each power update.

The effect of discrete power levels with distributed power control is to create a distribution of SIR levels between the desired level and the desired level multiplied by the power increment. Under stable conditions the SIR level of a user in a regular channel will be in the range:

$$\delta\gamma \leq r_i(k) < \alpha\delta\gamma \qquad (4.8)$$

except for users near the base station. These users will have SIRs higher than the upper

bound because they cannot decrease their powers below the minimum power setting, A_0. The bounds in equation (4.8) arise because feasible power vectors for the users will be quantized to points greater in magnitude than the minimum required. There will be a corresponding loss in the capacity of the regular channels compared to a system with finer power control and greater dynamic range. In the partitioned system, there is a small offset to this capacity loss because the power control will converge faster as the power step size increases. This decreases the load on the reserved channels as new users can probe more quickly. Fewer reserved channels are required and therefore more regular channels are available. These effects are explored below in a simulation of IS-54 TDMA with channel partitioning.

We have investigated the channel partitioning system applied to the uplink (mobile to base-station) of the IS-54 TDMA system. The system we simulated is similar to the one in Section 4.2, however the power control is restricted according to equation (4.5) through equation (4.8), and mobility is decreased somewhat. These changes reflect expected parameters in an upgraded IS-54 system. We examined two possible system upgrades. The first uses probing segments on each user frame. Power updates occur after every other complete TDMA frame, which contains two frames for each user [37]. The second system does not use probing segments but instead uses one out of every ten user frames as a probing frame. Power updates occur after every 5 TDMA frames. In general, the probing segment approach is more desirable since it can provide more accurate power control and faster probing. However, the probing segment

approach requires the ability to quickly change frequency, which represents a considerable design change for the mobile unit. The parameters for the simulations are given in Table 4-1.

Table 4-1: TDMA Simulation Parameters

Cell Diameter	7 Km
Mobile Velocity	30 mph (ave), 15 mph (s.d.)
Power Control Update Interval	80 msec (2 frames) with probing segments
	200 msec (5 frames) without probing segments
Average Call Time	106 seconds
Transmitter Dynamic Range	28 dB
Transmitter Power Steps	8 (4 dB intervals)
Regular Channels	140
Fixed Channels	28 (4 per cell)

In an actual system, there could be up to 1250 channels, based on current frequency allocations for IS-54 TDMA in the United States. We simulated a smaller system (168 channels) to limit the total number of computations. Once again, we simulated a 19 cell network and computed the blocking probability for users in the center cell. Power attenuation was assumed to follow an R^{-4} characteristic with log-normal shadowing. Shadowing was assumed to be independent every 100 meters and shadowing values were computed by interpolation as in the earlier simulations. When occupying a regular channel, the worst case was 15.5 dB and the average was over 19.5 dB. Fewer than 10% of all users had SIRs lower than 18 dB at any given time. These statistics correspond with the performance of a fixed channel system with K=7 [37]. The results are plotted in Figure 4-5.

Figure 4-5   IS-54 Comparison
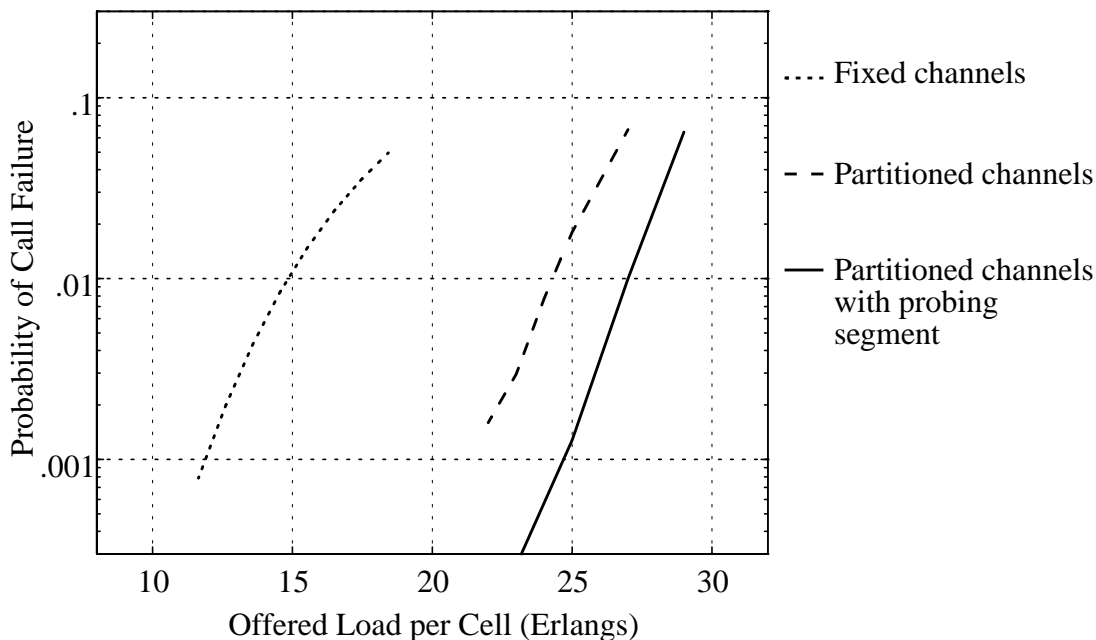
A plot of expected fixed assignment performance is included in Figure 4-5 as a comparison. With the operating parameters given in Table 4-1, the mobility parameter is $\theta = 0.22$. Based on results in [19] this will result in a capacity reduction of roughly 3%. The fixed assignment curve was computed using the Erlang-B formula [6] with this reduction factor. The partitioned curve was generated from the simulation results of the partitioned system. With call failure probabilities of 1% or less, the probability of a dropped call was less that 0.2%. At 1% failure probability, the partitioned channel system provided a capacity gain of about 60% without probing segments and up to 80% when probing segments are used.

The increase in Erlang capacity of the upgraded IS-54 TDMA system with

channel partitioning (Figure 4-5) was significant, but not as impressive as the capacity gain achieved in the first system simulation (Figure 4-4). This is due to the fact that the limited transmitter dynamic range (28 dB) and quantized power levels (4 dB) of the IS-54 TDMA system cannot provide precise power control. This leads to a wider spread in user SIR levels in the power control channels and a lower average frequency re-use.

4.4 Summary

This chapter introduced several new techniques for probing and applying DPCA to systems with time varying channels. In a time varying channel, such as in mobile radio, it is not possible to accurately probe the channel for maximum feasible SIR. Instead, the new user quickly probes to determine whether or not a channel is feasible or not. Separate probing segments (or time slots) are used to protect active users from excessive interference from the new user. The addition of channel partitioning allows users to transmit immediately on a fixed re-use channel while probing for a power controlled channel. This provides instant access for new users and continuous service for active users that must leave power controlled channels due to changes in channel characteristics or hand-offs.

The ratio of fixed channels to power controlled channels is set to maximize the Erlang capacity of the system. The required number of fixed channels depends on the SIR requirement, the amount of mobility, the length of the average connection, and the time required for probing. It is very difficult to determine the optimal channel allocation analytically so simulations are used. For the mobile radio applications discussed here,

1/6 of the available channels were assigned to a fixed re-use pattern.

As with any system that employs DPCA, the frequency re-use and Erlang capacity of the partitioned system depend on the ability to adapt to interference conditions. Consequently, systems that have high dynamic range and fine precision power adjustments can achieve higher capacities. This is consistent with previous DPCA research [39][66].

Chapter 5

Probing Channels with Adaptive Antenna Arrays

Adaptive antenna arrays provide three major benefits to a radio communication system. First, they help mitigate the fading effects of a multipath channel by providing antenna diversity. Second, they can help reduce intersymbol interference by combining spatially diverse signals with the desired time delay while rejecting signals with other delays. Third, they help reduce interference from other users by lowering the antenna gain in the direction of interferers. These three benefits are achieved when a minimum mean square error (MMSE) algorithm to adjust the antenna weights on the receiver. Additional benefit is possible with adaptive transmitter antenna arrays.

This chapter examines a new method for probing a channel where each user employs an MMSE adaptive antenna array. As in the previous chapters, it is assumed

that distributed power control is employed to allow users to maintain their SIR levels. The combination of adaptive antennas with distributed power control was first investigated in [43]. Here, a formal proof is given of the convergence of power control with the MMSE algorithm. Next, the probing algorithm is derived and its performance is explored.

Probing with adaptive antennas is much more difficult than the probing problem in Chapter 2 because the power control problem is no longer linear and the new user cannot entirely determine the channel SIR characteristics from signal and interference measurements. However, it is possible for the new user to anticipate how well its antenna array can adapt to the desired signal and interferer directions and power levels. This information is then used to estimate the SIR level at a desired transmitter power.

The adaptive antenna probing algorithm is practical because it can quickly predict SIR target levels that are accurate enough for bit allocation algorithms. Simulation results indicate that it works well with varying numbers of antenna elements and interfering users.

5.1 Adaptive Antenna Systems for Wireless Communication

Any wireless communication system can be made more efficient through the use of directional antennas. A directional transmitter antenna will increase the amount of desired signal in the direction of the receiver while minimizing the interference to

users in other directions. Likewise, a directional receiver antenna will acquire more of the desired signal and reject unwanted signals and noise. For mobile or movable systems it is necessary to point the antenna beam in the desired direction. With an antenna array, it is possible to perform this pointing operation electrically. Each signal from an antenna element is multiplied by a complex weight. The weights, combined with the antenna element patterns, determine the overall antenna pattern [54].

Researchers have explored numerous methods for computing the antenna element weights [16]. Of these, the MMSE method is the most appropriate for a high speed wireless radio modem since it maximizes the signal-to-interference ratio at the receiver. The MMSE solution can be computed with adaptive algorithms, such as least-mean-squares (LMS) and recursive-least-squares (RLS) [29]. Furthermore, MMSE adaptation is compatible with adaptive equalizers that employ the same algorithm.

The simplest multiuser system with antenna arrays is drawn in Figure 5-1.

Figure 5-1   Peer-to-Peer System With Adaptive Antennas
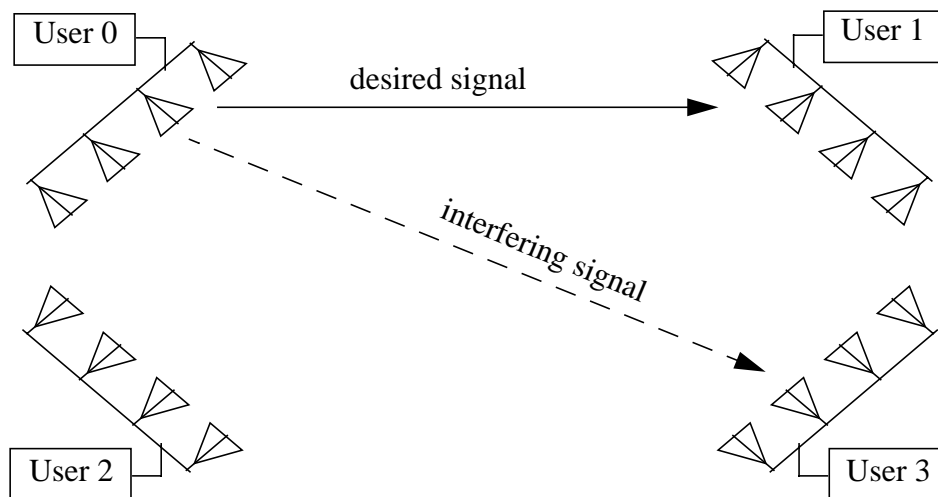
Each user has a transmitter and receiver array as shown in Figure 5-2 and Figure 5-3.
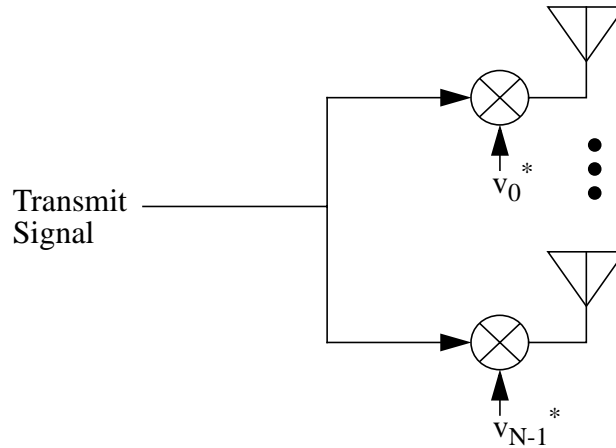
Figure 5-2   Transmitter Array

Figure 5-3   Receiver Array with Weight Update
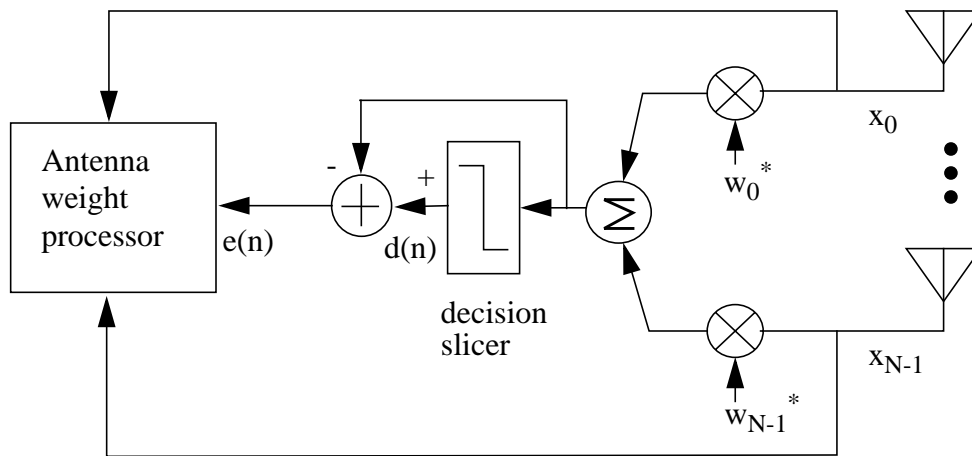
It is assumed that the transmit and receive antennas are either physically the same or are co-located. Each array has N elements. The receiver computes the MMSE solution for its antenna weights based on measurements of the received signal voltages,

x_i, on each antenna. In vector form, the antenna voltage can be expressed as the column vector:

$$x = [x_0, x_1, ..., x_{N-1}]^T \qquad (5.1)$$

Likewise, the receiver weights, w^*, and the transmitter weights, v^*, can be expressed the same way. The MMSE solution for the receiver tap weight vector is [29]:

$$w = R^{-1}\rho \qquad (5.2)$$

where R is the auto-covariance matrix of the received signal voltage:

$$R = E[xx^H] \qquad (5.3)$$

and ρ is the cross-correlation between the received voltage vector and the desired signal, d:

$$\rho = E[xd^*] \qquad (5.4)$$

We assume that the MMSE solution is computed with the LMS algorithm because it is the simplest to implement and has robust performance [29]. With the LMS algorithm, the receiver weights are updated on a symbol by symbol basis:

$$w(n+1) = w(n) + \mu x(n)e^*(n) \qquad (5.5)$$

where μ is scaling factor, and $e(n)$ is the received symbol error (the difference between the desired received symbol and the output of the antenna array):

$$e(n) = d(n) - w^H(n)x(n) \qquad (5.6)$$

The desired symbol, $d(n)$, can be determined either by a training sequence or by a decision device, as shown in Figure 5-3.

The MMSE solution for the receiver weights is employed because it will minimize the interfering signal energy and because it can be computed with well understood algorithms. However, the situation is quite different for computing the transmitter antenna weights. Transmitter weight settings will affect both the received signal and the interference seen by others. Consequently, maximizing the signal power seen at the receiver is optimal for one user but is suboptimal in a multiuser situation. Methods for optimizing the choice of transmitter weights for multiuser systems have been explored in [22][47]. These methods use the received signal covariance matrix, R, to compute transmitter antenna weights that attempt to minimize interference to other users. This is feasible, since by reciprocity the location of received interference is the same as the location where transmitter interference should be minimized.

The simplest of these methods is to use transmitter weights that are normalized versions of the receiver weights [43]:

$$v = \frac{w}{\|w\|} \tag{5.7}$$

While not optimal in all cases, this method is straightforward to implement. The normalization also allows the transmitter weights to be adapted independently of the transmitter power. This help simplify the combination of transmitter antenna weight adaptation and power control.

5.2 Adaptive Antennas with Power Control

If adaptive antennas were perfect at nulling interference, then there would be no

need for power control. Each user would simply null all the interference from other users, yielding a Gaussian channel. The multiuser channel problem would go away completely. In practice, this will never occur for several reasons. First, the number of interferers will often be greater than the number of nulls the antenna array can create. An N element antenna array can create only $N - 1$ nulls. If there are more than $N - 1$ distinct sources of interference (both from interfering users and multipath), then the MMSE solution will select a compromise that only limits the worst of the interference. Second, the nulls will have finite depth due to finite precision in the weight multipliers and coupling between antenna array elements. Therefore, it will be impossible to completely null any signal there will always be residual interference.

As with the earlier channel model, power control is used to limit the interference from other users and to allow active users to maintain their SIR levels. Once again, it is possible to use individual power control updates for users to compute their power levels in a distributed fashion. First, consider the case when the transmitter antenna weights are fixed. Each user computes an MMSE solution for its receiver weights and updates its transmitter power level, $p_i(m)$, according to:

$$p_i(m + 1) = \frac{p_i(m) j_{est}(m)}{j_i} \tag{5.8}$$

where j_i is the target mean squared error (MSE) level which is related to the SIR target by:

$$j_i = \frac{1}{1 + \gamma_i} \tag{5.9}$$

and $j_{est}(m)$ is the estimate of the current mean square error. This can be computed by averaging the symbol error $e(n)$. It is important to distinguish the time variables m, the power update time and n the symbol time. A suitable number of symbols (about 100 for 0.5 dB accuracy) are required to average the error between each power level update.

The original distributed power control algorithm given in equation (2.16) computed a matrix inversion by a matrix iteration formula [4]. The conditions for convergence could be determined from the gain matrix, yielding both the maximum feasible SIR for a new user given in equation (3.1) and the residual error due to the finite convergence rate given in equation (3.20). These provided the foundation for precise channel probing. Unfortunately, the power control update with MMSE antenna weights cannot be represented by a matrix iteration, and consequently it is more difficult to derive the conditions for convergence.

However, it is still possible to prove that power control with MMSE antenna adaptation will converge to a feasible solution if a solution exists. The vector of transmitter powers, $p = [p_0, p_1, ..., p_{M-1}]^T$, determines the state of the multiuser channel at any point in time. The power updates defined in equation (5.8) form a vector function, $I(p)$, of interference over the power vector. The system has converged when:

$$p = I(p) \tag{5.10}$$

The system will converge if the function $I(p)$ has the properties of positivity, monotonicity, and scalability [67]. Clearly, the MMSE function is always positive. The other properties are less obvious, but also true. A complete proof is given in Appendix A.

5.3 Transmitter Antenna Weights

The addition of transmitter weights complicates the power control problem. The state of the system is no longer determined by the vector of transmitter powers, but by a matrix of the transmitter weight vectors of every user sharing the channel. The exact conditions for convergence are unclear, but have been explored via simulation in [43]. In general, the system will converge when the coupling between interfering users is weak. This could be due to the fact that weak coupling implies the system is feasible without transmitter antenna adaptation at all. As the system adapts the receiver weights and power levels towards the fixed point solution, the transmitter antennas adapt to positions that will provide useful antenna gain and allow less transmitter power to be used.

Given the problems in analyzing the transmitter antenna array, it is tempting to leave it out of the probing algorithm. However, the transmitter array is very useful in practice. It supplies antenna gain which means that less transmitter power is required on all communication links. It also reduces interference to other users in the system. For these reasons, it is included in the probing algorithm even if an exact analysis of its

convergence properties is incomplete.

5.4 Probing with Adaptive Antennas

Probing with adaptive antennas is inherently difficult because it is difficult to know when a feasible solution will exist. The maximum feasible SIR for a new user without adaptive antennas was explored in Section 3.1. This level was determined from the point at which a feasible power control solution was no longer possible. At this point, the intersection of the user SIR constraints given in equation (2.13) moves out to infinity. With adaptive antennas the set of feasible solutions is more complicated to define. As a channel becomes more congested, convergence of the combined adaptive antenna and power control algorithm slows down until it can no longer converge in a useful period of time. A practical method is needed to determine an SIR level that each user can achieve while maintaining timely convergence.

To develop a probing algorithm, the properties of the MSE as seen by a new user are explored. The new user wants to determine the SIR level it can achieve at an access power level, p, on a channel with interfering users. It is assumed that a probing channel without any interferers is available for the user to probe. To insure that this channel has the same frequency response characteristics as the desired channel, the probing channel can use a separate time segment or frequency hop on the desired channel. In a frequency hopped system, this could be achieved with a spare hopping pattern.

5.4.1 MSE Bound for a New User

The received signal voltage on the antenna array will be a combination of the desired signal vector, x_d, the gaussian receiver noise x_n, and the interference signal x_i, scaled by a factor $\sqrt{\beta}$:

$$x = x_d + x_n + \sqrt{\beta}x_i \qquad (5.11)$$

By definition $\beta = 1$ when the new user is not transmitting on the channel. Once the new user begins transmitting, β will indicate the amount the interference power has increased from this nominal level.

The auto-covariance matrix for the received voltage is:

$$R = E[xx^H] = R_d + N_0I + \beta R_i \qquad (5.12)$$

which can be separated into a signal and noise matrix of rank N:

$$R_1 = R_d + N_0I \qquad (5.13)$$

and interference matrix which is approximated to be of rank 1:

$$R_i = bb^H \qquad (5.14)$$

This assumes that the interference matrix is dominated by a single user and a single signal path. In an indoor system with light coupling and moderate multipath, this approximation will hold true. The inverse of the total auto-covariance matrix can be computed by a small rank adjustment [30] from the inverse of R_1:

$$R^{-1} = R_1^{-1} - \frac{R_1^{-1}bb^H R_1^{-1}}{\frac{1}{\beta} + b^H R_1^{-1} b} \tag{5.15}$$

The cross covariance of the received signal with the desired signal is:

$$a = E[xd^*] \tag{5.16}$$

as in equation (5.4). The MMSE at the receiver will then be:

$$J = 1 - a^H R^{-1} a \tag{5.17}$$

Applying equation (5.15) to equation (5.16) yields:

$$= 1 - a^H R_1^{-1} a + \frac{\beta a^H R_1^{-1} bb^H R_1^{-1} a}{1 + \beta b^H R_1^{-1} b} \tag{5.18}$$

The first two terms correspond to the residual MSE without any interference, which will be called J_0:

$$J_0 = 1 - a^H R_1^{-1} a \tag{5.19}$$

Define

$$q_1 = a^H R_1^{-1} bb^H R_1^{-1} a \tag{5.20}$$

and

$$q_2 = b^H R_1^{-1} b \tag{5.21}$$

Then the MSE as a function of scaled interference power will be:

$$J = J_0 + \frac{\beta q_1}{1 + \beta q_2} \tag{5.22}$$

and the maximum possible MSE can be upper bounded:

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$$J_{max} = \lim_{\beta \to \infty} J = J_0 + \frac{q_1}{q_2} \tag{5.23}$$

This bound measures the ability of the new user to adapt to changes in the interference level of one resolvable interfering signal. Consequently, it will only apply when a single interferer dominates and the multipath on that signal is relatively low. When these conditions do not apply, the MSE cannot be expressed in the simple form shown in equation (5.22).

5.4.2 Probing with Receiver Measurements

A new user will probe the channel for the values of q_1 and q_2 in order to bound the MSE it can achieve on the channel. To do this, it needs to measure three values, J_0 the MSE on the channel with no interference, X_1 the additional MSE with $\beta = 1$, and X_2, the additional MSE with $\beta = 2$. These measurements are made with a modified version of the receiver shown in Figure 5-4.

The new user first measures and stores the interference voltages on each antenna while receiving on the desired channel. It then initiates transmitting on the setup channel (or frequency hop) and adapts the receiving array until convergence. This yields an MSE measurement of J_0. Next, the stored interference measurements are fed forward into the receive path for each antenna. This simulates the interference present on the desired channel. The array is adapted again until convergence, yielding a second MSE measurement, J_1.

Figure 5-4   Probing Receiver Structure
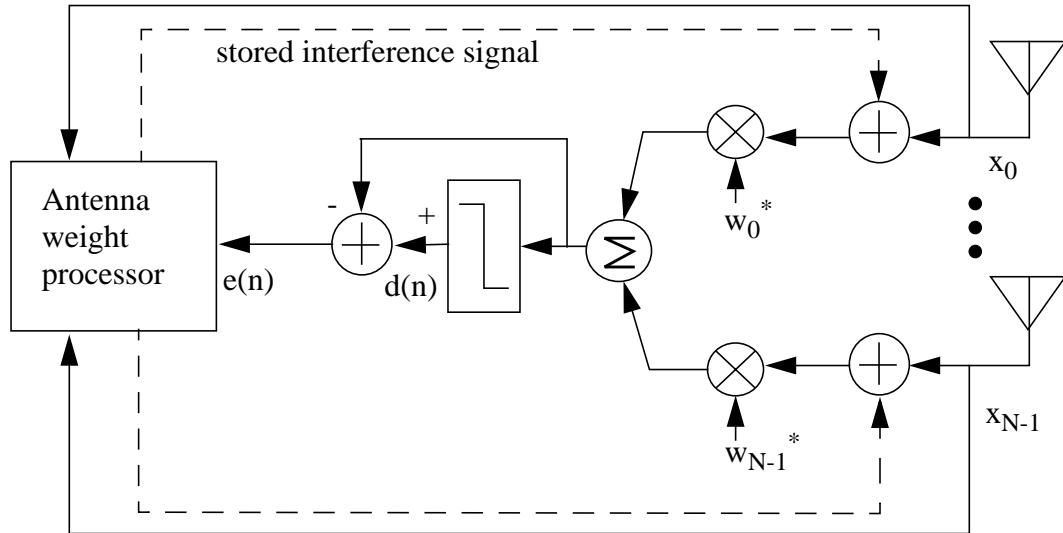
The stored interference power is then scaled by a factor of two and the antenna

is adapted a third time. The third MSE level is stored in J_2. Two new quantities are

computed:

$$X_1 = J_1 - J_0 \text{ and } X_2 = J_2 - J_0. \tag{5.24}$$

From these, the parameters in the MSE bound can be found:

$$_1 = X_1 + \frac{2X_1^2 - X_1 X_2}{2(X_2 - X_1)} \tag{5.25}$$

$$q_2 = \frac{2X_1 - X_2}{2(X_2 - X_1)} \tag{5.26}$$

and the ratio has the simplified form:

$$\frac{q_1}{q_2} = \frac{X_2 X_1}{2X_2 - X_1} \tag{5.27}$$

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With this information, the new user can predict the MSE it will see on the desired channel as a function of the interference power on that channel.

A simulation plot in Figure 5-5 demonstrates how the probing measurements can be made.

Figure 5-5　Simulation of Probing Algorithm
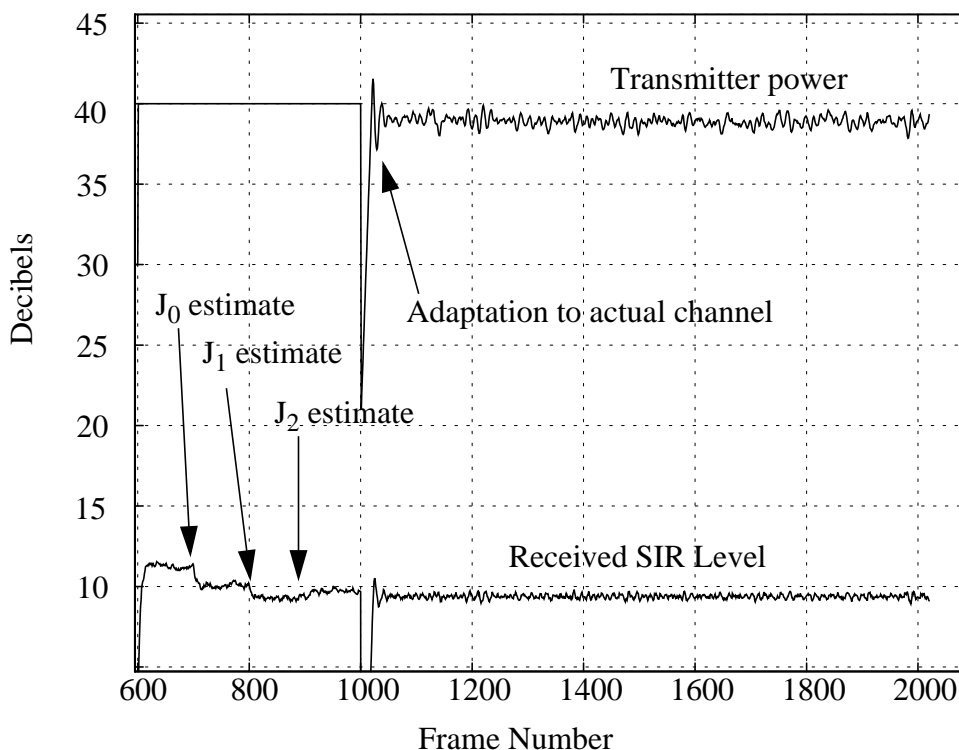
In this simulation, two pairs of active users, each with a two element antenna array, maintain SIR levels of 13 dB on the channel. A third pair of users probes the channel to determine what SIR level they can achieve. After the active user power levels have stabilized, the new user pair starts probing.

The new user measures J_0, J_1, and J_2 as described above. In this case the SIR

level at $\beta = 2$ is 9.4 dB while the MSE bound for worst case interference is 6.7 dB. The new user chooses to operate with an SIR of 9.4 dB and adapts to the necessary transmitter power over the course of about 25 frames. The required power level is about 1 dB less than the target level of 40 dB.

This probing technique will work with an arbitrary number of antenna elements and interfering users. It is limited by the fact that one interferer must dominate in order for the MSE bound to hold. However, even when this condition has been met, the bound will tend to under-predict the SIR level that the new user can achieve. In practical systems, the active users will only increase there power levels by a small amount when a new user enters the system. They will often be able to adapt their receivers to null the interference from a new user. They will also adjust their transmitter antenna patterns to help limit interference to the new user. These facts can be incorporated into the probing strategy to make a better algorithm.

5.5 Practical Considerations

A practical probing algorithm must be both fast and precise enough to allow the new user to predict what type of bit allocation it can use on a set of channels. The MSE estimator described in the previous section could not achieve high precision under many conditions because it is impossible to know how much the active users will increase their transmitter powers. Another problem is that accurately measuring the parameters X_1 and X_2 will be difficult because the change in MSE will often be very small.

Accurate measurements take a long time, and this slows down the admissions process.

Given the problems in precisely determining the exact MSE level, it is simpler and faster to make a rough guess of the SIR level that can achieved at the target power level. It turns out that a good estimate is simply:

$$\gamma_{est}(p_{t\arg et}) = \frac{1 - J_2}{J_2} \tag{5.28}$$

where $p_{t\arg et}$ is the target power level and J_2 is the MSE measurement described above.

This estimate works well for lightly coupled systems that employ adaptive transmitter antennas as described in Section 5.3. On un-congested channels where it is possible to achieve a high SIR level, the mean square error will be a loose function of β. (The MSE will be dominated by J_0.) Consequently, it is not necessary to actually estimate β, but merely to use a value that is reasonable. $\beta = 2$ is reasonable since in almost all systems with feasible solutions, active users will be able to tolerate the new user without significant increases in their transmitter powers. Except in extreme cases, the increase in interference power will be less than 3 dB.

On more congested channels, the estimate is less accurate. However, in these cases, the estimate tends to under-predict the achievable SIR level. This occurs because active users adapt their transmitter antenna arrays and the actual interference power seen by the new user does not increase as much as predicted.

5.6 Simulation Results

A simulation program was developed to test the performance of the estimator in equation (5.28). In the simulation, users probe and are subsequently admitted in pairs. Once admitted, each user follows the power control algorithm to maintain the SIR level it selected during probing. A total of 5 pairs of users are admitted on each run. Each user adapts its receive antenna array with the LMS algorithm and uses normalized receiver weights for transmission as in equation (5.7).

A typical layout for users is shown in Figure 5-6.

Figure 5-6   User Location Grid
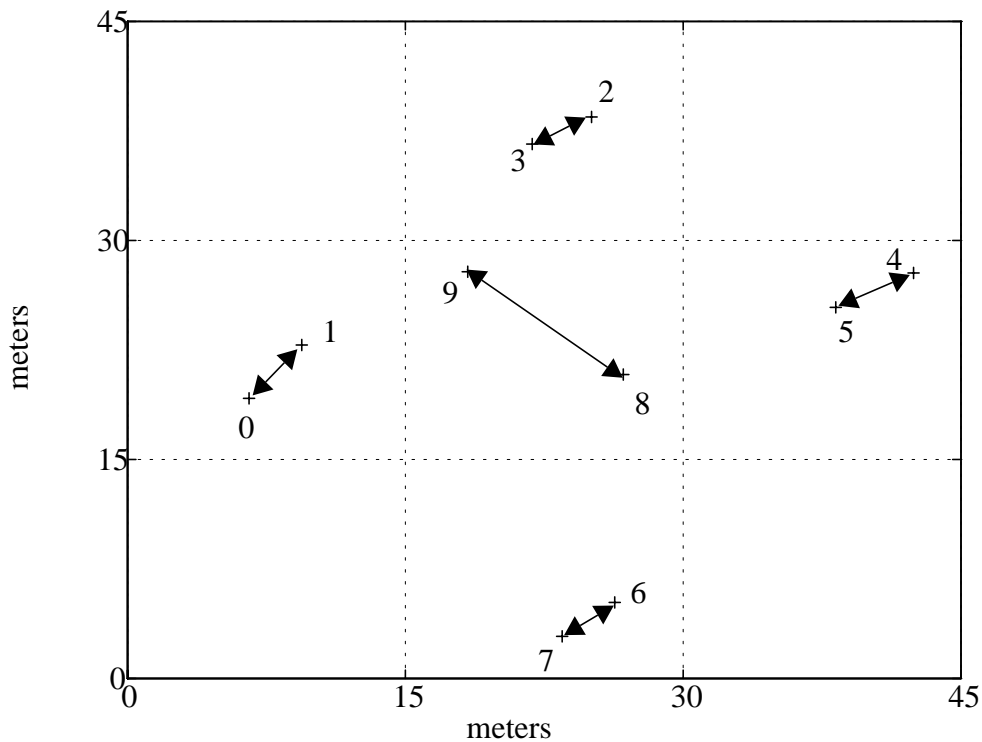
Each user pair is randomly located within one of 5 cells in the center of the room. Only

one link is allowed in each cell. This reduces coupling between interfering links which helps to insure convergence of the distributed power control with the adaptive receiver and transmitter antenna arrays. An impulse response is computed between each transmitting antenna element and each receiving element on every user with a ray-tracing technique described in [43].

The model assumes an operating frequency of 2.45 GHz and a bandwidth of 10 MHz. Antenna arrays vary in size from 2 to 4 elements. The arrays are linear with half-wave spacing. Each array element has an omnidirectional pattern. MSE at each receiver is a combination of both interference from other users and intersymbol interference (ISI).

Each user adapts its receive antenna array with the LMS algorithm on a symbol by symbol basis. MSE is averaged over frame is 256 symbols. After each frame, the transmitter weights are updated according to equation (5.7). Active users also update their transmitter power levels after each frame according to equation (5.8).

The results for a typical simulation run are given in Table 5-1.

Table 5-1: Typical Simulation Results

User	SIR Estimate	Power Required
0	25 dB	30 dB
1	25	30
2	22	30
3	18	27
4	17	27
5	17	27

Table 5-1: Typical Simulation Results

User	SIR Estimate	Power Required
6	13	28
7	13	29
8	1	23 (fail)
9	3	30

In this simulation, each user has a four element antenna array and a target transmitter power of 30 dB.

A user begins probing by measuring the SIR it can achieve with equation (5.28). The user is then admitted to the channel and increases its power in fixed steps starting at 10 dB until its SIR is at the probing level. It then follows the distributed power control algorithm to maintain its SIR. If the probing is accurate, the new user's power level will be exactly 30 dB after power control is initiated. The third column in Table 5-1 show's the actual power level required to meet the target SIR level. Values over 30 dB are considered probing failures because the user cannot actually achieve the target SIR at the desired power level. Likewise, power values under 27 dB are also considered probing failures because they indicate that a higher target SIR (perhaps enough to allocate an additional bit) would be feasible.

A total of 15 sets of simulations were performed with 10 users admitted in each

simulation. The results are given in Table 5-2.

Table 5-2: Probing Simulation Results, p_{target} = 30 dB

Array Elements	Probing Attempts	Probing Failures
2	50	3
3	50	0
4	50	8

The probing algorithm was successful 139 times out of 150 admissions, 92% of the time. In general, the algorithm seemed to work best with 3 antennas, but there was no obvious relationship between the number of antennas and the accuracy of the channel probing algorithm.

The simulation program was run a second time to test the performance of the probing algorithm when user interference is more tightly coupled. The results are given in Table 5-2.

Table 5-3: Probing Simulation Results, p_{target} = 35 dB

Array Elements	Probing Attempts	Probing Failures
2	50	11
3	50	11
4	50	11

The user locations and channel responses were the same as the first run, but the target power level was increased by 5 dB. This allows the first users entering the system to achieve higher SIR levels, at the expense of later users who achieved lower SIR levels

than in the earlier simulation. It also increased the probing failure rate. Out of 150 probes, 117 were successful, or roughly 78%. The probing algorithm was equally accurate for different array sizes.

In general, this simple probing algorithm worked fairly well under moderate interference levels. At higher target power levels, the system coupling became so high that the power control and adaptive antenna algorithm would not always converge. This is consistent with the results in [43] where it was first shown that the adaptive antenna algorithms require light coupling between interferers in order to converge properly. The probing algorithm doesn't place any new restrictions on the use of the adaptive antenna algorithms.

5.7 Summary

The goal of channel probing with adaptive antenna arrays is to quickly produce an estimate of the achievable SIR at a target power level. Since the combination of power control and adaptive antennas is very complicated, it is impossible to produce a precise algorithm comparable to the one for power controlled channels. Therefore, the best probing algorithm for most situations is to measure J_2 at the desired transmitter power level as described in Section 5.4.2. The target SIR level can then be computed with equation (5.28). The new user can then begin transmitting on the desired channel at very low power and increase in fixed steps until the target SIR is reached.

In situations where time is less critical, the new user can compute the full set of

parameters described in Section 5.4. Then, J_1 will lower bound the MSE level (upper bound the SIR) and J_{max} will loosely upper bound the MSE. The new user can begin increasing its transmitter power until it can measure an increase in the interference power from the active users. This interference increase, β, can be substituted into equation (5.22) to estimate the MSE at the target power.

Chapter 6

Conclusions

The primary purpose of channel probing algorithms is to allow dynamic power and channel allocation to be made distributed. With channel probing, each user will have the information necessary to make its own allocation decisions. If users cooperate, they can use this information to make distributed admission and resource allocation decisions. The exact methods depend on the nature of the communication channel.

Channel probing is most successful when the channel characteristics vary very slowly compared to the symbol rate of the communication system. In this case, the precise probing algorithm described in Chapter 3 can be applied. This algorithm allows the probing user to exactly compute both its maximum feasible SIR level and the SIR level it can achieve as a function of transmitter power. The maximum feasible SIR is the maximum level the user can pursue with distributed power control and still guarantee convergence. The ability to accurately estimate this value means that users will know the exact limits on the bit rate they can achieve on one channel or over a group of channels.

The particular example systems explored in Chapter 3 were a slow frequency hopped CDMA system and a DMT ADSL wireline system. However, the probing technique is also directly applicable to other systems, including direct sequence CDMA. The key feature is that a power control algorithm that equalizes the SIR level must be employed. Since power control algorithms of this type are now well understood it is likely that more systems of this type will be seen in the future. Consequently, more opportunities to use probing will arise.

Chapter 4 explored a wireless system where accurate probing is not possible. This is typical of high mobility systems, such as cellular networks in urban areas. In this case, the access algorithm is modified to determine whether it is appropriate to use a power controlled channel. This type of decision is more robust than precise probing. Even with high mobility, the probing algorithm works well enough to make distributed power control practical.

The addition of adaptive antennas to a power controlled system adds new challenges. These were discussed in Chapter 5. For probing to be feasible, the power controlled system must converge to a fixed point. Otherwise, it is impossible to predict whether or not a feasible solution exists. Convergence to a fixed point was proved for the MMSE adaptive receiver system with power control (Appendix A). When adaptive transmitter antennas are added we know there are situations were convergence is not guaranteed. However, simulation results where normed receiver weights are used for transmission converged consistently when coupling between users was light.

In a system with adaptive transmitter antennas, active users will increase their power when a new user arrives but will often limit their interference in the direction of the new user. This actually helps to simplify the probing process. The new user can assume that the interference will not increase greatly if a channel is feasible. Therefore,

it can often estimate the SIR level at a target transmitter power by storing interference measurements and adapting its antenna on a separate setup channel or segment.

There are several directions that look promising for future research work in channel probing. This work examines the cases when very accurate probing is possible and when only simple probing is possible. There are a wide variety of channels that are somewhere between these two extremes. For example, a high bit rate mobile radio channel might benefit from probing for feasible SIR level, but it could not generate the precise results reported in Chapter 2. It could, however, still use probing to help select from a set of channels, rates, and, equalizer settings.

Another area for future work is in adaptive antenna probing. If the receiver employs a more sophisticated antenna processing algorithm than LMS, then a wide variety of signal processing options become available. Sub-space methods could be applied to the received auto-covariance matrix to isolate different interfering signals. This could make probing faster, and allow the receiver to distinguish between ISI and other user interference. Such information would be useful in choosing symbols rates, constellation sizes, and equalizer settings.

As wireless systems become more complex, the need for probing grows. More processing and decision making must be made in a distributed fashion in order to insure both high performance and robustness. However, distributed problem solving requires distributed information. Channel probing allows each user to gather its own information on the state of the channel that it will use. Complicated, information gathering and distributing backbones are simplified or eliminated. Consequently, more resources can be devoted to achieving high capacity.

Appendix A

MMSE Receiver with Distributed Power Control

A.1 Background

Yates [67] defines a "standard" distributed power control algorithm as one that will converge to a single fixed point if a feasible solution exists. Below is a proof that minimum mean square error (MMSE) antenna adaptation combined with distributed power control is standard. The constraints for the user transmitter powers are expressed as:

$$p \geq I(p) \tag{A.1}$$

where p is the vector of user transmitter powers and $I(p)$ is the vector function of interference seen by each user:

$$I(p) = (I_1(p), I_2(p), ..., I_N(p)) \tag{A.2}$$

The iterative power control algorithm is:

$$p(t+1) = I(p(t)) \tag{A.3}$$

and, of course, $p > 0$. Vector inequalities are defined as strict inequality in all components.

An iteration is standard if the following properties hold:

$$I(p) > 0 \quad \forall p \tag{A.4}$$

$$\text{if } p \geq p', \text{ then } I(p) \geq I(p') \tag{A.5}$$

$$\forall \alpha > 1, \quad \alpha I(p) > I(\alpha p) \tag{A.6}$$

Now, the interference function for each user is defined to be:

$$I_i(p) = \frac{p_i J_i(p)}{J_i} \tag{A.7}$$

where $J_i(p)$ is the MMSE at user i given power vector p and J_i is the target MMSE for user i. At the output of the antenna array the received power is fixed at 1, so the MMSE level can be set by the SIR target level, γ_i:

$$J_i = \frac{1}{\gamma_i + 1} \tag{A.8}$$

The MMSE is represented by:

$$J_i(p) = 1 - r_i^H R^{-1} r_i \tag{A.9}$$

where

$$r_i = E[u d^*] \tag{A.10}$$

is the correlation between the received antenna voltage vector u and the desired signal

d. The signal is normalize to give $\|d\|^2 = 1$. The covariance matrix is defined by:

$$R_i = E[uu^H] \qquad\qquad (A.11)$$

A.2 Proof

The update in equation (A.3) using the definition in equation (A.7) will converge to a unique fixed point if a feasible solution exists. This is proved by showing that equation (A.4), equation (A.5), and equation (A.6) are always true.

A.1.1 Positivity Property (equation (A.4))

By definition, p_i, $J_i(p)$, and J_i are all positive. Consequently, equation (A.7) is positive for all i.

A.1.2 Monotonicity Property (equation (A.5))

A.1.2.1 Case I

For a given user i we assume that some $_j > p_j'$ for $j \neq i$. Then $I_i(p) \geq I_i(p')$ because an increase in power from interfering users will always increase the MMSE. When the MMSE increases, the interference function must increase whether or not p_i increases.

A.1.2.2 Case II

We will show that $I_i(p) \geq I_i(p')$ for the case $_j = p_j', j \neq i$ and $p_i \geq p_i'$. Start with equation (A.7) and substitute equation (A.9) into the right hand side:

$$I_i(p) = \frac{p_i}{J_i}[1 - r_i^H R_i^{-1} r_i] \tag{A.12}$$

then substitute:

$$r_i = \sqrt{p_i} a_{ii} \text{ and} \tag{A.13}$$

$$_i = \sum_{j=1}^{N} p_j a_{ij} a_{ij}^H + N_0 I = p_i Q_i + \sum_{j \neq i} p_j Q_j + N_0 I = p_i Q_i + Q \tag{A.14}$$

where a_{ij} are the cross correlation terms from the transmitter antennas to the receiver antenna array and $Q_j = a_{ij} a_{ij}^H$. Each Q_j will have rank equal to the number of resolvable multipath components between the antennas. I is the identity matrix. Then:

$$I_i(p) = \frac{p_i}{J_i}[1 - p_i a_{ii}^H [p_i Q_i + Q]^{-1} a_{ii}] \tag{A.15}$$

Applying the matrix inversion lemma to the inner matrix inverse yields:

$$[p_i Q_i + Q]^{-1} = Q^{-1} - \frac{p_i}{1 + p_i q_1}[Q^{-1} Q_i Q^{-1}] \tag{A.16}$$

where $q_1 = a_{ii}^H Q^{-1} a_{ii}$. Note that:

$$a_{ii}^H [Q^{-1} Q_i Q^{-1}] a_{ii} = a_{ii}^H Q^{-1} a_{ii} a_{ii}^H Q^{-1} a_{ii} = q_1^2 \tag{A.17}$$

Applying equation (A.17) to equation (A.15) yields:

$$I_i(p) = \frac{1}{J_i}\left[p_i - p_i^2 q_1 + \frac{p_i^3 q_1^2}{1 + p_i q_1}\right] = \frac{1}{J_i}\left(\frac{p_i}{1 + p_i q_1}\right) \tag{A.18}$$

which increases monotonically with p_i. Therefore, $I_i(p) \geq I_i(p')$ for the case

$_j = p_j', j \neq i$ and $p_i \geq p_i'$.

A.1.3 Scalability Property (equation (A.6))

Scalability is true if and only if

$$J_i(p) > J_i(\alpha p) \tag{A.19}$$

holds for all i with $\alpha > 1$. Using the notation from above:

$$J_i(p) - J_i(\alpha p) = \alpha p_i a_{ii}^H [Q_1 - Q_2] a_{ii} \tag{A.20}$$

where

$$Q_1 = \left[Q + \frac{N_0}{\alpha} I \right]^{-1} \text{ and} \tag{A.21}$$

$$Q_2 = [Q + N_0 I]^{-1} \tag{A.22}$$

Note that:

$$[Q_1 - Q_2] = N_0 \left(1 + \frac{1}{\alpha} \right) \left[Q^2 + N_0 \left(1 + \frac{1}{\alpha} \right) Q + \frac{N_0^2}{\alpha} I \right]^{-1} \tag{A.23}$$

The inverse term on the right hand side can be divided into the inverse of the sum of two Hermitian, positive definite components:

$$\left[\left(Q + \frac{N_0}{\alpha} I \right)^2 + \left[N_0 \left(1 - \frac{1}{\alpha} \right) Q + N_0 \left(\frac{\alpha - 1}{\alpha^2} \right) I \right] \right]^{-1} \tag{A.24}$$

The first term is square of an auto-covariance matrix and will always be Hermitian, positive definite. The second term is also a valid auto-covariance matrix and will also always be Hermitian, positive definite. Since the sum of two Hermitian, positive definite matrices is Hermitian, positive definite, and the inverse of a Hermitian, positive definite

matrix is also Hermitian, positive definite, the difference $[Q_1 - Q_2]$ is always positive

definite. Therefore equation (A.20) is always positive and the scalability property is

proved.

Appendix B

Glossary

B.1 List of Acronyms and Abbreviations

AMPS　　　　Advanced Mobile Phone System

AWGN　　　　Additive white Gaussian noise

BER　　　　Bit error rate

CDMA　　　　Code division multiple access

DCA　　　　Dynamic channel allocation

DPCA　　　　Dynamic power and channel allocation

DPC　　　　Distributed power control

FCC　　　　Federal Communications Commission (U. S.)

FDMA　　　　Frequency division multiple access

FH　　　　Frequency hop

HO	Hand off
Hz	Hertz or cycle per second.
IS-54	Interim Standard 54 (TIA/EIA TDMA cellular standard, U. S.)
IS-95	Interim Standard 95 (TIA/EIA CDMA cellular standard, U. S.)
ISDN	Integrated Services Digital Network
ISI	Inter-symbol interference
ISM	Industrial, Scientific, and Medical (bands, devices)
LAN	Local area network
LOS	Line of sight
MTSO	Mobile telephone switching office
P_{block}	Probability of blocking
P_{drop}	Probability of dropping
PC	Power control
PCN	Personal Communications Network (Europe)
PCS	Personal Communications Services (U. S.)
QAM	Quadrature amplitude modulation
QOS	Quality of service
RF	Radio frequency
SIR	Signal-to-interference ratio
SNR	Signal-to-noise ratio
SS	Spread Spectrum

TCM   Trellis coded modulation

TDMA   Time division multiple access

TIA   Telecommunications Industry Association (U. S.)

B.2 Definitions

Baud: The transmission rate in symbols per second.

Bit error rate: The ratio of the number of bits incorrectly received to the total number of bits transmitted.

Blocking: New users to the system are declined services due to the lack of channel resources.

Capacity: Maximum number of users a system can support.

Cellular radio: A system in which a service area is divided into smaller areas called cells where users in each cell communicate with a base station usually located near the center of the cell.

Channel: A transmission medium for communications.

Channel coding: Adding controlled redundancy to the information sequence to improve reliability of data transmitted through a noisy channel.

Coherent detection: Detection using a reference signal that is synchronized in frequency and phase to the transmitted signal.

Code division multiple access: A way of sharing a common spectrum in which signals from different transmitters are distinguished by a code known to the intended receiver. It is usually divided into two categories: direct sequence (DS) and frequency hopped (FH).

Dispersion: The spreading, separation, or scatter of a waveform during transmission.

Diversity: The reception of different versions of the same information bearing signal.

Down-link: The radio link where the base station is transmitting to a user in the coverage area. Also known as the forward link.

Dropping: Users already in the system are denied services due to the lack of channel resources.

Dynamic channel allocation (DCA): A system of allocating channel resources to the user depending on the channel condition and the availability of the channel resource.

Dynamic power and channel allocation (DPCA): A system of assigning channel and power to the user depending on the channel condition and the availability of the channel resource.

Erlang: A unit-less measure of the offered load to a communications network.

Fading: The variation of the intensity or relative phase of any frequency component of a received signal due to changes in the characteristics of the propagation path with time.

Flat fading: Fading resulting in similar attenuation of all frequency components of signal.

Forward link: The radio link where the base station is transmitting to a user in the coverage area. Also known as the down-link.

Frame: A set of consecutive time slots in which the position of each slot can be identified in reference to the frame start time.

Frequency diversity: A transmission technique that employs different frequency channels to achieve diversity.

Frequency hopping (FH): A spread spectrum technique in which the transmitter rapidly varies its carrier frequency in order to expand the transmission bandwidth.

Frequency reuse: The system of assigning different frequencies to different cells to limit interference while allowing a channel to be used multiple times.

Frequency-selective fading: Fading in which not all frequency components of the received radio signal are attenuated equally.

Hand-off (HO): The process of a user changing the base station it communicates with as it moves across the cell boundaries. Also known as hand-over.

Interference: Undesired signals in the communication channel.

Offered load: The ratio of the new user arrival rate divided by the system service rate. It may be normalized to the number of channels that are available to the system.

Modulation: The process of varying certain characteristics of a carrier in accordance with an information signal.

Multipath: The large set of propagation paths that the transmitted signal takes to the receiver. The multiple paths could be caused by scattering.

Multipath fading: Fading that results from multipath.

Multiple-access: A system for users to simultaneously access a common channel resource.

Network: An organization of terminals capable of intercommunication.

Outage: A condition when a user is deprived of service due to unavailability of the communication system.

Personal Communication Services (PCS): For standard purposes, it is an umbrella term to describe services and supporting systems that provide users with the ability to communicate anytime, anywhere, and in any form.

Power control (PC): A technique employed to adjust the transmit power from every radio link to the minimum level required for reliable transmission.

Quadrature amplitude modulation: A coherent digital modulation technique that uses the amplitude in both the I-channel and the Q-channel of the signal to represent information.

Receiver: A device that converts signals used for transmission back to information signals.

Reverse link: The radio link where a user is transmitting to a base station. Also known as the up-link.

Signal-to-Interference Ratio (SIR): The ratio of the desired signal power divided by the total power of the interference.

Spread spectrum (SS): A signaling scheme in which the transmission signal bandwidth is much greater than the information bandwidth.

Transmitter: A device that converts information signal to electrical or optical signals

for transmission purposes.

Transceiver: A contraction of "transmitter/receiver." The term is used when a communication device can both transmit and receive.

Trellis coded modulation (TCM): A digital bandwidth-efficient modulation technique that incorporates the concept of set partitioning and channel coding.

Up-link: The radio link where a user is transmitting to a base station. Also known as the reverse link.

White noise: Noise whose frequency spectrum is uniform over a wide frequency band.

Wireless communications: General term for communication with electromagnetic waves.

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