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Power Control Strategies and Variable Bit Allocation for FH-CDMA Wireless Systems

A dissertation submitted in partial satisfaction of the

requirements for the degree Doctor of Philosophy

in Electrical Engineering

by

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ABSTRACT OF THE DISSERTATION

Power Control Strategies and Variable Bit Allocation For FH/CDMA Wireless Communication Systems

by

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Frequency hopped code-division multiple access (CDMA) is proposed for wireless communication systems as it has the flexibility to provide a variety of services to many users under different propagation conditions. With limited spectrum, an FH-CDMA wireless communication system is interference limited.

Interference avoidance and interference averaging can reduce the interference of the system and increase the system capacity. Two fully distributed methods for a mobile user to avoid communicating in a slot with high interference are proposed. Users can avoid large interferers by transmitting only in the M slots out of the N slots in a frame. Users can also employ distributed channel probing algorithms to determine in which of the M slots to transmit and to select the hopping patterns that require the least transmitted power while meeting their signal-to-interference ratio (SIR) requirements. In addition, coding and interleaving protect the signals from the different interference levels in the slots used. Simulations show that interference avoidance increases the capacity of FH-CDMA systems.

Simulations also show that a system with orthogonal hopping pattern can achieve Erlang capacity close to a system with users continually searching for the best group of users to share hopping patterns with much reduced complexity.

In the indoor environment, the channels may vary slowly. An FH-CDMA system can take advantage of the different interference statistics in a hopping pattern and assign different bit rates to the slots to minimize the system interference. We show that the maximum throughput bit rate/channel assignment problem is NP-hard. Several *ad hoc* bit allocation algorithms are proposed. The algorithms that achieve the highest system capacity perform interference avoidance. Users concentrate their throughputs in a small fraction of the slots by transmitting large signal constellations and avoid sharing channels with large interferers. A system with variable bit allocation has more flexibility than an *M/N* system as users can vary their throughputs to adjust to the interference environment. Simulations show that a variable bit allocation system can achieve capacity 50% or higher than an *M/N* FH-CDMA system for blocking probability of 1%.

Chapter 1

INTRODUCTION

Wireless communication has brought many conveniences to modern daily lives. It frees people from working at fixed locations and allows people to stay connected as they travel. Wireless communication was born when G. Marconi first demonstrated the radio's ability to provide continuous contacts with ships in 1897. It has since then been used in space exploration, navigation, dispatching emergency and police vehicles, and many other applications. However, message and voice wireless communications devices have only become affordable and popular in the last twenty years because of the advances in signal processing and semiconductor fabrication. The demand for wireless services has been growing rapidly ever since.

1.1 Brief History of Wireless Communications

Person-to-person wireless communication is different from broadcasting. While there has been significant progress in broadcasting since Macroni's first demonstration in 1897, person-to-person wireless communication was mainly confined to military, government, and industries until the 1960's. It was not until the recent two decades that the advances in communication theories, signal processing, and semiconductor miniaturization were applied to wireless communication to make it accessible to the general public.

The first widely deployed cellular system was developed by the Nippon Telephone and Telegraph company (NTT) in 1979 using analog frequency modulation (FM) techniques. Similar systems were deployed in Europe and North America shortly after. The analog FM technologies used in these systems were based on the radio communication techniques developed around World War II. They did not take full advantage of the advances in digital communication and circuitry.

The first digital cellular standard, GSM (Global System for Mobile), was adopted by the European community and was first deployed in 1991. GSM incorporated the advances in digital speech and channel coding and used digital control for more precise and flexible system management. A new spectrum was allocated throughout Europe for the system to solve the problem of incompatible frequency bands used by the various earlier analog systems in different countries. Similar digital cellular standards were soon adopted in North America and Japan. All of these systems use time-division multiple access (TDMA). TDMA increases the system capacity, or the number of users a system can support simultaneously, by assigning users to cyclically take turns to transmit in the same frequency bin.

While most of the cellular industry adopted the TDMA cellular standards, Qualcomm Inc. proposed using the spread spectrum technique of direct sequence code-division multiple access (DS-CDMA). Although the idea of using spread spectrum in cellular environment was first proposed in 1978 [16], it was not until the late 1980's that the advances in semiconductor fabrication, more specifically very-large scale integration (VLSI), made DS-CDMA viable. The proposed system was standardized in 1993. It has been shown to be able to provide services to more users than the TDMA standards through more sophisticated signal processing and speech coding.

The public soon realized the conveniences wireless communication could bring. The demand for better and more flexible wireless services continues to rise. The concept of a communication service anywhere, anytime, in any form, or personal communication systems (PCS), has recently arisen. Future wireless communications systems will need to provide a variety of services like voice, video, and data to their subscribers using the limited bandwidth designated by the government regulatory agencies in very different propagation environments. These systems need to support more users and yet be flexible enough to adapt to different channel impairments and to accommodate different demands by the users.

1.2 Overview of the Thesis

Our goal is to design a high capacity wireless system that can operate under different indoor and outdoor environments and provide enough flexibility to carry different formats of information the users desire. Since the number of users a wireless system can support is usually determined by the interference generated by the users communicating in the system, we introduce the concept of interference avoidance and variable bit allocation. The basic idea is for the users to intelligently select the channels in which they transmit so that they do not share their channels with large interferers. The overall system interference is reduced and more users can thus share these channels. A slow hopped CDMA system is chosen as the baseline system for comparisons of the various algorithms we propose. Slow hopped CDMA has the potential to achieve high system capacity and can be flexible enough to support different types of users.

This thesis is divided into six chapters. In Chapter 2, we introduce various aspects of wireless systems including propagation environments and multiple access techniques. We also describe the important issues and trade-offs that need to be considered when designing a wireless communication system. In Chapter 3, we describe the concept of interference avoidance in detail. We then introduce several power and channel assignment algorithms using this concept and compare their effects on the system capacity. In Chapter 4, the concept of variable bit allocation is introduced for the slowly changing indoor environment. The proposed bit allocation algorithms adjust the power and bit rate assignment according to the slowly varying channels to maximize the system throughput. We then discuss the impact of channel codes and limited transmitted power on the system capacity in Chapter 5. Finally, some concluding remarks are presented along with suggestions for possible future research in the last chapter.

2.5 Summary

In order to design a high capacity wireless system, the problems of the vastly different operating conditions and limited resources like bandwidth and power need to be overcome. To combat the difficult propagation conditions, diversity techniques and powerful channel error correcting codes are needed. Information symbols are interleaved to mitigate the burstiness of the channel. Appropriate multiple access and interference suppression schemes need to be devised in order for the system to accommodate a large number of users under the limited resources. Power control is essential to guarantee users can achieve reliable communication links and yet minimize the mutual interference.

The comparisons between different access protocols described in Section 2.3.2 are subject to debate. The merits of each system depend greatly on the system models and the assumptions used particularly with regard to implementation complexity. Under the system models proposed in Section 2.2 and the numerous assumptions made throughout this chapter, slow hopped CDMA systems show the potential to achieve the highest capacity in wireless communication systems among the common multiple access protocols described. The following chapters examine the slow hopped CDMA system and discuss different algorithms that can further improve the system capacity.

diagonal elements (i, j) are equal to G_{ij}/G_{ii}.

The centralized power control algorithms require solving the set of linear equations (2.5). A centralized control unit and communications among all users are required. The algorithms also require the knowledge of all of the link gains G_{ij}, desired SIR for each user γ_i, and white noise floor, n_i which may be difficult to obtain. Both of these problems can be overcome by the distributed power control algorithms.

2.4.2 Distributed SIR-Based Power Control Algorithms

Unlike the centralized power control algorithms, the distributed algorithms [12][25][49] do not require coordination and communication between various users sharing a channel. Only feedback from a receiver to the intended transmitter is needed for power adjustment. The distributed algorithms can usually converge to the same minimum power solution that satisfies (2.5) as the centralized algorithms given the feasible power vector exists.

One algorithm is of particular interest [12]. It guarantees that all the users already admitted to the system are able to sustain their respective γ_i as new arrivals try to obtain enough SIR to enter the system. If there exists a feasible solution to (2.5), the new arrival would eventually find the proper transmitted power. If not, the SIR of the new arrivals would approach asymptotic bounds that are below their desired SIR, while the users already in the system can still sustain the desired SIR. [82] proves that most of the distributed power control algorithms converge to the same solution as solving (2.5) and that the distributed algorithms converge geometrically if the solution exists.

users communicating in the slot. Denote G_{ij} as the link gain from a user in cell j sharing the same slot to base station i, and n_i as the noise power at base station i. Then, the received signal-to-interference ratio (including white noise), R_i, can be expressed as

$$R_i = \frac{P_i G_{ii}}{\sum_{j \neq i} P_j G_{ij} + n_i} \tag{2.3}$$

Denote the desired SIR for the user in the *i-th* cell by γ_i. All feasible power solutions have to satisfy the following inequality,

$$P_i G_{ii} - \gamma_i \sum_{j \neq i} P_j G_{ij} \geq \gamma_i n_i \tag{2.4}$$

for $1 \leq i \leq B$. Dividing G_{ii} for each inequality, we can rewrite the B inequalities in matrix form,

$$HP \geq N \tag{2.5}$$

where $H = [h_{ij}]$ and $h_{ij} = -\gamma_i G_{ij} / G_{ii}$ when $i \neq j$ and $h_{ii} = 1$ for $1 \leq i, j \leq B$. $P = [P_i]$, where $1 \leq i \leq B$, and $N = [\gamma_i n_i / G_{ii}]$, where $1 \leq i \leq B$. The minimum power solution that satisfies (2.5) is found by replacing the inequalities by equalities. If there exists an all-positive power vector for this set of equations, the desired SIR can be achieved for all users. Otherwise, these users may not all achieve their desired SIR while sharing the same slot.

If all users desire the same SIR, [83] proves that the maximum achievable SIR such that these B users can share a channel is equal to the inverse of the largest eigenvalue of $B \times B$ matrix F. The diagonal elements of F are equal to zero and the off-direct digital frequency synthesizer (DDFS), these problems may be overcome.

2.4 Power Control

Since high capacity wireless systems are interference-limited, it is essential to adjust the power of the users so that enough power is transmitted to ensure signal integrity while not generating excessive interference for the unintended receivers. There are usually two types of power control: power-based and signal-to-interference ratio (SIR)-based. Power-based power control algorithms usually adjust the transmitter power so that the received power or the transmitted power for each user is the same. Although these algorithms are easier to implement and may even be optimum for DS-CDMA [28], signal-to-interference (SIR)-based algorithms have been shown to maximize channel capacity for wireless systems such as FDMA, TDMA, and slow hopped CDMA. There are generally two classes of SIR-based power control algorithms -- centralized and distributed. In this section, we only describe these algorithms for the reverse link in a cellular system (users transmitting to base stations), although the same algorithms can also be applied to the forward link (base stations transmitting to the users) or to the peer-to-peer communication systems where there is no base station infrastructure. It can be noted that frequency-reuse is a simple form of power control. It imposes spatial separations among the users so that their transmitted power does not cause too much interference with the desired signal.

2.4.1 Centralized SIR-Based Power Control Algorithms

The centralized power control algorithms assume that a system has knowledge of all the link gains among all users in the system [3][83]. For the reverse link, denote P_i as the transmitted power of a user in cell *i*, where $1 \le i \le B$ and B is the number of into fast-hopped systems and slow-hopped systems. A fast-hopped system has the hopping rate greater than the data rate. That is, during an information symbol, the system transmits over many bands with shorter duration. Fast-hopped systems are more prevalent in military applications where security is vital. With the fast hopping rate, it is difficult to track the phases of the signals. Coherent detection is often difficult to achieve. More signal power, thus more interference, is needed to maintain successful transmission. A slow-hopped system, on the other hand, has one or more information symbols per hop or slot. Coherent detection can be performed. It is more suitable for a high capacity wireless communication system.

An FH-CDMA system has many of the advantages of DS-CDMA. No frequency reuse is necessary if the sophisticated power control algorithms described in Section 2.4 are implemented. With interleaving and channel coding, the probability of blocking and dropping is determined by the average interference statistics. Since the total bandwidth used is greater than the symbol rate and can possibly be greater than the coherent bandwidth of the channel, an FH-CDMA system can overcome propagation impairments by using diversity techniques as in a DS-CDMA system. It is, however, more difficult to take advantage of the silent period in the speech and the gain over sectoring each cell is not as great as in a DS-CDMA system. There is, however, no intra-cell interference as users do not share any channels with the other users in the same cell in FH-CDMA. Since the majority of interference in DS-CDMA systems comes from users in the same cell, FH-CDMA systems may obtain higher system capacities.

There are a few difficulties when designing high bit rate, high capacity FH-CDMA systems. As in TDMA, timing needs to be tracked accurately. Equalization is also necessary. Furthermore, accurate tracking of the frequency and phase is required for coherent detection. With recent development of digital integrated circuits like the received power from the base station the user is communicating with, a new link between the user and the nearby base station is established. As the user moves farther into the neighboring cell, when the received signal power from the old base station is below some threshold of the received power strength of the new base station, communication between the user and the old base station is terminated. This is called soft hand-off. During the soft hand-off, the user communicates with at least one base station at all time. Fewer users are dropped compared to the traditional hand-off procedures. During the soft hand-off process, the user transmits at the lowest power required to sustain just one reliable link, either to the old base station or the new one. Interference is thus better controlled.

A user in a DS-CDMA system has to contend not only with *inter-cell* interference from users outside of its cell, but it would also have to mitigate the effects of *intra-cell* interference from the users within the same cell. However, with the additional signal processing, a DS-CDMA system like IS-95 has many desirable features and is capable of achieving capacity many times greater than the analog cellular systems like AMPS and other second generation digital cellular systems.

2.3.2.3.2 Frequency Hopped CDMA (FH-CDMA)

An FH-CDMA system is similar to a hybrid combination of FDMA and TDMA. The spectrum is divided into non-overlapped bands as in an FDMA system. Time is divided into narrow bins as well. A user transmits at different frequency bands during different time bins as shown in Figure 2-3. The sequence of the band-bins or slots that a user uses is called its hopping pattern. Only the intended receiver has the knowledge of the hopping pattern and can successfully decipher the transmitted signal. As in DS-CDMA, FH-CDMA uses more spectrum than needed. FH-CDMA systems are divided small group of interferers. The system capacity increases. In addition, unlike FDMA and TDMA where the system capacity is limited to the number of channels available, a DS-CDMA system has a soft capacity. The system capacity depends on the interference statistics of the system. If the users do not transmit at high power, more users can be accommodated.

A DS-CDMA system can also take advantage of the silent period in the speech to reduce the mutual interference. It is shown that this can increase the system capacity by a factor of 1.7 to 2.5. Directional antennae can be used to further reduce the interference. A cell can be divided into several non-overlapped regions or “sectors.” A different antenna is assigned to communicate with users in each region. A user would only have to mitigate the effects of the interference generated by other users within the same “sector.” A DS-CDMA system with the small chip duration also allows the receivers to combat multipath fading.

DS-CDMA systems are sensitive to the transmitted power of the users. A user located further away from the base station needs to transmit at a higher power than a user closer to the base station to ensure signal integrity. This is called the near-far problem, which can be solved by power control. Since the users near the cell boundaries need to transmit at much higher power to maintain reliable communication, they not only produce the majority of the interference within their own cells, but they also affect all the nearby cells especially in the reverse-link (users to base stations). It is estimated that up to 40% of the interference comes from the users in the neighboring cells [28]. A sophisticated and robust hand-off process is needed to reduce the interference generated by these users. DS-CDMA systems like IS-95 set aside a receiver for each user specifically for tracking the signal strength of the nearby base stations. If the received power from one of the nearby base stations is within some threshold of the

2.3.2.3 CDMA

Unlike FDMA and TDMA which assign users to distinct frequency or time slots, CDMA or code division multiple access assign each user a “code.” The code is shared by the transmitter and the designated receiver. If a receiver does not have the proper code, the signal appears noise-like. CDMA protocols use spread spectrum technology where the transmission bandwidth is several orders of magnitude greater than the information symbol rate. The code is usually a pseudo-noise (PN) sequence that has low cross correlation. It converts the information sequence into a broadband noise-like signal. CDMA is not bandwidth efficient in a single user system. However, in a multi-user system, CDMA can allow many users to share the same bandwidth by spreading the interference into a larger spectrum so that interference is reduced. This makes CDMA a good candidate for a multiple access protocol. CDMA systems are usually classified into two categories: direct sequence CDMA (DS-CDMA) and frequency hopped CDMA (FH-CDMA).

2.3.2.3.1 Direct Sequence CDMA (DS-CDMA)

In direct sequence CDMA systems, each information symbol is “modulated” or multiplied by a PN sequence of much smaller duration called *chips* to generate the broadband signal [28][71][72][77]. This signal is noise-like to a receiver without the correct PN sequence. Many users can share the same broad bandwidth as shown in Figure 2-3. Frequency reuse is no longer necessary. Unlike TDMA and FDMA where the probability of dropping and blocking depend on a small fraction of users who have to share the same channels with nearby interferers, P_{block} and P_{drop} of CDMA systems are determined by the average interference statistics. That is, users have to contend for channels with a large number of users whose signals appears noise-like instead of a into shorter non-overlapped time slots as shown in Figure 2-3. A user is assigned a time slot when service is requested. No other users in the same cell can transmit in the same band during the call. A frame is made of several time slots. Users cyclically take turns to communicate their assigned slots in each frame.

TDMA allows many users to share the same frequency band, thus increasing capacity. Although the FDMA systems can further divide the frequency bins to increase the system capacity, it is easier to achieve orthogonality in the time domain than in the frequency domain in implementation. Also, in cellular networks, hand-off can be made more reliable with the so called *mobile assisted hand-off* [57]. Users can monitor the power level from the surrounding cells while waiting for their turn to transmit. Information regarding signal strength from all nearby cells can be sent back to the communicating base stations. These base stations have more information in determining when to hand-off these users to an adjacent cell. More receivers are needed if a similar FDMA system implements mobile assisted hand-off.

TDMA signals are, however, bursty as information needs to be transmitted within shorter time slots. Elaborate synchronization is needed so the receivers can keep track of the transmitter's timing even during the idle period. The transmission rate is also higher since the same amount of information is sent in shorter time. Equalization is needed as TDMA is more susceptible to inter-symbol interference (ISI) [55]. Frequency reuse is still needed and the ratio is still determined by the worst case statistics as in FDMA. However, TDMA can significantly increase the capacity compared to the analog frequency modulation (FM) systems with the additional signalling and hardware. TDMA is currently used in the second generation of cellular radio in North American (IS-54), Japan (JDC), Europe and other parts of the world (GSM).

again until cells are far enough apart to provide sufficient spatial separation for large attenuation of interfering signals. The ratio has to be small enough so that even the users with severe channels can establish and maintain reliable communication links. These two factors make FDMA unsuitable for high capacity wireless systems. FDMA is, however, relatively simple compared to the other multiple access protocols. It is used in the first generation of wireless cellular networks like AMPS and is used for the backup access scheme for the current cellular systems.

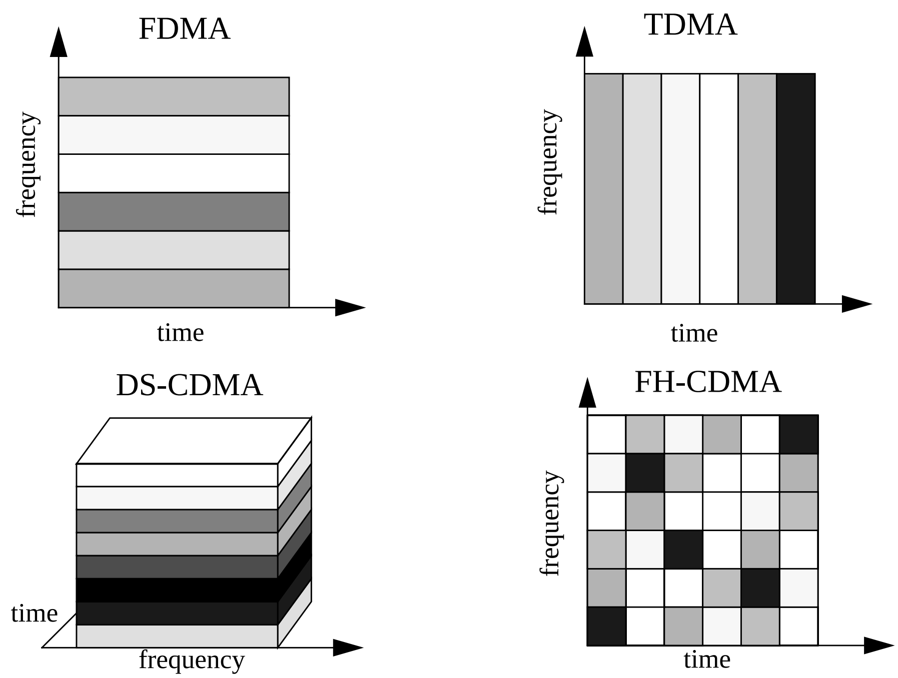

Figure 2-3   An illustration of various common multiple access protocols.

2.3.2.2 TDMA

Instead of dividing the spectrum into non-overlapping frequency bands/ channels as in FDMA, TDMA, or time division multiple access, divides the time line

2.3.2 Multiple Access

In wireless multi-user systems, users dispersed throughout the coverage area compete with each other to establish reliable communication links with the limited channel resources. Protocols are needed so that users sharing the same channels do not generate too much mutual interference. These multiple access protocols systematically assign users to the channel resources available while reducing the system interference. There are three common multiple access schemes: frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA).

2.3.2.1 FDMA

FDMA, or frequency division multiple access, divides the available spectrum into non-overlapped frequency bands as shown in Figure 2-3. A user is assigned a frequency band when service is requested. No other users in the same cell can transmit in the same band during the call. Interference is usually controlled by frequency reuse. Since transmission is continuous during the call, little overhead is required for synchronization, which is the process of aligning the symbol rate of the transmitter and the receiver.

One disadvantage of FDMA is that when a band is not assigned to any user or is simply idle in a cell, it cannot be used by the other users nearby. This is wasteful of bandwidth. Furthermore, wireless systems are usually designed to meet a specific probability of blocking (P_{block}), where new users are denied services, and a specific probability of dropping (P_{drop}), where established communication links are terminated due to lack of channel resources. The frequency reuse ratio in FDMA is determined by the worst case interference statistics. That is, the same frequency band cannot be used to the adjacent base stations is also reduced, a user may suffer from poor signal quality due to other users transmitting at the same channel in the adjacent cells. Frequency reuse is often needed to solve this problem. Frequency reuse divides the available spectrum into smaller frequency bands. One band is assigned to each cell. Each of the adjacent cells is assigned a different band. The same frequency band is not “re-used” until there is sufficient spatial attenuation to dampen the interference. Figure 2-2 shows the frequency reuse pattern of 1/7 where each frequency band is surrounded by six cells each transmitting at a different frequency. The letter at the center of each cell indicates the frequency band used in the cell. This frequency reuse pattern of 1/7 is used in the AMPS and IS-54 systems. A frequency reuse pattern of 1/4 is used in the European GSM system.

There are, however, trade-offs for dividing the coverage area into smaller cells. Additional hardware is needed for each cell and more real estate is needed. Each cell, in turn, needs to be connected to the mobile telephone switching offices (MTSO) which interface with the public switched telephone network (PSTN). The mobility of the users can also cause problems to the cellular network. Each time a user moves across the cell boundary, it needs to establish a new communication link to the base station of the new cell. This process is called hand-off (H.O.). Hand-off requires information regarding the user to be exchanged between the old and the new base stations. As the cell size decreases, users cross the cell boundaries more often and the number of hand-offs increase. The processing of the hand-off information can become overwhelming. Worse yet, a user may be denied service due to the lack of channel resource in the new cell and the call may be terminated by the system. This is very undesirable especially for voice calls for obvious reasons.

of how users contend for the channel resources so that they do not generate too much interference to one another and describes a few common access schemes.

2.3.1 Cellular Structure

In order to reduce the total interference in a wireless system and provide services to many users with limited spectrum, the coverage area is often divided into smaller regions called “cells”. Each cell has a base station located near its center which communicates with the users within the cell boundary. This division of the coverage area results in large reductions in the transmitted power level of both base stations and users. Figure 2-2 shows an idealized cellular structure. It assumes users are uniformly distributed throughout an infinitely large coverage area. In a practical system, this assumption is not true. Cells often take on irregular shapes depending on the concentration of users and the topography of the coverage area.

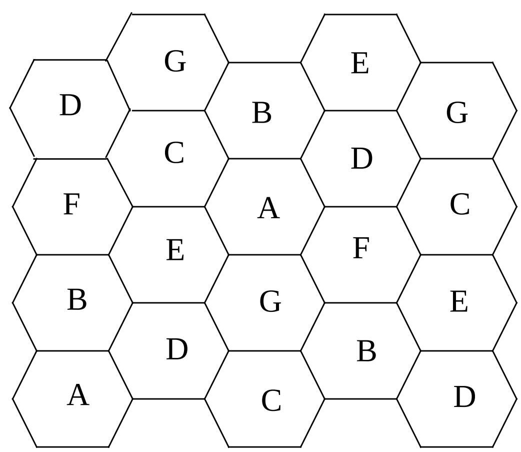

Figure 2-2 A simple idealized hexagonal cellular pattern with reuse factor of 1/7.

Simply dividing the coverage areas into cells, however, does not guarantee that users can sustain reliable communications. Since the propagation loss from each user

Techniques like ray tracing are often required.

In this thesis, we are mainly interested in different channel allocation algorithms and in their effects on the system capacity. Detailed bit error rate (BER) simulations are avoided because they are very time consuming and require elaborate channel models that incorporate short-term channel variations. The propagation models used in this thesis capture the long term statistics of the radio channels and provide a fair frame work for comparisons of system capacity with different channel allocation algorithms.

In our simulations for the indoor environment, the propagation loss is modelled by the third degree power loss (a is equal to three in (2.1)). Shadowing is modelled by a lognormal distribution with standard deviation of 10.0 dB. We assume fading can be modeled by a very slowly changing Rayleigh process.

2.3 Wireless Communication Systems

Our goal is to design a wireless communication system that can achieve high system capacity. We would like the system to be able to accommodate a large number of users, each sustaining reliable communication. As bandwidth is usually a scarce resource, there is often more than one user transmitting in a channel. We assume that the system does not have the capability to decipher the signals from the unintended transmitters. These undesired signals are treated as interference and degrade the quality of the intended signal. The total number of users a system can support depends on the mutual interference generated by the users. The wireless system is, thus, interference limited. Reduction in interference can directly lead to an increase in system capacity.

Many schemes have been developed to reduce the interference in the system. Section 2.3.1 introduces the idea of a cellular structure which divides the coverage area of the system into smaller regions called “cells”. Section 2.3.2 briefly describes the idea and the faded signal can be modeled by a Rayleigh distribution.

The effects of Rayleigh fading on the probability of bit error (P_b) are severe. P_b, which usually decreases exponentially as a function of signal-to-noise ratio (SNR) in a channel with additive Gaussian white noise, decreases as the reciprocal of the SNR [54]. In order to achieve a low probability of error, very high SNR is needed. To solve this problem, diversity techniques can be used. Diversity amounts to the use of several independent copies of the transmitted signal to combat fading. It can be achieved using multiple antennae with sufficient spatial separation, repeating the same signals, or through special designed receivers.

In this thesis, we use the standard models for propagation loss and shadowing. We assume fading, either modelled by the Ricean or the Rayleigh distribution, is too fast to be tracked as users and the nearby objects move at a relatively high speed. The gain between a transmitter-receiver pair is modelled as the product of propagation loss and shadowing. The exponent for propagation loss is chosen to be 4.0 and the standard deviation for lognormal shadowing is chosen to be 8.0. These parameters are within the reported measured values and are similar to the model used in [28].

2.2.2 Indoor Environment

In indoor systems, the environment undergoes slow changes. Users and surrounding objects move at low speeds such that even multipath fading can be tracked. Unlike the outdoor mobile environment, there are often only a small number of strong reflections depending on the dimensions of the room. The propagation conditions are highly correlated to the topography of the room and building materials. The assumption of Ricean/Rayleigh fading or lognormal shadowing is usually not true [20][33][34]. It is much more difficult to produce a model to characterize the channel environment.

closely related to the normal or Gaussian distribution. It is equal to the Gaussian distribution when the mean and the standard deviation are in the units of dB. The standard deviation of the lognormal distribution varies depending on the environment. It is about 8 dB in a suburban macro-cellular environment for the 900 MHz cellular band and about 4.5 dB in an urban micro-cellular setting for the 1.7 GHz PCS band [31]. It can be larger than 12 dB in mountainous terrain.

In outdoor mobile radio, there are often many strong received paths. As a user moves in the system, signals may be reflected off nearby buildings and moving vehicles. The signals arrive at the receiver with various delays and amplitudes. Depending on the phase and amplitude differences of these rays, the resulting signal may have very large variations as signals add constructively or destructively depending on the relative phase differences. This is called multipath fading. If the average delay of these different paths is less than a symbol duration, the fading is called frequency non-selective. That is, fading is flat across the band. If the average delay is greater than a symbol length, fading is called frequency selective fading. Frequency selective fading is difficult to model and wide band measurements are needed for these channels.

For frequency non-selective channels, fading is usually modeled as a Ricean process:

$$p_X(x) = 2x(1+K)\, e^{-[K + x^2(1+K)]}\, I_o(2x\sqrt{K(1+K)}) \qquad (2.2)$$

where x is the amplitude of the received faded signal and I_o is the zeroth-order modified Bessel function of the first kind. K is ratio of the power in the direct or line-of-sight (LOS) component to that in the diffuse component. When there is no LOS, K is zero due to signal attenuation, signals may refract or be reflected off different surfaces of different objects located at a wide range of distances. Power variations due to obstruction and channeling effects are called shadowing and often change slowly. Power variations which often change quickly due to reflections from nearby objects and due to user's mobility are called fading. In addition, users may move at a high speed resulting in rapid changes in propagation conditions.

In Section 2.2.1, the outdoor cellular propagation environment is discussed. A few words about the techniques needed to mitigate the effect of severe channels are given. The outdoor channel model used throughout this thesis is also presented. In Section 2.2.2, a brief overview of the indoor propagation environment is presented.

2.2.1 Outdoor Cellular Environment

In the outdoor cellular environment, the mobile users are often far from the base stations they are communicating with. Loss due to attenuation of power with distance is important. The average propagation loss is often modelled by [43][57]

$$P_{Received} \propto \left(\frac{1}{d}\right)^{a} \tag{2.1}$$

where d is equal to the distance between the transmitter and the receiver. In free space, a is equal to two. In the cellular environment, due to the ground reflected wave, absorption, ducting effects and other factors, a can range from 1.6 to 6.

Power variations due to obstruction and channeling effects is called shadowing. These variations take place over a distance scale on the order of meters or tens of meters, related to the size of the object causing the obstruction. The statistical model often used is the lognormal distribution [28][43][57]. A lognormal distribution is

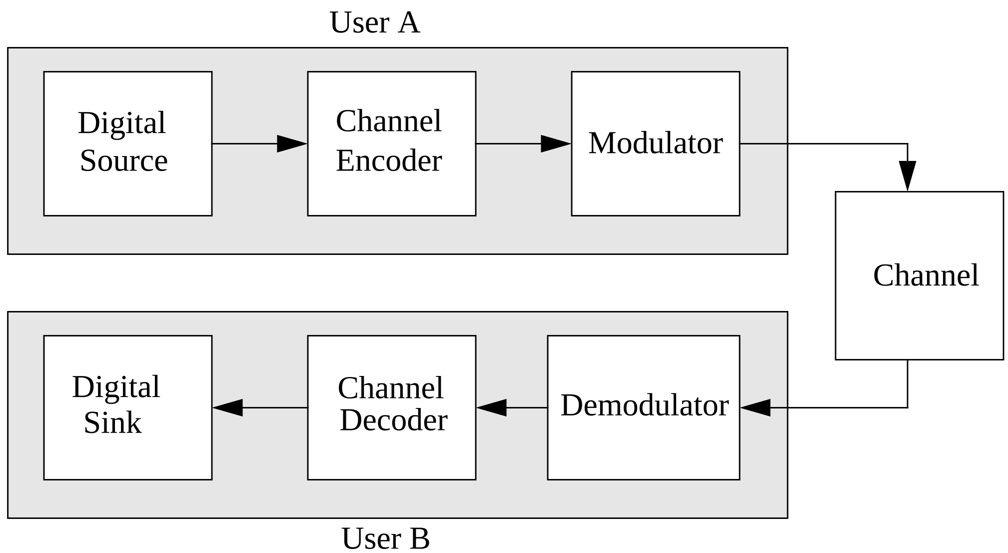

Figure 2-1 Block diagram for a digital communication system.

At the receiver at User B, the received signal first passes through a demodulator which converts the received analog waveform into the format the channel decoder can understand. The channel error-correcting decoder performs the inverse operation of the channel encoder. It tries to recover the digital information from the corrupted signal by exploiting the redundancy patterns inserted by the channel encoder. Depending on the channel condition and the noise power, the transmitted data can hopefully be successfully understood by User B without any error.

More details on the channel error correcting encoder/decoder pair, the channel, and the modulation schemes are discussed in the later chapters. In particular, the wireless communication channel characteristics is presented in Section 2.2.

2.2 Propagation Environment

Due to different topography, frequency bands, and user types, the propagation environment varies greatly among different wireless systems. Besides propagation loss impairments in Section 2.2. The characteristics of the cellular wireless system are presented in Section 2.3. In the same section, we also discuss the different coordination schemes commonly used to allow multiple users share the same channels. In Section 2.4, we give a short description of the power control algorithms which are essential in high capacity wireless communication systems and present the merits of these algorithms. Finally, we offer some concluding remarks at the end of this chapter.

2.1 Digital Communication Systems

Digital communication systems have many desirable characteristics that make them suitable for the wireless application. These systems can transmit information through the channels more efficiently than their analog counter-parts and at the same time offer better signal quality. Digital communication systems can offer enough flexibility to accommodate different types of users which may request voice, video, or data services. In addition, digital communication systems allow the system designers to control the system parameters more tightly so that more users can communicate in the same channels.

A simplified digital communication can be presented by the block diagram in Figure 2-1 [54][70] where User A is sending information to user B. The digital source at User A generates information to be transmitted. The digital information is then encoded via an error-correcting encoder. The encoder adds controlled redundancy symbols to the information. The redundancy protects the information from corruption due to transmission over a noisy channel. The coded digital information is then fed to a modulator which maps the digital information to an analog signal waveform suitable for transmission over the channel. The analog waveform then travels through a noisy channel that corrupts the signals.

Chapter 2

BACKGROUND

A wireless communication system is a multi-user system. As we aim to design a high capacity wireless system that can accommodate a large number of users, users have to compete with one another to communicate in the limited spectrum. Coordination among the users is necessary so that channel usage can be maximized in a fair matter. Digital communication techniques are needed. These techniques not only utilize the spectrum more efficiently to allow more users to communicate, but they also offer enough flexibility to accommodate different combinations of user traffics. The radio channels that wireless communication system operate in are often severely impaired by difficult propagation conditions. Special techniques are needed to mitigate these problems. These and many other factors have to be considered in designing a system that can support a large number of users such that each one can maintain good signal quality.

In this chapter, we first describe the fundamentals of digital communication systems in Section 2.1. We then present a short discussion on the radio channel and its pattern. With no mobility, the fixed assignment system has Erlang capacity of about 0.072 for P_{drop} of 0.001 and 0.089 for P_{drop} of 0.01. That is less than 50% of the Erlang capacity for an orthogonal system with M/N=10/23 with users moving at 0.5 m/frame (or 90 km/hr for 20 ms frames) and is less than 35% of the Erlang capacity of the orthogonal system with stationary users. The orthogonal system is able to achieve higher capacity due to more sophisticated power control and interference avoidance and averaging schemes which give users the flexibility to adapt to the changing environment.

3.4 Summary

We have presented results of dynamic simulations with mobile users. We have shown that by simple channel probing and selectively transmitting only in the M most favorable slots out of every N, interference of a FH-CDMA cellular system is reduced and the system capacity increases. Both of these two interference avoidance techniques can be implemented in a distributed fashion. We have also shown that a system with simple orthogonal hopping patterns has capacity close to a system that has users continually searching for the best channels for mobile users. The Erlang capacity of an orthogonal system with interference avoidance and averaging more than doubles the capacity of a fixed assignment cellular system for P_{drop} between 0.1% to 1%. Simulations also show that the orthogonal system has three times the capacity of the current generation of digital wireless system assuming the current systems have sophisticated enough power control algorithms to sustain its desired SIR.

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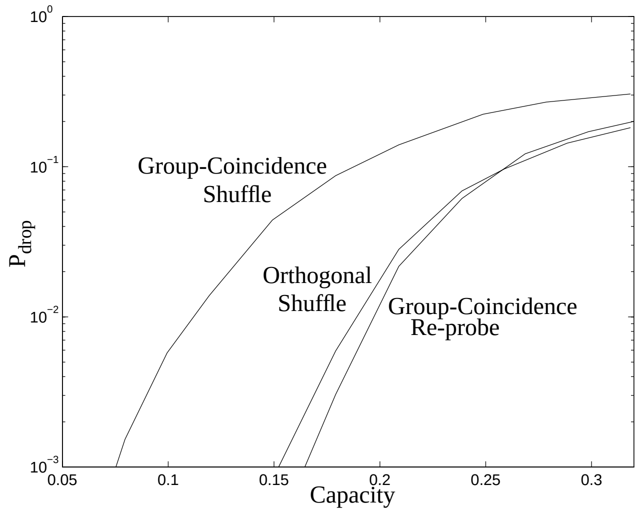

Figure 3-3 P_{drop} as a function of Erlang capacity for M/N=10/23 and users moving at 0.5 m/frame.

These simulations show that an orthogonal FH-CDMA system with shuffling can achieve most of the capacity of a "re-probe" group coincidence system that has to continuously search for a better hopping pattern when a user moves into a difficult interference environment. However, in our simulations, we assume that "re-probing" can be performed instantly, even though it requires probing all the slots in all unused hopping patterns to determine the M slots to transmit and the minimum power SIR distribution. This takes a great deal of coordination between the user and its base station and the delay inherent in distributed updates may cause the user to be dropped from the system due to poor call quality during the process. Thus in practice, system capacity will be lower.

The results from Figure 3-3 are compared to a fixed channel assignment system with 24 frequency bins [26] and reuse factor of seven. We assume the fixed assignment system requires the same SIR of 18 dB (as in IS-54) and that this requirement can be fulfilled via power control and the propagation loss introduced by the frequency reuse require "re-probing." Receivers in this system can easily monitor the interference in the remaining *N-M* unused slots without any delay or interaction with other users. The higher capacity of the shuffling orthogonal system over an equivalent group-coincidence system lies in the fact that there is a different group of interferers in every slot and that interference can be "averaged" more efficiently. A user in the group-coincidence system shares its slots with the same group of users for the duration of the call as it moves in the system. The interference avoidance and averaging techniques are not very effective as the achievable SIR distribution among the slots in the hopping pattern of the user is limited by this group of interferers. On the other hand, the orthogonal hopping patterns take into account the changing interference statistics as the users move in the system. These hopping patterns provides another way to perform interference averaging by assuming that as a user traverses the system, all other users are equally likely to be large interferers. Some slots in a hopping pattern would have low achievable SIR as the user shares slots with the large interferers while some slots have large achievable SIR as the interferers sharing the slots are far away. The interference avoidance and averaging schemes can better utilize the SIR distribution by avoiding the slots with low achievable SIR/high interference and taking advantage of the slots with high achievable SIR/low interference via interference averaging. "Re-probing", however, does not increase the capacity of the orthogonal system as much as the group-coincidence system as different hopping patterns only change the combination of interferers in each slot, but do not allow users to avoid sharing slots with large interferers. The interference avoidance techniques of *M/N* and channel probing are still critical to achieve high capacity.

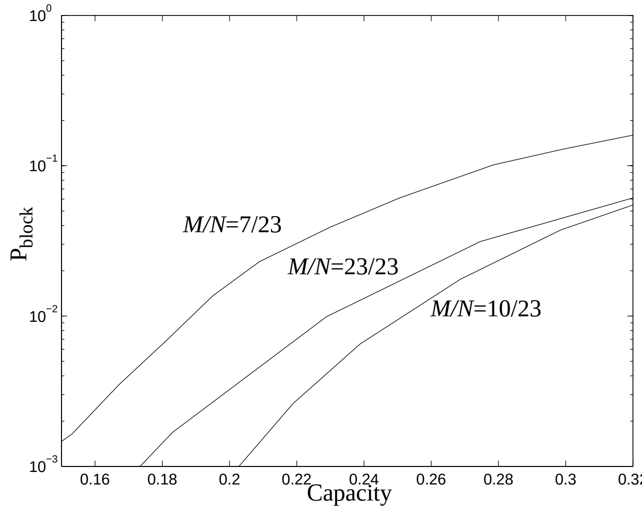

Figure 3-2 P_{block} as a function of Erlang capacity for a group coincidence system with stationary users for three different values of *M/N*.

We now allow users to roam in the coverage area. All users are assumed to be moving at the speed of 0.5 m/frame. Users needs to change the transmitted slots to adapt to the changes in interference conditions. They are allowed to shuffle which of the *M* slots they transmit and the SIR distribution among these slots periodically. This, however reduces the system capacity greatly for the group coincidence system compared to a similar system with stationary users. Additional flexibility is needed. We then allow users to probe and change their hopping pattern when they move into a difficult propagation environment and cannot sustain the required average SIR. We call this the “re-probe” system.

Figure 3-3 shows the performance curves of three different systems with *M/N*=10/23 and users moving at 0.5 m/frame. It shows that the orthogonal system with shuffling has much higher capacity than a group-coincidence system with shuffling and that the orthogonal system has capacity only 7% to 10% less than a “re-probing” group-coincidence system at P_{drop} of 0.1% to 1%. The orthogonal system, however, does not

$$Erlang\ Capacity = \frac{Arrival\ rate\ per\ system}{No\ of\ cells \times No\ of\ frequency\ bins} \times Service\ time \times \frac{M}{N}$$

The frequency reuse factor is one and the number of frequency bins, N, is 23. The desired average SIR is set at 18 dB and the minimum required SIR for transmitted slot is 10 dB.

Figure 3-2 shows the probability of blocking, P_{block}, as a function of Erlang capacity for a group coincidence FH-CDMA system with interference averaging and interference avoidance. It shows the system capacity increases as users have the flexibility to avoid sharing slots with large interferers. Users are assumed to be stationary. Once a user chooses a hopping pattern and determines which of the M slots to transmit and the SIR distribution in these slots, it maintains these until the call is completed. For P_{block} of 0.01, reducing the ratio of M/N from 23/23 to 10/23 increases the capacity by about 10% as users have more flexibility to avoid some large interferers sharing their hopping pattern. For P_{block} of 0.001, it becomes more crucial for the users to avoid nearby interferers as the difference in capacity increases to more than 16%. As the ratio of M/N decreases to 7/23, the system becomes so congested that many more users are blocked because there are no hopping patterns available. The capacity is lower. Similar results are found for the orthogonal FH-CDMA system except for the case of M/N = 23/23. When M/N=23/23, the system capacity of the orthogonal system is very low as a user has to share a slot with all of the users in the system. Some of which may generate very large interference. The system capacities of the group coincidence system and the orthogonal system are pretty close for the M/N ratio of 10/23 which in both systems maximizes the system capacity.

distance between adjacent base stations is 8 km. Nineteen cells are simulated for three concentric layers of cells. Users arrive with a Poisson distribution. The duration of the calls are exponential and i.i.d. All users are assumed to have the same desired information throughput, have the same desired SIR, and use the same code. They move at the same speed with directions that are uniformly distributed between 0 and 2π. Hand-offs are assumed to be instantaneous. A user is blocked from entering the system if there is no available hopping pattern or if there is no feasible power vector to satisfy the average SIR requirement. A user is dropped when it moves into a location with difficult propagation conditions such that there is no feasible power vector or when it moves into the coverage area of a new cell and there is no hopping pattern available.

Two different FH-CDMA systems are simulated. The first one has a user sharing its hopping pattern with the same group of users. We call this the "group-coincidence" (GC) system. The other system assigns users to orthogonal hopping patterns such that a user encounters a different set of interferers in every hop. We call this the orthogonal system. In both systems, a new user probes all the slots in all unused hopping patterns. It then selects the hopping pattern that requires the least total transmitted power in the M out of N slots used if it can maintain the desired average SIR in these M slots. Simulations have shown that with only the average SIR requirement among the M transmitted slots, the system capacity is much higher with users concentrating all of their SIR in one or few slots. Since we do not allow variable bit allocation in the system, a minimum SIR requirement for the transmitted slot is imposed. We defined the normalized Erlang capacity as the average arrival rate per channel divided by the average service rate per user. In M/N FH-CDMA systems, the normalized Erlang capacity can be expressed as by probing. To have a precise estimate, large transmitted power is needed so that the SIR can be measured more accurately. (Larger transmitted power of the probing user also induces large interference and provides more accurate interference measurement.) The probing user, however, creates more interference and other users sharing the slot need to compensate for the additional interference by transmitting at larger power. One way to avoid this problem is to use the average values over several power levels at the expense of longer probing time.

The proposed distributed channel probing algorithm not only predicts whether a user can achieve the SIR it desires in systems where power is controlled for SIR, but it also estimates the transmitted power needed. This algorithm can be used in combination with the *M/N* scheme to select the *M* slots that require the least transmitted power. It can also be used to probe all the slots in the available hopping patterns to allow users to select the hopping patterns that require the least total transmitted power.

3.3 Simulation Results

The results of computer simulations for the reverse-link of a nineteen-cell FH-CDMA system with interference averaging and avoidance are presented in this section. The centralized power control algorithm is used to reduce simulation time. All signals are assumed to experience fourth power propagation loss as in [28]. Noise power is assumed to be the same at every receiver. We assume that the shadowing has log-normal statistics with standard deviation of 8 dB. The coverage area of the cellular system is divided into 100 m-squared blocks. Shadowing is linearly interpolated in dB among the four corner points of the same block, and the shadowing values at the corner points are independently generated random numbers. Base stations are located in the center of equal size hexagons packed in the honeycomb configuration an the infinite plane. The

$1/G_{BB}$ using

$$I_o = \frac{\frac{1}{\gamma_1} - \frac{1}{\gamma_2}}{\frac{1}{P_1} - \frac{1}{P_2}} = \frac{I_1 P_2 - I_2 P_1}{G_{BB}(P_2 - P_1)} = \frac{I_1 P_2 - I_2 P_1}{\Delta P \times G_{BB}} \tag{3.10}$$

and the maximum achievable SIR by

$$\gamma_{max} = \frac{P_2 - P_1}{\frac{P_2}{\gamma_2} - \frac{P_1}{\gamma_1}} = \frac{P_2 - P_1}{I_2 - I_1} G_{BB} = \frac{\Delta P \times G_{BB}}{\Delta I} \tag{3.11}$$

where G_{BB} is the gain of the new user to its base station, and ΔP and ΔI are the differences of transmitted power and interference. That is, γ_{max}, is equal to the change in received power divided by the change in interference. From (3.10) and (3.11), to determine γ_{max} and I_o, the new user can transmit at two different power levels and observe the change in SIR and interference level. G_{BB} can be measured easily. Since we may use distributed power control [4], this channel probing algorithm only requires some measurements and coordination between the new user and its intended base station. No knowledge of any link gains and other users' desired SIR is necessary. (3.11) is similar to the channel probing algorithm described in [37].

(3.8), (3.10), and (3.11) show that only γ_1 and γ_2 (or only I_1, I_2, and G_{BB}) are needed to estimate the final transmitted power needed to achieve any desired SIR below γ_{max} since transmitted power P_1 and P_2 are known to users. There is a trade-off between the accuracy of the channel estimates and the disturbance to the existing users caused power to compensate for the additional interference generated by the new user and maintain its SIR requirement. From (3.8), as the transmitted power of the new user goes to infinity, γ approaches γ_{max}. If a new user needs to choose among two slots to transmit, it can use Theorem 3.1 to determine whether the slots can achieve the desirable SIR. If both slots have γ_{max} greater than the desired value, the new user can then use (3.7) to determine the transmitted power needed in the slots and use the slot that requires less power to achieve the desired SIR, generating less interference.

The achievable SIR as a function of transmitted power for a new user may seem simple. It is only a function of the initial interference and noise floor divided by the link gain of the user to its base station and the maximum SIR achievable for the user in the slot. However, $\gamma_{\max}$ and I_o are functions of the link gains from any user sharing the slot to all the base stations communicating in the slot, the desired SIR for the (B-1) existing users, and the noise floor at all these base stations.

We now show that a new user can estimate both $\gamma_{\max}$ and I_o relatively easily and can thus determine the transmitted power needed without disturbing the users already in the system. Replacing P_B by P, we can rewrite (3.8) in the following form,

$$\frac{1}{\gamma} = \frac{I_0}{P} + \frac{1}{\gamma_{max}}$$

Let P_1 be some transmitted power of the new user. γ_1 and I_1 are the SIR and the interference after all the other users have adjusted their power to maintain their SIR. Let P_2 be a different transmitted power of the new user, and γ_2 and I_2 are the corresponding SIR and interference. We can find the initial interference plus the white noise scaled by power vector.

$$P_B = \frac{n'_B - h_2^T H'^{-1} N'}{\frac{1}{\gamma} - h_2^T H^{-1} h_1}$$

If the original B-1 users were transmitting at their minimum power before the new user arrived, the initial interference to the new user is $G_{BB} \times (-h_2^T H'^{-1} N')$. The numerator is equal to the sum of initial interference and the noise floor at the intended base station for the new user scaled by $1/G_{BB}$. We denote it with I_o. The second term in the denominator is equal to $1/\gamma_{\max}$. We can rewrite the above equation as

$$P_B = \frac{I_o}{\frac{1}{\gamma} - \frac{1}{\gamma_{max}}} \tag{3.7}$$

Looking at the problem from another angle, the maximum achievable SIR for a given transmitted power is

$$\gamma = \frac{1}{\frac{I_o}{P_B} + \frac{1}{\gamma_{max}}} \tag{3.8}$$

The first derivative is equal to

$$\frac{d\gamma}{dP_B} = \frac{I_o}{\left(I_o + \frac{P_B}{\gamma_{max}}\right)^2} \tag{3.9}$$

The above derivation assumes every existing user is able to increase its transmitted sufficiently large such that thermal noise is negligible and the existing users transmit only enough power to maintain their desired SIR.

We now turn our attention to finding the minimum transmitted power needed for a new user to achieve a feasible SIR, $\gamma (\gamma \leq \gamma_{max})$. From (3.5), we scale the last equation, the SIR constraint for the new user, by $1/\gamma$. We know that the transmitted power for the new user is minimum when all other users transmit just enough power to maintain their required SIR. That is,

$$\begin{bmatrix} H' & h_1 \\ h_2^T & \frac{1}{\gamma} \end{bmatrix} P = \begin{bmatrix} N' \\ n'_B \end{bmatrix} \tag{3.6}$$

where $N' = [\gamma_1 n_1 / G_{11}, \ldots, \gamma_{B-1} n_{B-1} / G_{B-1, B-1}]$ and $n'_B = n_B / G_{BB}$. Apply Cramer's Rule to solve for the new user's transmitted power, P_B,

$$P_B = \frac{det\left(\begin{bmatrix} H' & N' \\ h_2^T & n'_B \end{bmatrix}\right)}{det\left(\begin{bmatrix} H' & h_1 \\ h_2^T & \frac{1}{\gamma} \end{bmatrix}\right)}$$

Now, apply Lemma 3.0 and divide both the numerator and the denominator by $det(H')$, which is greater than zero because the original B-1 users have a feasible matrix *T*, the following equation

$$(sI - T)\,x = c$$

for any $c \geq 0$, $c \neq 0$ has an all-positive solution *x*, if and only if

$$\Delta_i(s) > 0, \quad \text{for} \quad i = 1, 2, \ldots, B$$

where $\Delta_i(s)$ is the principle minor of *(sI-T*) which consists of the first *i* rows and *i* columns of (*sI-T*). Applying this theorem to (3.5) and setting *H* to *(sI-T)* and *s* to 1, there exists an all positive power vector for (3.5) if and only if all the principle minors of *H* are greater than zero. Since the original (*B*-1) users have feasible solutions, the first (*B*-1) minors are greater than zero. The necessary and sufficient condition for (3.5) to have a feasible solution is $det(H) > 0$. Applying Lemma 3.0, the condition can be expressed as

$$det(H) = det\left(\begin{bmatrix} H' & h_1 \\ \gamma h_2^T & 1 \end{bmatrix}\right) = det(H') - \gamma h_2^T adj(H')\, h_1 > 0$$

But, $det(H') = \Delta_{B-1} > 0$. Divide the above inequality by *det(H')* and observe H'^{-1} is equal to $adj(H') / det(H')$, we have

$$\frac{1}{h_2^T H'^{-1} h_1} > \gamma$$

That is γ_{max} is equal to $1/h_2^T H'^{-1} h_1$.(QED)

Theorem 3.1 states that the maximum SIR for the new user is a function of all the link gains and the desired SIR's of the existing users only. It is independent of the noise floor at each base station as no limitation on the maximum transmitted power is imposed. The new user can obtain SIR close to γ_{max} when the transmitted power is

$h_2^T = [h_{2i}]$ where $1 \le i \le N-1$. The determinant of D is

$$det(D) = d_{NN}det(G) - h_2^T adj(G) h_1$$

where *adj(G)* is the adjoint of G which is defined as the transpose of the cofactor matrix of G. The cofactor matrix of G is an $(N-1) \times (N-1)$ matrix with the *(i, j)-th* element defined as the determinant of G with the *i-th* row and *j-th* column removed.

Proof: Appendix A.

Assigning the newest user the index B, we can express (2.5) as

$$HP = \begin{bmatrix} H' & h_1 \\ \gamma h_2^T & 1 \end{bmatrix} P \ge N \tag{3.5}$$

$H' = [h'_{ij}]$ is the $(B-1) \times (B-1)$ link gain matrix for the original (B-1) users. $h'_{ij} = -\gamma_i G_{ij} / G_{ii}$ when $i \ne j$ and $h'_{ij}=1$ if $i = j$, h_1^T =**[**- γ_1 $G_{1,B}$ / $G_{1,1}$, ... , -γ_{B-1} $G_{B-1, B}$ / $G_{B-1\ ,\ B-1}$ **]** and $h_2^T = [-G_{B,1}/G_{B,B}, \ldots, -G_{B,B-1}/G_{BB}]$. γ is the SIR for the newest user.

Theorem 3.1: The maximum achievable SIR for a new user, γ_{max}, is equal to

$$\gamma_{max} = \frac{1}{h_2^T H'^{-1} h_1}$$

Proof:

From the Perron-Frobenius theorem [27][60], for a $B \times B$ irreducible non-negative simulated. However, as we shall see in the following sections, the results share similar characteristics with the equal received power system.

3.2.2 Channel Probing

In a system with power controlled for SIR, channel probing can also be used as an interference avoidance strategy to increase the capacity. Probing is a technique for users to quickly determine the channel condition without disturbing other users already in the system. Having determined the interference condition, users may then selectively transmit in the slots with low interference. In this section, we first derive an expression for the maximum achievable SIR and then find the transmitted power needed to achieve any feasible SIR for a new user. We then propose a distributed channel probing algorithm that not only provides the interference statistics, but also determines whether a user can obtain its desired SIR in the slot and how much power is needed to achieve this SIR.

We assume that there are B-1 users each with a different SIR requirement, γ_i, already in the system transmitting in the slot and that there exists a feasible power vector so that these B-1 users can all meet their SIR requirement. Before we present the derivation for the maximum achievable SIR, we state the following lemma:

Lemma 3.0: For any $N \times N$ square matrix D,

$$D = \begin{bmatrix} G & h_1 \\ h_2^T & d_{NN} \end{bmatrix}$$

where G is an $(N-1) \times (N-1)$ matrix, $h_1^T = [h_{1i}]$ where $1 \leq i \leq N-1$, and

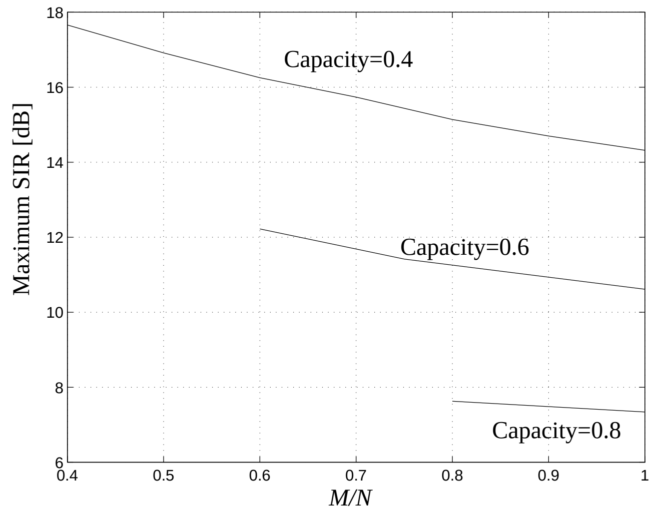

Figure 3-1 Maximum achievable SIR of an orthogonal equal received power system for various system capacities as a function of *M/N*.

The major problem with this equal received power system is that the users sharing some of the *M* transmitted slots of a new user may not be able to maintain their average SIR requirement because of the additional interference generated by the new user. These users would then have to change their *M* transmitted slots which may lead to more users changing the slots they transmit. Some forms of coordination between users may be necessary. This problem can be avoided in a system with power controlled for SIR where users already in the system are guaranteed to sustain their SIR requirement. The capacity for an M/N FH-CDMA system with power controlled for SIR is, however, difficult to compute. We can no longer collect the SIR distribution by randomly placing users in the system as in the equal received power case. We have no knowledge of the SIR distributions for the users already in the system. Furthermore, the SIR a new user can obtain in a slot depends on all the link gains rather than just the interference level. The capacity of a system with power controlled for SIR needs to be where $p(\gamma)$ is the probability density function of γ_i and $\hat{\gamma}$ is the SIR that satisfies

$$\frac{M}{N} = \int_{\hat{\gamma}}^{\infty} p(\gamma)\, d\gamma \qquad (3.4)$$

From (3.1), system capacity cannot be greater than *M/N*. The probability density function of $p(\gamma)$ is generated via computer simulations for the center cell in a nineteen-cell cellular system for the reverse link. The standard deviation of lognormal shadowing is 8 dB and propagation loss is inversely proportional to the fourth power of the distance between the transmitter and the receiver. Figure 3-1 shows that as the ratio of *M/N* decreases, the achievable SIR decreases as users have less choices on which slots to transmit and cannot avoid large interferers. The achievable SIR is the highest when *M/N* is equal to the capacity. When the capacity is 0.8, the system becomes so congested that choosing *M/N* does not allow users enough freedom to avoid large interferers. Simulations also show that the maximum achievable SIR decreases as the capacity increases. We can find the maximum capacity for a specific required SIR. We have found that if a system requires every user to have average SIR of 14.6 dB, without interference avoidance (*M/N*=1), the capacity is 0.4. With interference avoidance, the largest possible capacity is 0.55. The flexibility to assign users to the slots with lower interference gives a 34% capacity gain for this desired average SIR.

$$Capacity \equiv \frac{\text{total users in the system}}{\text{total hopping hopping patterns available}} \times \frac{M}{N} \tag{3.1}$$

The obvious drawback for using only M out of every N slots is that the throughput for every user is lowered. The gain is in the increased number of users that a system can support.

We can calculate the capacity for a coded FH-CDMA system with equal received power for every receiver with infinite diversity. Denote the set of SIR's for N slots as $\{\gamma_1, \gamma_2, \gamma_3, \ldots, \gamma_N\}$. Since the set of interferers a user encounters in every slot is different in an orthogonal system, and the received power is the same, the γ_i's are independent and identically distributed random variables. In a coded M/N FH-CDMA system, a user is blocked only when

$$\sum_{i=1}^{M} \gamma_{max_i} < M\gamma_{avg} \tag{3.2}$$

where γ_{max_i} is the i-th largest SIR in N slots and γ_{avg} is the desired average SIR for some code over the M slots transmitted. As N goes to infinity, the distribution of an ensemble of N SIR samples is equal to the distribution of γ_i. Choosing the M best SIR out of N slots so that a user is not blocked as $N \to \infty$ is equivalent to satisfying the inequality,

$$\frac{\int_{\hat{\gamma}}^{\infty} \gamma\, p(\gamma)\, d\gamma}{\int_{\hat{\gamma}}^{\infty} p(\gamma)\, d\gamma} \geq \gamma_{avg} \tag{3.3}$$

to estimate the channel conditions without disturbing the users already in the system. We have developed a channel probing algorithm that lets users determine whether they can achieve the desired SIR in a slot and estimate the transmitted power needed to achieve the desired SIR. It allows users to avoid large interferers by selectively transmitting in the slots with low interference and using the hopping patterns that require the least total transmitted power. Both the *M/N* scheme and the channel probing algorithm can be performed in a distributed fashion requiring only the cooperation of a user and the intended receiver.

3.2.1 Interference Avoidance (*M/N*) for Orthogonal Systems

Even though we are mainly interested in FH-CDMA systems with power controlled for SIR, we present the capacity analysis for an equal received power FH-CDMA system with orthogonal hopping patterns to demonstrate the trade-offs of transmitting only M out of every N slots [78][79][80]. A user with an orthogonal hopping pattern shares exactly one out of every N slots with every user in a different cell. That is, a user would encounter a different set of interferers in every hop.

We suppose all users desire the same information throughput. An orthogonal FH-CDMA system with dynamic channel allocation (DCA) then directs every user to transmit in M slots with the lowest interference out of N in its hopping pattern. M is chosen based on the information throughput for each user and/or overall system capacity. In this paper, we choose M to maximize the capacity of the system. We define capacity as the fraction of all time-frequency slots used in a system given a specific SIR or probability of error, P_e, distribution for the users, P_{block} and P_{drop}. It is a measure of the global throughput of the cellular systems. In a frequency hopped system where all users occupy M out of N slots, the capacity is defined as in Section 3.3.

3.1 Interference Averaging

Interference averaging is achieved through channel codes and interleaving. The capacity of cellular systems is frequently specified for particular values of probability of blocking (P_{block}) and probability of dropping (P_{drop}). In a conventional TDMA system, P_{block} and P_{drop} are determined by the worst case interferers as users are blocked or dropped when a small group of users sharing the slots generate intolerably large interference. In an FH-CDMA system, channel coding and interleaving across the slots can be used to average out the variations in interference among the transmitted slots. P_{block} and P_{drop}, in this system, are determined by the average interference statistics and the capacity increases. Interference averaging is especially crucial for a system where a user encounters different groups of interferers in the transmitted slots. For simplicity, we assume that with coding and interleaving, each user requires the same average SIR in this chapter.

3.2 Interference Avoidance

The basic idea of interference avoidance is simple. Users in the system avoid sharing transmitted slots with large interferers nearby and need less power to meet their SIR requirement on average. Interference is lower and the capacity is increased. Interference avoidance can be performed by transmitting in M out of every N slots and by channel probing. If the hopping patterns repeat every N slots, users can observe the interference levels and only transmit in the M slots with the lowest interference, thus avoiding sharing slots with large interferers. Channel probing is a technique for users

Chapter 3

POWER AND CHANNEL ASSIGNMENT ALGORITHMS

It is known that the problem of assigning users to a set of channels and determining the transmitted power so that the maximum number of users can be admitted into the system is an *NP*-complete problem. Practical assignment algorithms need to incorporate channel information to maximize system capacity without resorting to large signal processing complexity. Since a frequency hopped CDMA (FH-CDMA) system is interference limited, interference reduction concepts of interference avoidance and interference averaging can be applied when assigning power and channels.

In this chapter, we first discuss the concept of interference averaging and avoidance in Section 3.1 and Section 3.2. We then introduce a few new algorithms and study their effects on the system capacity. We conclude this chapter with simulation results of FH-CDMA systems with interference averaging and interference avoidance with large interferers nearby seems to be the best strategy. These bit allocation algorithms gives the system more flexibility to adapt to the interference statistics. The system capacity increases.

The optimum throughput for a single channel variable throughput system is also difficult to find. We introduce a channel resource measure and a centralized algorithm that can achieve the maximum system throughput in most of the cases. More work is needed to develop a distributed algorithm. The proposed centralized algorithm can be modified to dedicate more throughput to the users with more *importance*. We can weigh the reduction of the channel resources with the *importance* of the data or user when we assign bits. This would allow a channel to serve vastly different types users. Some of the users which may require constant throughput as in speech, some may desire variable or bursty throughput as in data, and some may require a minimum throughput with periodic spurs of data as in video.

variable bit allocation algorithms can achieve throughput of nearly 72% higher. The higher total throughput from the exhaustive search and the *ad hoc* search can be attributed to the fact that the system can assign higher bit rates to the users that are close to their communicating base stations. These users on the average cause lower interference among the users sharing the slot and have smaller cost to channel resource measure. The total throughput is higher as these two searches favor users with high link gain to their base stations and have low mutual link gain with all the other users in the system.

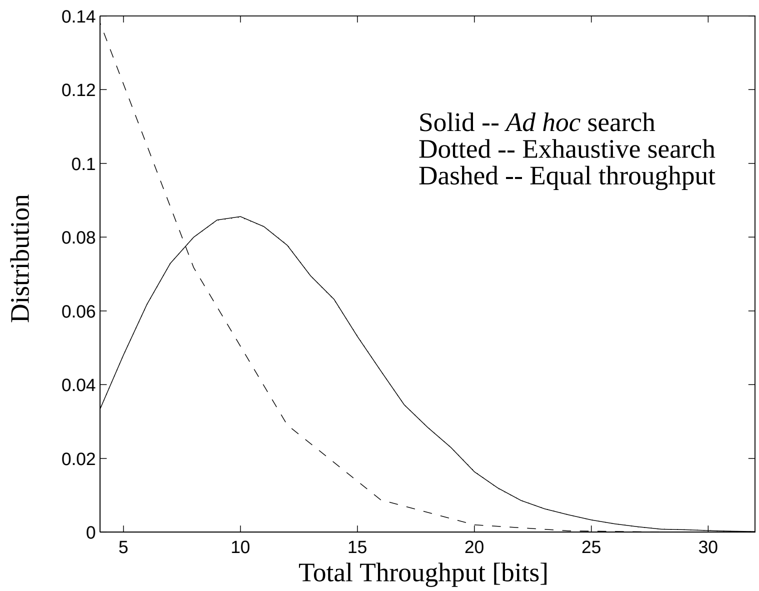

Figure 4-9 Distribution of total throughput for variable throughput system with four users.

4.3 Summary

Finding the bit allocation that maximizes the system throughput is a difficult task. In an FH-CDMA system where every user requires the same bit rate, we propose several *ad hoc* algorithms that utilize the insights we have obtained from exhaustive searches. Interference avoidance which asks the users to avoid transmitting in the slots

4.2.2 Results

Simulations have been performed for the reverse link of a nineteen-cell indoor system. Propagation loss is modelled by the third power law and shadowing is modelled by a lognormal distribution with standard deviation of 10 dB. We assume an SIR of 10 dB is needed for the smallest constellation carrying one bit of information. For every additional bit, we assume an additional 3 dB of SIR is needed. The results are compared with the results from exhaustive searches and from assigning the same throughput for all users. For systems with three users, the *ad hoc* algorithm always finds the bit allocation with the maximum system throughput and the minimum total power. The *ad hoc* algorithm also finds the total maximum system throughput for most cases (99.6%) for systems that have four to six users. However, about 15% of the bit allocations found by the *ad hoc* scheme do not correspond to the minimum total power allocation, but the average deviation from the minimum total power is less than 25%. In about 1% of the simulations, the *ad hoc* bit allocation algorithm finds the bit allocations that achieve the maximum system throughput, but the $det(H)$ found is not the largest $det(H)$ for the same system throughput. These simulations show that the bit allocations found by the *ad hoc* algorithm, although local, well approximates the maximum throughput. These allocations are also reasonably close to the minimum total power bit allocations.

Figure 4-7 shows the distribution of the total throughput for a system with four users sharing the channel. Similar distributions are found for systems with different numbers of users. Figure 4-7 shows that systems performing the *ad hoc* bit allocation algorithm and the exhaustive search bit allocation have almost identical distribution of total throughput as the two curves fall on top of one another. Both of these systems have average total system throughput of 11.5 bits. The system that assigns all users the same throughput can achieve total system throughput of 6.66 bits, on the average. The each user as it tries to increase its throughput. We thus propose an *ad hoc* bit allocation algorithm allowing the user that causes the smallest reduction in $det(H)$ to increase its throughput. The algorithm can be described below:

1. Start with a feasible set of users all capable of sustaining the minimum required SIR, γ_{min}.
2. Each user takes turns to probe the channel and calculate the cost or reduction to $det(H)$ for the additional SIR needed for an extra bit, when the SIR needed is less than γ_{max}.
3. Allocate an extra bit to the users with the minimum cost.
4. Repeat step (2) and (3) until the required SIR needed for an extra bit is greater than the maximum achievable SIR for all users.

This algorithm does not guarantee that it would find the bit allocation that achieves the maximum throughput, nor does it guarantee that the final $det(H)$ for the bit allocation found is the maximum $det(H)$ for the same system throughput. It also does not guarantee that the bit allocation found is the minimum total power bit allocation. The algorithm tries to minimize the cost to $det(H)$ for an additional bit at every step so that the maximum channel resource, $det(H)$, is available for the additional bit allocation. The solution found is a local maximum at which no more bits can be assigned. Trying to minimize the $det(H)$ has the additional benefit that the transmitted power for the bit allocation found would be relatively small on the average as the solution to (4.8) is scaled by $1/det(H)$ by Cramer's Rule. This bit allocation algorithm requires a centralized control to schedule the users to take turns to probe the channel and then assign the additional bit to the user with the least cost to the channel resource.

expressed as a function of the SIR of the *i*-th user, γ_i, by

$$det\ H(\gamma_i) = det(H')\left(1 - \frac{\gamma_i}{\gamma_{i,\,max}}\right) \tag{4.9}$$

where *det(H')* is the determinant of the $(B-1) \times (B-1)$ sub-matrix of *H* with the *i*-th row and column of *H* removed. $\gamma_{i,max}$ is the maximum achievable SIR for user *i*. (4.9) shows *det(H)* is a linear function of γ_i as in the figure below.

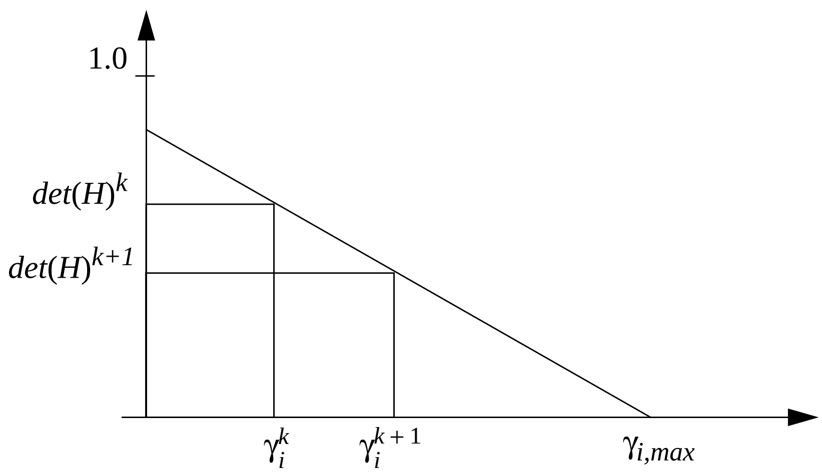

Figure 4-8 Using *det*(*H*) as a channel resource measure.

We propose using the determinant of *H* as a channel resource measure. When there is only one user in the system, *det(H)* is equal to one. As the channel becomes congested, *det(H)* decreases. When *det(H)* is equal to zero, all available channel resources are used and no user can increase its SIR while having all users transmit with positive power to sustain their desired SIR. The maximum achievable SIR for each user can be obtained from the distributed channel probing algorithm described in Chapter 3.

Assuming there exists a feasible power vector for the current SIR distribution among the *B* users, *det*(*H*) is greater than zero. *det*(*H*) decreases by a different value for throughput most of the time.

4.2.1 Centralized Search Algorithm

Again, we examine the reverse link of a cellular system. We assume that there are B users in the system. Each transmits enough power to sustain its SIR requirement. That is,

$$HP \geq N \tag{4.8}$$

H is a $B \times B$ matrix with diagonal elements equal one and the off diagonal-element at the (i, j)-th position equals $\gamma_i G_{ij} / G_{ii}$. γ_i is the desired SIR for user i and G_{ij} is the link gain from user j to base station i. P is a $B \times 1$ positive power vector and N is a $B \times 1$ vector with the i-th element equals to $\gamma_i\ n_i / G_{ii}$. n_i is the noise floor at base station i. There is often more than one bit allocation that maximizes the total system throughput.

We suppose that user i with k bits of throughput and desired SIR of γ_i^k would like to increase its throughput by one bit. The SIR needed for the symbol to carry the additional bit of information while sustaining good signal quality is γ_i^{k+1}. Recall from Perron-Frobenius, in order for (4.8) to have an all-positive power vector, all the principle minors of H have to be greater than or equal to zero. Since the other $(B-1)$ users in the system can maintain their desired SIR with the i-th user transmitting with SIR of γ_i^k, all of the principle minors of H excluding the i-th row and column are greater than zero. The necessary and sufficient condition for user i to be able to transmit at the higher SIR is that the determinant of H with the SIR of the i-th user substituted by γ_i^{k+1} to be greater than zero.

Applying the lemma described in Appendix A, the determinant of H can be

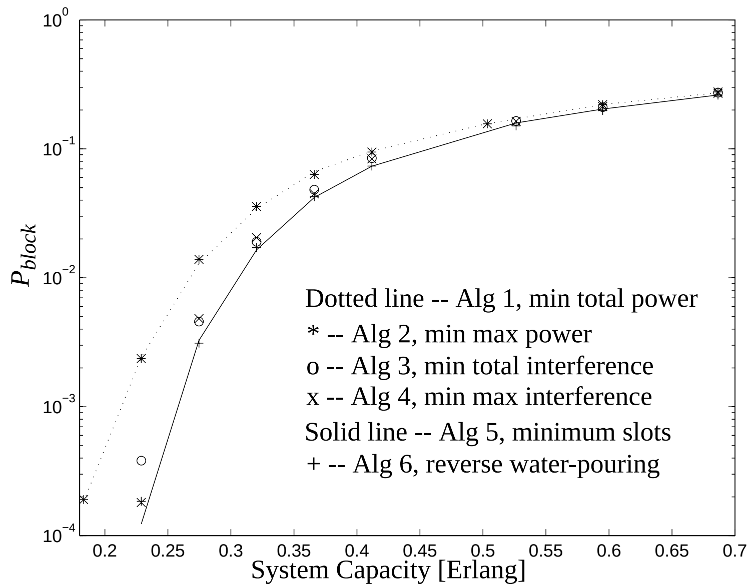

Figure 4-7 Bit allocation simulations for orthogonal systems.

4.2 Single Channel with Variable Throughput

We are now interested in finding the bit allocation for a set of users sharing a channel that maximizes the system's information throughput. We assume that all users are transmitting with at least the minimum constellation. This variable bit allocation system can serve as a model for a data dedicated wireless system. It can also be used as a model for a system with variable quality of service (QOS) where every user is guaranteed a minimum quality of service. If there are enough channel resources available, some users can obtain better quality of service with higher data throughputs.

Unfortunately, the difficulty of the non-convex feasible region for (4.4) also applies to this problem. Exhaustive searches are needed to find the bit allocation for the maximum throughput. Here, we introduce a channel resource measure and present a centralized search algorithm that finds the bit allocation that can achieve the maximum results show the same characteristics as in the group-coincidence systems. The minimum-slot Algorithm 5 has the highest capacity. The interference-based algorithms and the reverse water-filling algorithm have capacities that are close to one another and are slightly lower than that of Algorithm 5. The transmitted power-based algorithms have the lowest capacities. Simulations have also shown that the bit distributions for these six algorithms are very close to those of the group-coincidence systems shown in Figure 4-5. The improvement in capacity of Algorithm 5 over Algorithms 1 and 2 is smaller than in the group-coincidence systems. With the orthogonal hopping patterns, users encounter a different set of interferers in every slot. Users need to compete with more interferers for the channels. Algorithm 5 may not offer enough capability for the users to avoid all of the large interferers in their slots as in the group-coincidence systems. This is also the reason that the capacities of the orthogonal systems are lower than the capacities of the group-coincidence systems for all six bit allocation algorithms studied. However, with channel coding across the slots used, we expect the differences in capacities for the orthogonal and the group-coincidence systems to be smaller as in the coded *M/N* systems described in Chapter 3.

however, has the additional flexibility to allocate bits according to the congestion condition in the hopping patterns. It can admit users that are unable to achieve the fixed constellation in every slot used as in the *M/N* = 8/23. The system capacity improves significantly.

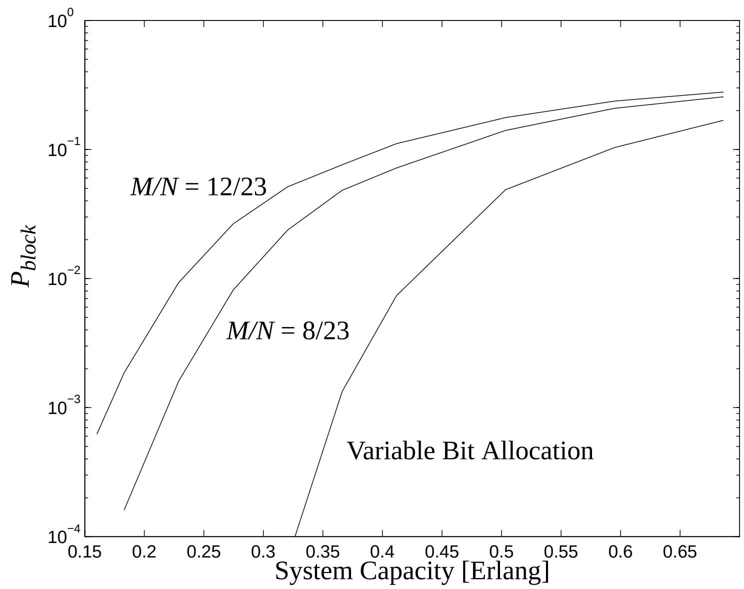

Figure 4-6 Simulation results for variable bit allocation and *M/N* systems with all users having the same throughput.

However, variable bit allocation may not be possible for the wireless environments that change quickly, e.g. cellular mobile. Probing needs to be performed constantly under these conditions. In a distributed system where channel probing and power control take time to adapt, the delay, along with the time it takes to calculate the new bit allocations, may render the new bit allocations difficult or even impossible to obtain as the channels vary.

4.1.3.2 Orthogonal Hopping Patterns

Figure 4-7 shows the simulation results for the six variable bit allocation algorithms described earlier for the systems with orthogonal hopping patterns. The filling of SIR, also obtains the most throughput desired in very few slots. These slots usually have very high achievable SIR and on the average, have no interferers or have interferers that have very low mutual link gain with the new user. The bit distribution of Algorithm 6 also takes on the general shape of Algorithm 5.

We now compare the system capacity of the variable bit FH-CDMA systems with the FH-CDMA systems deploying interference avoidance in the form of transmitting in M out of every N slots. N is set equal to twenty-three so that N slots correspond to one frame. The M/N systems assign a fixed constellation in the M slots they view as favorable. We assume that these systems are operating in the same environment and have the same bit rate of $48 \times C$ bits/frame where C is the number of symbols per slot. The variable bit allocation system utilizes the minimum-slot Algorithm 5. The variable bit allocation can carry as much as six bits of information in one symbol. Two M/N systems are simulated. In one of the systems, each symbol transmitted carries four bits of information. Twelve out of every twenty-three slots are used (M/N =12/23). In the other M/N system, every symbol transmitted carries six bits of information (M/N = 8/23). The results are shown in Figure 4-6. The system with M/N = 8/23 can obtain higher system capacity than the M/N = 12/23. The users in the M/N = 8/23 system concentrate their throughput in fewer slots and is more effective in avoiding large interferers. This concurs with the results from the bit allocation exhaustive searches. Figure 4-6 also shows that the system capacity of the variable bit allocation system is 50%-64% better than that of the M/N= 8/23 system for P_{block} of 0.1% to 1% and 75% to 100% better than that of the M/N = 12/23 system. The bit distribution among the slots of the variable bit allocation system is similar to Figure 4-5 for Algorithm 5. The largest constellations, which are the same as the M/N=8/23 system, are used in most of the slots that carry information. The bit allocation system,

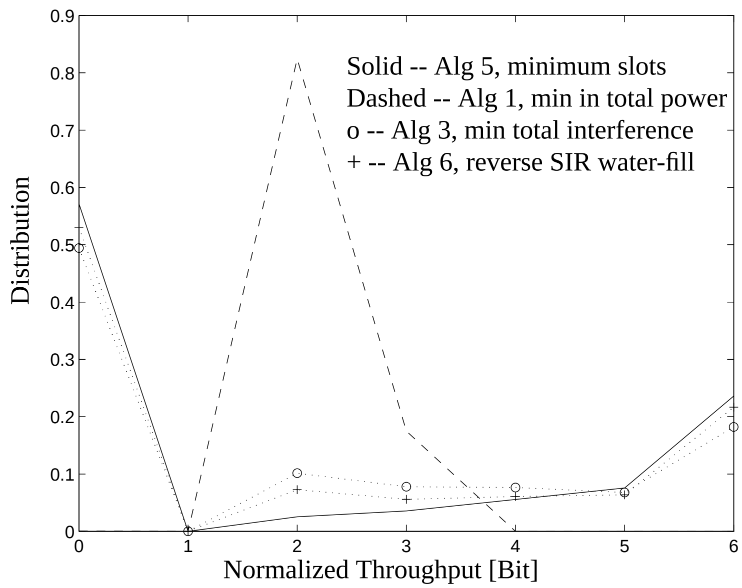

Figure 4-5 Distribution of the bits allocated from simulations.

The transmitted power-based algorithms tend to assign the smallest constellations to all of the slots as they often require the least power. There are usually no slots left unused. These algorithms do not perform interference avoidance and are similar to the equal throughput algorithm in Section 4.1.2. The interference-based algorithms, on the other hand, assign large constellations to the slots that have no interference or have interferers that are far away. In these slots, the new users can obtain the highest throughput without inducing much additional interference from the system and leave many of the slots unused. The bit distributions of these algorithms are very similar to Algorithm 5. The interference-based algorithms better use the statistics derived from channel probing than the power-based algorithms. Instead of passively minimizing the interference generated by the new user as in Algorithms 1 and 2, Algorithms 3 and 4 estimate how the users already in the system would react to the interference generated by the new user. Algorithm 6, which performs reverse water-

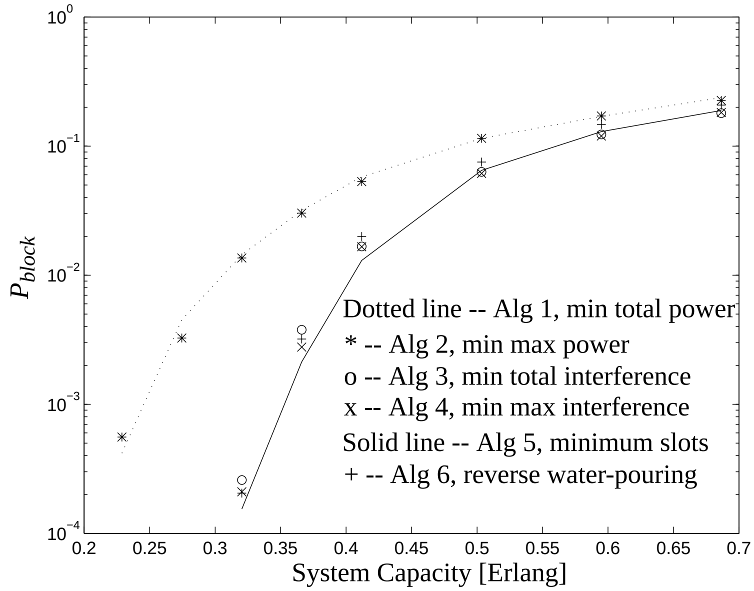

Figure 4-4 Bit allocation simulations for group-coincidence systems.

Figure 4-5 shows the distributions of the slots used by the six algorithms as a function of the bits carried per symbol. No slots carry just one bit of information as BPSK is not allowed. Algorithm 5, which achieves the highest system capacity, is able to assign the maximum constellation of 64-QAM to the most slots among the six algorithms and at the same time leave the most slots unused. It minimizes the number of slots a new user transmits and concentrates its throughput and power in these slots. The new user, at the same time, avoids the slots with large interference when possible. These are the characteristics associated with the maximum throughput bit assignments found by the exhaustive searches in Section 4.1.2. Minimizing the transmitted slots that a user generates power also gives future arrivals more flexibility to perform interference avoidance.

coincidence (GC) systems assign a new user to share every slot its hopping pattern with one group of users. That is, the group of potential interferers is the same is every hop. The orthogonal systems assign a new user a hopping pattern such that the user encounters a completely different group of interferers in every hop. In both of these types of systems, there is no *intra-cell* interference as the users do not share any slot in their hopping patterns with the other users in the same cells.

4.1.3.1 Group-Coincidence Systems

Before presenting the simulation results, we define system capacity in units of Erlangs as the average arrival rate divided by the total number of hopping patterns available in the system which is equal to the number of base stations multiplied by the number of hopping patterns available in each cell.

Figure 4-4 is a figure of probability of a new arrival is blocked, P_{block}, as a function of system capacity. It shows that the transmitted power-based Algorithms 1 and 2 have the lowest system capacity. Algorithm 5, which minimizes the number of slots a new user uses, achieves the highest capacity among the six algorithms. The interference-based Algorithms 3 and 4 and the reverse water-filling of SIR, Algorithm 6, all have similar system capacities and achieve capacity close to Algorithm 5. The difference in system capacities for Algorithm 5 and Algorithm 1 for P_{block} of 0.1% to 1% is approximately 30% to 45%.

6. reverse water-filling of SIR

Algorithms 1 and 2 are both transmitted power based. Algorithms 3 and 4 are interference based. Algorithm 5 performs interference avoidance by limiting the number of slots used. It is designed to give the users that arrive later more freedom to perform interference avoidance. Algorithm 6 performs reverse water-filling of SIR. Reverse water-filling of SIR can be best described by turning Figure 4-4, which shows the maximum achievable SIR for all available slots, upside-down. A new user first determines the maximum achievable SIR, γ_{max}, in each slot via channel probing. SIR is then "poured" into these slots with uneven "depth" until the desired throughput is achieved with SIR of γ'. Reverse water-filling of SIR is proven to be the optimum bit allocation for the multitone system at high SIR [41].

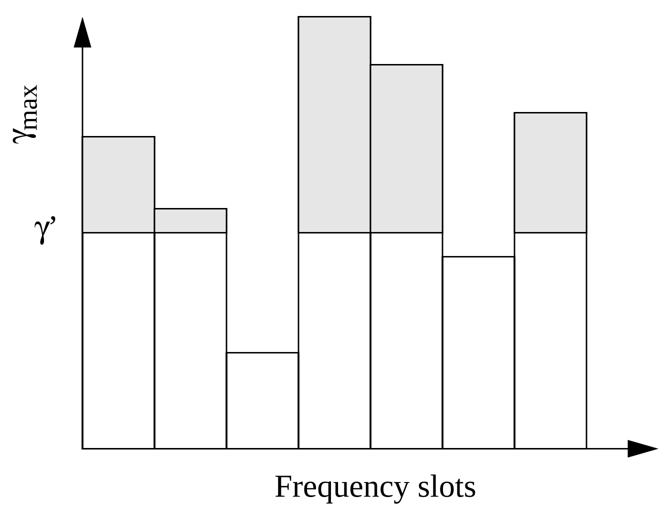

Figure 4-3 Reverse water-filling of SIR for a multislot system.

We present the simulation results for indoor FH-CDMA wireless systems with two different hopping patterns: group-coincidence and orthogonal. The group-

4.1.3 Simulation Results

In this section, we test several *ad hoc* bit allocation algorithms in dynamic simulations. The simulations are performed for the reverse link of a nineteen-cell indoor wireless system as described in the last section. QAM is used. The minimum constellation is 4-QAM with desired SIR of 10 dB. 3 dB is needed for every additional bit. We impose an additional constraint for the maximum constellation due to hardware linearity constraints. 64-QAM is the largest constellation possible. We assume the users arrive with a Poisson distribution and have i.i.d. exponential service time. The systems have twenty-three frequency bins. Each frame contains twenty-three time slots. There are twenty three hopping patterns available in every cell. Each slot has C symbols. Unless otherwise stated, we assume every user desires $50 \times C$ bits/frame. We further assume that the users and surrounding objects are stationary so that the channel conditions do not change for the duration of the calls.

Channel probing is performed for every new user. Probing provides enough information to allow the system to estimate the maximum achievable throughput in every slot and predict the transmitted power needed and interference induced for any throughput less than or equal to the maximum throughput. The system then uses the statistics obtained from probing to determine how the bits are allocated. We compare six different bit allocation algorithms. They are:

1. minimizing the total transmitted power in the hopping pattern
2. minimizing the maximum transmitted power in the hopping pattern
3. minimizing the total interference induced in the hopping pattern
4. minimizing the maximum of the interference induced in the hopping pattern
5. minimizing the total number of slots used in the hopping pattern

concentrating the throughput of each user in one slot and transmitting no power in the rest. This can be viewed as a form of interference avoidance as in the *M/N* FH-CDMA systems in Chapter 3. The users transmit in the slots with low interference. They, on the average, do not generate too much interference to the system. The system throughput increases. In the variable bit allocation system, users that are close to each other achieve most of their throughput from different slots. They are decoupled by avoiding transmitting in the same slots. The users arrange themselves so that they only share the transmitted slots with users that have very low mutual link gains. This allows the users to achieve high throughput. As the number of slots increases, the users have more freedom to avoid each other. The maximum achievable throughput increases. When the number of slots becomes as large as the number of users (B=N), the maximum throughput is infinite. This is achieved again by assigning each user to a different slot, thus avoiding any interference.

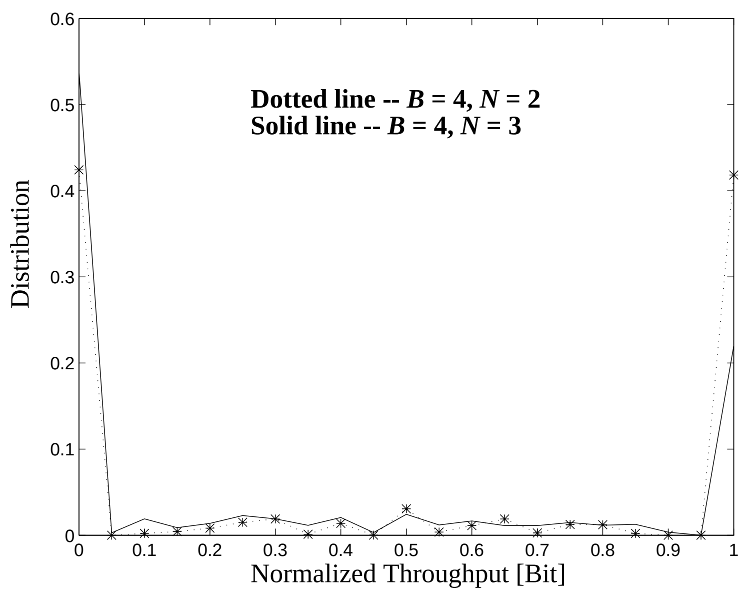

Figure 4-2   Distribution of the bits allocated from the exhaustive searches.

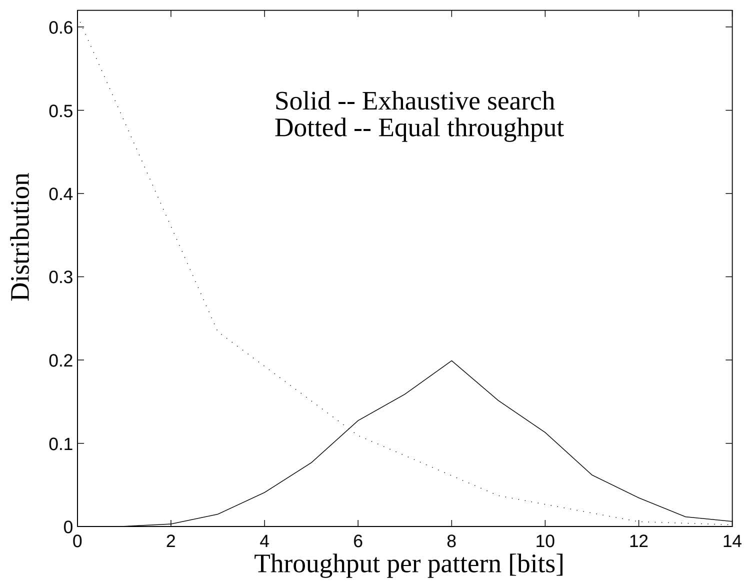

Figure 4-1 Distribution of total throughput for four users and three slots.

From Table 4-1, for systems with four users, the exhaustive searches show that the average maximum achievable throughput per slot increases if the number of slots is increased from two to three for a system with four users. On the other hand, the throughput stays the same for the equal throughput system as the maximum throughput per slot is independent of the number of available slots. The increase in throughput per slot may seem similar to information theory in source coding which states as the number of dimensions (slots in this case) increases, the average amount of information that can be represented by a symbol per dimension also increases. Figure 4-2, however, is more indicative of why the system throughput is much higher from exhaustive searches as the number of slots increases. Figure 4-2 shows the normalized bit distributions among the N slots from the maximum throughput found by the exhaustive searches. It is normalized to the total maximum throughput of the N slots for each sample. As Figure 4-2 shows, the maximum throughput is usually achieved by

Table 4-1: Results of exhaustive searches for the maximum average bit allocation per slot.

	Equal Throughput [bits]	Exhaustive Searches [bits]	Difference [%]
B = 4, N=2	0.5833	2.0722	255.3
B = 5, N=2	0.1915	1.4556	660.1
B = 4, N=3	0.5895	2.6314	346.4

Table 4-1 shows that the equal throughput algorithm does not find the best allocation possible. As the number of the users increases, the difference in throughputs between the equal throughput algorithm and the exhaustive searches increases. Figure 4-1 show the distribution maximum achievable bits for a system with four users and three slots. The equal throughput algorithm is not able to allocate throughput to the users if the users are close to each other in a large fraction of the simulations. The distribution decreases rapidly as the maximum achievable throughput increases. The distribution from the results of exhaustive searches tends to concentrate around the average maximum throughput and tapers off as the number of bits increases and decreases at about the same rate. These characteristics are also observed for the systems with different number of users and slots tabulated in Table 4-1.

size is 4-QAM and requires an SIR of 10 dB. We use the approximation that an additional 3 dB is needed for every additional bit of information to be carried by a symbol. Let X denote the throughput of every user. If there are B users sharing N slots, the exhaustive search starts with one bit of throughput for all users (X=1), the search tries all possible bit allocations in these N slots for the total X bits for each user and all possible combinations of bit allocations among the B users. The exhaustive search does not stop until a feasible power vector for every slot is found such that every user can maintain X bits of throughput. We then increase the system throughput by allocating X+1 bits to all users and search for feasible power vectors again. This process is repeated until no more feasible power vectors can be found for the desired throughput.

Unfortunately, the number bit allocations that need to be searched is prohibitively large for a system with even moderate number of slots and/or users. The number of allocations is closely upper bounded by $[C_X^{(X+N-1)}]^B$ where $C_X^{(X+N-1)}$ is the combination of selecting X items out of (X+N-1).

Table 4-1 shows the results of the exhaustive searches for systems with three to five users sharing two slots and a system with four users sharing three slots. One column tabulates the maximum throughput per slot for a bit allocation algorithm that assigns the same number of bits in every slot for every user. This is computed using the single channel eigenvalue techniques described in Section 4.1. The other column lists the results from the exhaustive searches.

Table 4-1: Results of exhaustive searches for the maximum average bit allocation per slot.

	Equal Throughput [bits]	Exhaustive Searches [bits]	Difference [%]
B = 3, N=2	1.4881	3.1726	113.1

Since $\gamma_2^1 > 0$ and $\gamma_2^2 > 0$,

$$\left(\frac{\gamma_2^1}{\gamma_2^2} - \frac{\gamma_2^2}{\gamma_2^1}\right) \geq 2$$

and is equal two only if $\gamma_2^1 = \gamma_2^2$ which violates our initial assumption of $(\gamma_1^1, \gamma_2^1) \neq (\gamma_1^2, \gamma_2^2)$. Since *a* and (1 - *a*) are positive, (4.7) is less than zero. The feasible region for the 2×2 principle minor is non-convex and the optimum bit allocation problem (4.2) is *NP*-hard. The optimization problem can also be proved to be *NP*-hard without invoking the Perron-Frobenius theorem. The proof is shown in Appendix B.

4.1.2 Exhaustive Searches

Since the optimization problem (4.2) is *NP*-hard, exhaustive searches are needed to find the optimum bit allocation. In this section, we present the results of the exhaustive searches. We hope to gain insights on how we can develop bit allocation algorithms that can better use the statistics obtained from channel probing and achieve high system capacities.

Exhaustive searches are performed again for the reverse link of a nineteen-cell indoor system. The cells are hexagonal in shape and form three concentric layers. The users are uniformly distributed in the coverage area. We assume propagation loss due to attenuation of signal through space can be modeled by the third power attenuation model. Shadowing, which is caused by signals traveling through objects or through a room with the wave guide effect, is modeled by a lognormal distribution with standard deviation of 10.0 dB.

Quadrature-amplitude modulation (QAM) is used. The minimum constellation

$p_{m,i}$, from the problem.

Even though the cost function (4.2) is a linear function and the feasible region for (4.3) is convex, the optimization problem is unfortunately *NP*-hard. There are no algorithms that can solve this problem in polynomial time. To prove the optimization problem is *NP*-hard, we only have to show that the feasible region for one of the constraints is non-convex. The proof is straight-forward. We expand the 2×2 principle matrix from (4.5) and drop the slot index k for simplicity in notation. We assume that there are two sets of SIR (γ_1^1, γ_2^1) and (γ_1^2, γ_2^2) that lie on the boundaries of the feasible region:

$$\begin{aligned} 1 - \gamma_1^1\gamma_2^1 G_{12}G_{21}/G_{11}G_{22} = 0 \\ 1 - \gamma_1^2\gamma_2^2 G_{12}G_{21}/G_{11}G_{22} = 0 \end{aligned} \tag{4.6}$$

Let $(\gamma_1^1, \gamma_2^1) \neq (\gamma_1^2, \gamma_2^2)$. We would like to show that for some positive number a, $0 < a < 1$, $(a\gamma_1^1 - (1-a)\gamma_1^2, a\gamma_2^1 - (1-a)\gamma_2^2)$ is not in the feasible region. That is, we need to show

$$1 - [a\gamma_1^1 - (1-a)\gamma_1^2][a\gamma_2^1 - (1-a)\gamma_2^2] G_{12}G_{21}/G_{11}G_{22} \tag{4.7}$$

is less than zero. After some algebraic manipulation and substitution using (4.6), (4.7) is equal to

$$a(1-a)\left[2 - \left(\frac{\gamma_2^1}{\gamma_2^2} - \frac{\gamma_2^2}{\gamma_2^1}\right)\right]$$

γ_{ik}. $\vec{\gamma}_k$ is the vector form of the B desired SIR's in slot k for the users. $H(\vec{\gamma}_k)$ is an $B \times B$ matrix similar to the matrix H in (2.5). The diagonal elements of $H(\vec{\gamma}_k)$ are equal to one and the off diagonal element (i, j) is equal to - $\gamma_{ik}\, G_{ij} / G_{ii}$. $P_k = [\, p_{ik}\,]$ is the $B \times 1$ non-negative power vector for the set of desired SIR $\vec{\gamma}_k$ in slot k. $N(\vec{\gamma}_k)$ is a $B \times 1$ noise vector similar to the vector N in (2.5). The i-th element of N is equal to $\gamma_{ik}\, n_i / G_{ii}$.

If the number of slots is greater than or equal to the number of users ($B \le N$), the throughput of each user is infinite since we do not impose a maximum power constraint. The infinite throughput is achieved by assigning each user to a different slot. Since there is no interference, the maximum achievable SIR is unbounded. If there is only one slot $(N = 1)$, the maximum achievable SIR for these B users is equal to the reciprocal of the largest eigenvalue of a $B \times B$ matrix F. F is closely related to the matrix $H(\vec{\gamma}_1)$ and has diagonal elements equal to zero and the off diagonal element (i, j) equal to G_{ij} / G_{ii} [83].

(4.4) is a non-linear equations with $2 \times B$ unknowns: γ_{ik} and p_{ik} for each slot k. We can reduce the number of variables by half by applying the Perron-Frobenius theorem [27][60]. The theorem states that in order for (4.4) to have non-negative feasible power solution, the necessary and sufficient condition is that

$$\Delta_{i,\,k} \ge 0 \tag{4.5}$$

for all $1 \le i, k \le B$, where $\Delta_{i,\,k}$ is the i-th principle minors of $H(\vec{\gamma}_k)$. In other words, the determinants of all of the principle submatrices of $H(\vec{\gamma}_k)$ along the diagonal have to be greater than or equal to zero. Since $\Delta_{i,\,k}$ is only a function of the desired SIR, γ_{ik}, replacing (4.4) by (4.5) removes all of the variables representing transmitted power, transmit to the users and for a peer-to-peer system where no base station infrastructure is available. We assume that there are B users and N frequency slots in the wireless system. In each of the N slots, the desired SIR of user i in slot k, γ_{ik}, has to satisfy the following inequality,

$$\frac{P_{ik} G_{ii}^{k}}{\sum_{j \neq i} P_{jk} G_{ij}^{k} + n_{ik}} \geq \gamma_{ik} \tag{4.1}$$

where P_{jk} is the transmitted power of user j in the k-th frequency slot, n_i^k is equal to the noise floor at base station i, and G_{ij}^k is the link gain from user j to the base station in cell i. We assume G_{ij}^k and n_i^k are independent of the frequency slots used and drop the superscript k. There are B such inequalities for each of the N slots.

The optimization can be stated in the following compact matrix form:

$$max \quad \sum_{i=1}^{B} X_i \tag{4.2}$$

$$X_i \leq \sum_{k=1}^{B} log_2 (1 + \gamma_{ik}) \tag{4.3}$$

$$X_i = X_j \qquad 1 \leq i, j \leq B$$

$$H(\vec{\gamma}_k) P_k \geq N(\vec{\gamma}_k) \tag{4.4}$$

$$P_k \geq 0 \qquad \vec{\gamma}_k \geq 0 \qquad 1 \leq k \leq N$$

We try to maximize the total throughput of the system. X_i is the throughput of the i-th user. The logarithm function with base two is used to upper bound the achievable bit rate for the desired SIR of γ_{ik} [17]. $\vec{\gamma}_k$ is a $B \times 1$ vector with the i-th element equals to

4.1 Equal Throughput FH-CDMA Systems

At first glance, the FH-CDMA wireless system with variable bit allocation is similar to the multitone wireline communication system [9][38]. In both of these systems, the users first probe the channels that are available to them to obtain enough statistics. They then estimate the maximum achievable signal to interference ratio (SIR) and the transmitted power needed [37][80]. Using these estimates, the users allocate bits and power in the slots that have favorable channel conditions. In the multitone wireline communication system, however, the system has an average power constraint. That is, there is a limitation on the total transmitted power permitted for each user. In an FH-CDMA wireless system, there is usually no such limitation, although low transmitted power is desirable as it generally leads to low interference. A maximum transmitted power for every slot due to hardware limitations is more often the case.

In Section 4.1.1, we first state the basic idea of the variable bit allocation problem for a wireless system that requires all users have the same throughput. We would like to determine the maximum achievable bit rate for a given set of users which share the same slots. We then show the difficulties in solving this optimization problem. In Section 4.1.2, we present the results of the exhaustive searches. In Section 4.1.3, we discuss the results of simulations for several bit allocation algorithms and comment on their performance.

4.1.1 Basic Idea

We would like to find the maximum throughput that a set of users can all achieve in the slots they share. In this section, we state this optimization problem for the reverse link in a cellular system where users transmit information to the base stations. The problem can be formulated in a similar fashion for the forward link where base stations

Chapter 4

BIT ALLOCATION ALGORITHMS

In an indoor wireless FH-CDMA system, the channels vary slowly as users and interferers move at slow speeds. The system can take advantage of the different interference statistics in a hopping pattern and assign different throughputs to the slots to minimize the interference the user causes. Since FH-CDMA systems are interference limited, reduction in interference can lead directly to higher system capacity.

In Section 4.1, we study the problem of bit allocation in a system where every user desires the same throughput in an FH-CDMA indoor wireless system. Our goal is to design bit allocation algorithms that can achieve high capacity by permitting more users to communicate in the system. In Section 4.2, we briefly describe the problem of a wireless system with a single channel and variable bit allocation. In this system, we attempt to maximize the throughput of the channel given a set of users, each of whom has a minimum throughput requirement. A centralized bit allocation scheme is presented. We then offer some concluding remarks and suggestions for future research in Section 4.3.

in every slot into the system by averaging out the differences in SIR levels. Simulations show that with a simple 32-state convolutional code, an *M/N* outdoor system can achieve higher capacity than a IS-54 cellular system. For the indoor systems, we have proposed a simple multilevel pragmatic TCM code that can offer sufficient coding gain for different constellation sizes with a simple decoder. This TCM code is suitable for a variable bit allocation system where all bits are equally important.

We have also looked into the effects of the maximum and minimum transmitted power constraints on the system capacity. Simulations show that in an interference-limited system, the effects of limited dynamic power range is small if the users can perform interference avoidance and if the desired SIR is large. The large desired SIR indirectly promotes interference avoidance since users that are close to one another are not able to obtain the high SIR in the same slots. The system capacity depends more on the ability of the users to dynamically arrange their transmitted slots to avoid sharing channels with users nearby. Our simulations, however, do not take into account of the additional power range needed for various adaptive algorithms. Full distributed simulations which are a lot more computationally intensive are required.

interference as the propagation loss follows the third degree distance law rather than the fourth degree. The additional flexibility of allocating variable bits allows users that face difficult channel conditions into the system. It gives the users that are unable to maintain a fixed constellation in all transmitted slots as required in an *M/N* system to adjust bit rates to accommodate the difficult channels. These users, on the average, require a larger transmitted power range to overcome the difficult propagation conditions.

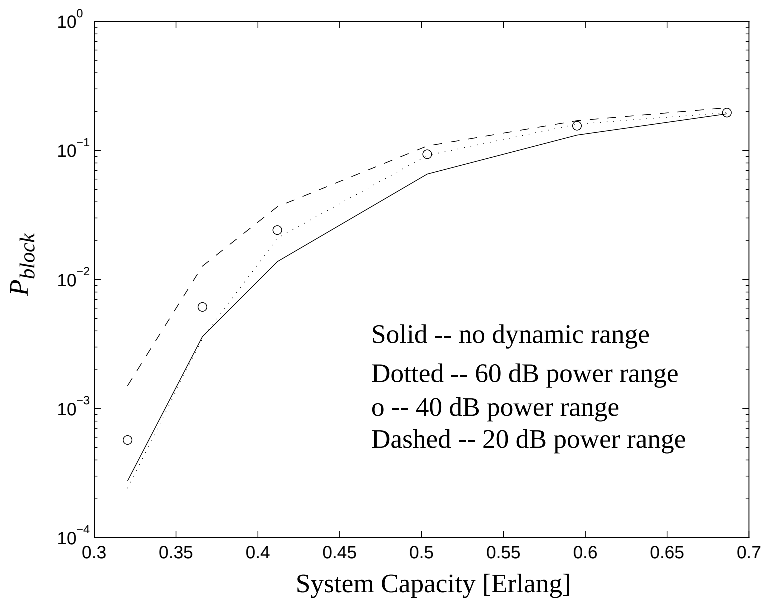

Figure 5-5 System capacity of an equal throughput variable bit rate system with various dynamic power ranges.

5.3 Summary

We have examined the effects of coding on the outdoor wireless systems. Along with interleaving, coding not only combats fading and protects against noise and interference, but it also allows the users who are unable to sustain a good signal quality an SIR of 10 dB for the desired P_b. An additional 3 dB of SIR is needed for a symbol to carry an extra bit of information. We assume there is some hardware linearity constraint such that 64-QAM is the maximum constellation. Propagation loss is modelled by the inverse third power distance law and shadowing is modelled by a lognormal distribution with standard distribution of 10 dB. We assume the receivers have infinite diversity to overcome the effects of multipath fading.

Figure 5-5 shows the probability of blocking, P_{block}, as a function of the system capacity. The minimum-slot bit allocation algorithm, which is shown to achieve the highest system capacity in Chapter 4 among the algorithms studied, is used. This algorithm minimizes the number of slots each user transmits by assigning the largest possible constellations. Since the users concentrate their throughput in a small fraction of the available slots, they are able to avoid sharing the channels with large interferers. In addition, since users minimize the number of transmitted slots, this algorithm allows the newer arrivals more flexibility to perform interference avoidance. For $10^{-3} \le P_{block} \le 10^{-2}$, Figure 5-5 shows that 40 dB of dynamic power range is sufficient to achieve approximately 95% of the capacity for a similar system without the transmitted power constraints. Even with a small dynamic power range of 20 dB, the system can still obtain about 90% of the maximum capacity. Similar to the outdoor *M/N* system, the effects of dynamic power range are small because the bit allocation performs interference avoidance and assigns large SIR to the slots used. Users sharing the same transmitted slots are sufficiently far away on the average. Compared to the outdoor *M/N* system, it takes a larger dynamic power range for the indoor system to achieve the capacity of a similar system without power constraints. This can be attributed to the fact that the indoor propagation environment are more prone to the system capacity [46]. A larger transmitted power range is needed for the interference averaging system in the slots where the channel code cannot ensure signal integrity. The transmitted power has to be raised significantly to overcome the large interference.

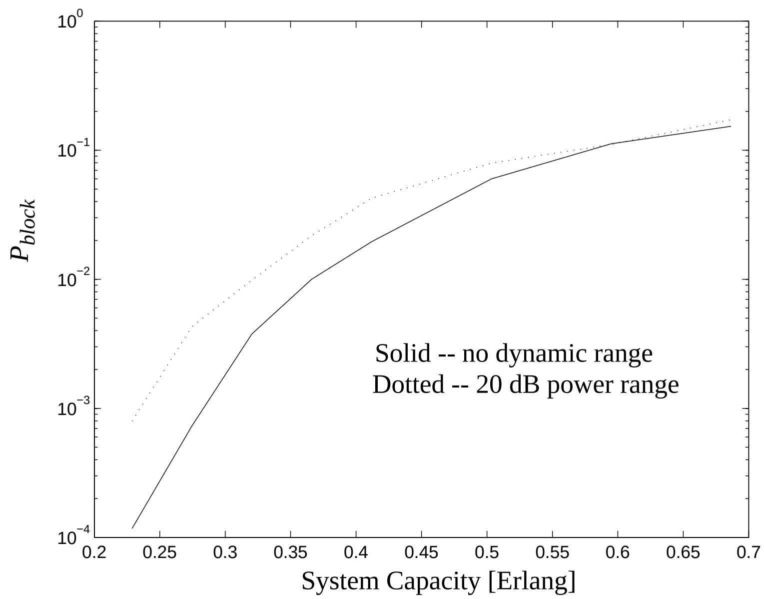

Figure 5-4 System capacity of an *M/N* = 8/23 outdoor system with various dynamic power ranges.

5.2.2 Indoor Systems with Bit Allocation

For indoor channels that vary slowly, a system can allocate different throughputs to different slots to improve the system capacity. We assume that there are 23 slots per frame and that each slot contains C information bearing symbols. Each user requires the same throughput of $50 \times C$ bits/frame, has Poisson arrivals, and has i.i.d. exponential service time. Simulations are performed for the reverse link of a nineteen-cell indoor system. QAM is used. The smallest constellation is 4-QAM which requires the simplex algorithm is used to find the feasible power vector that minimizes the combined transmitted power of all users. This, however, does not account for the additional dynamic power range needed for various adaptive algorithms to converge. Full simulations with all distributed algorithms used require much more simulation time.

Figure 5-5 shows the performance curve for an FH-CDMA system with *M/N* = 8/23. That is, every user transmits in eight out of every 23 slots. A large desired SIR of 22 dB is chosen since it is shown in Chapter 4 that systems with users concentrating their throughputs in a small fraction of the slots with high bit rates have higher system capacities. For P_{block} between 0.1% and 1%, Figure 5-5 shows that a system with a small dynamic range of 20 dB can achieve about 90% of the system capacity of a system without transmitted power constraints. In other words, the system capacity would not improve significantly if the dynamic range of each user is increased. This can be attributed to the fact that we set the dynamic power range such that even users that are far away from the base station can achieve large SIR if there are no interferers. The system is interference-limited rather than noise-limited. With the large desired SIR and the flexibility of users to dynamically find the suitable slots in which to transmit, users transmit in the slots where there are no large interferers. The interferers sharing these slots are far enough apart such that the mutual interference they generate for each other is small. With sufficient transmitted power and *M/N* for interference avoidance, the system capacity depends more on the ability of the users to avoid sharing the transmitted slots with one another than each user having a large dynamic power range.

While an *M/N* FH-CDMA system implementing interference avoidance needs 20 dB of dynamic power range to achieve most of the system capacity, an interference averaging FH-CDMA system needs 60 dB of dynamic power range to achieve 90% of with more complex coding schemes so that the required SIR's are lowered for the desired P_b. The lower desired SIR leads to lower system interference which, in turn, increases the system capacity.

5.2 Limited Dynamic Power Range

In practical wireless systems, there are often limitations on the minimum and maximum transmitted power. These limitations are often characterized by the hardware architecture and power supply. These limits affect the system capacity as users may no longer have the large transmitted power needed to sustain the desired SIR in difficult propagation conditions and may no longer transmit at low enough power to avoid generating too much interference to the other users. In this section, we examine the effect of the limited dynamic power range for both the outdoor *M/N* system and the indoor bit allocation system.

5.2.1 *M/N* Outdoor Systems

Simulations are performed for the reverse link of a nineteen-cell outdoor system. We assume each user shares all of the slots in its hopping pattern with the same group of interferers. That is, the users are assigned the group-coincidence (GC) hopping patterns. Propagation loss is modelled by the inverse fourth power distance law and shadowing is modelled by a lognormal distribution with standard distribution of 8 dB. Dynamic simulations are performed for stationary users. Users arrive at the system with a Poisson arrival rate and have i.i.d. exponential service time. New users determine which M out of N slots to transmit after probing the channels. We assume the receivers have infinite diversity to mitigate the effects of multipath fading. Since the additional power constraints are linear, as are the rest of the power-SIR constraints equations (2.5),

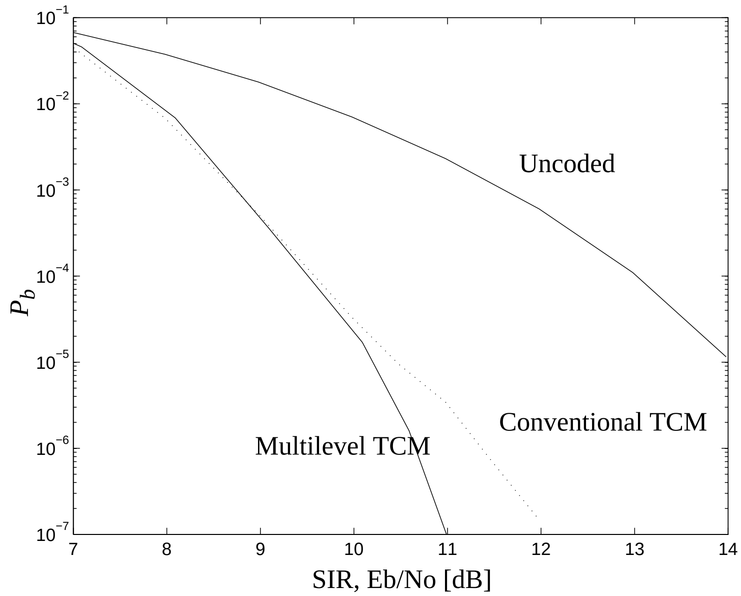

Figure 5-3 P_b as a function of SIR for the multilevel TCM code with 32-QAM constellation.

The proposed coding scheme provides moderate coding gain. If higher coding gain is desired, more complex encoding scheme should be used. A more complex encoder can be used in place of the parity code to protect the uncoded bits. A rate-2/3 convolutional code can also be used in the place of the rate-1/2 code to achieve higher coding gain. A 32-state rate-2/3 convolutional code, however, does not offer the same coding gain as the rate 1/2 code for the coded bits. To provide the same coding gain, the number of states of the Viterbi decoder needs to be higher. In addition, the smallest constellation that can be mapped simply by a rate-2/3 convolutional code is 8-QAM. The 4-QAM constellation can no longer be used. This may reduce the system capacity as the system has less flexibility in assigning bits in each slot. Simulations from Chapter 4, however, show that the bit allocation algorithms that achieve the highest system capacity tend to assign the largest constellations almost exclusively. The reduction in system capacity may not be significant. Higher system capacity can also be achieved which is very difficult at low SIR.

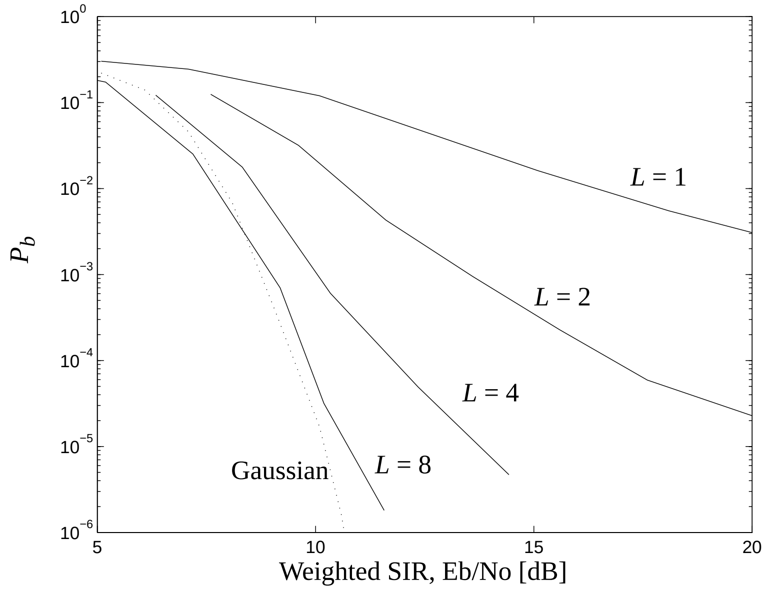

Figure 5-2 P_b as a function of weighted SIR for different orders of diversity combining for 32-QAM.

Figure 5-3 shows the error performance curve for 32-QAM in an AWGN channel for the proposed encoder. The multilevel code can achieve 4 dB of coding gain at P_b of 10^{-7}over an uncoded system. The simple rate 9/10 parity code gives the multilevel code a 1 dB gain over a similar TCM code without the parity code at P_b of 10^{-7}. The asymptotic coding gain of the rate-9/10 parity code is approximately 2.1 dB. Similar coding gain for the multilevel TCM is also found for the other QAM constellations of interest. No interleaving technique is used as we assume the diversity order is large and the channels are Gaussian-like. Simulations of the proposed coding scheme for all constellations are needed so that an SIR threshold can be found for each bit rate such that the required P_b can be maintained. These thresholds can then be used to determine the system capacity through simulations with power control.

are not used since they do not offer sufficient protection for the smallest constellation.

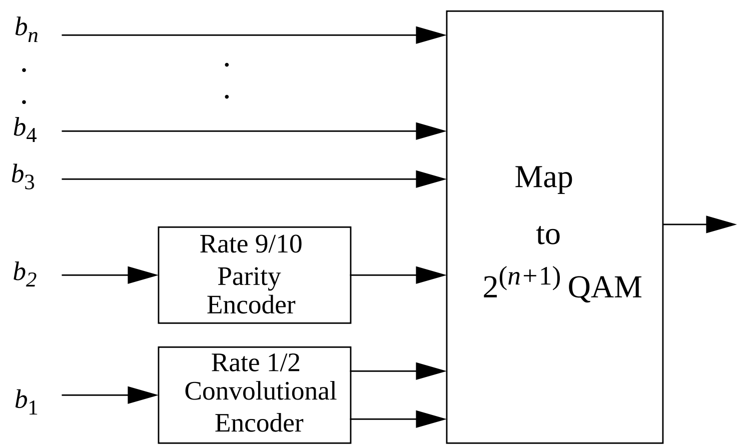

Figure 5-1 Multilevel TCM encoder for the indoor wireless system with variable bit allocation.

The indoor radio environment suffers from multipath fading which changes slowly. Antenna diversity can be used to combat this problem by using several receiving antennae at sufficient distance apart such that each received signal undergoes independent multipath Rayleigh fading. Figure 5-2 shows the probability of bit error, P_b, as a function of SIR for various orders of antenna diversity, L. We assume that the receivers have perfect channel knowledge so that we can obtain the phase to demodulate the QAM signal and the fading amplitude to apply maximal ratio combining. As the diversity order increases, for example $L = 8$, the error performance of the system approaches transmission over an additive white Gaussian noise (AWGN) channel. We assume that the receiver in our system has a large order of diversity so that we can use the additive white Gaussian noise channel as our channel model. In Figure 5-2, at low SIR, the error performance of the system with diversity order of eight seems to have better performance than a system operating under an AWGN channel. This is due to the assumption that the diversity receiver can obtain perfect fading statistics congested. Quadrature amplitude modulation (QAM) is used to accommodate different bit rates with high bandwidth efficiency. The minimum constellation size is 4-QAM. The maximum constellation size is 64-QAM. We are interested in finding a coding scheme that provides sufficient coding gain for all constellations used and yet is simple enough that it does not require several encoder/decoder pairs for different constellations. A simple pragmatic trellis coded modulation (TCM) scheme is chosen.

The proposed TCM encoder is shown in Figure 5-1. It is a simple multilevel TCM encoder [53] based on a 32-state rate-1/2 convolutional code. There are n input bits to the encoder. One of the input bits is coded by the rate-1/2 convolutional encoder to form two coded bits. This convolutional code is chosen so that even in difficult propagation conditions where only the smallest constellation, 4-QAM, can be sent, the information would have sufficient protection from the channel impairments. If the input bits to the encoder is greater than one bit, an additional parity encoder is added to protect the uncoded bits $\{b_2, b_3, \dots, b_n\}$. The parity code rate is 9/10. It adds a parity bit after nine input bits of b_2. The conventional pragmatic encoders proposed in [73] is not used because these encoders have lower code rates and do not protect non-square constellations like 8-QAM and 32-QAM. The punctured TCM codes proposed in [42] power control for signal-to-interference ratio improves the occupancy rate by 20% for a coded system. This improvement is an underestimate since many users in the interference avoidance system with power controlled for SIR can lower their transmit power in some of the slots while maintaining the desired P_b. This reduces the interference of the system and more users can communicate in the same channels.

For a digital cellular system like the IS-54 with frequency reuse factor of 1/7 and an 8Kb/sec speech codex, the information throughput of the system is

$$\frac{3 \times 8\text{Kbits/sec}}{30\text{KHz}} \times \frac{1}{7} = 0.114 \text{ bits/sec/Hz}$$

This capacity measurement is optimistic because it assumes that there exist some power and channel assignment algorithms such that all users can have good signal quality when the system is full. With the same bandwidth efficiency and the same code rate, the information throughput for a rate-1/2 coded DQPSK *M/N* CDMA-FH system without channel information is 0.384 bits/sec/Hz. Although we have left out the overhead and control bits in the computation for the IS-54 system, the *M/N* FH-CDMA system is able to achieve higher capacity with a more sophisticated power control scheme and with the flexibility to allow new user to avoid transmitting in the slots with large interference.

5.1.2 Variable Bit Indoor systems

In indoor environments, the radio channels often change slowly. We can take advantage of the different interference statistics each user encounters in every slot of the hopping pattern and assign large throughputs in the slots where the user can achieve large signal-to-noise ratio (SIR) and little or no throughput in the slots that are already occupancy rate/efficiency for each of the code and corresponding SIR threshold. While the rate-1/4 code has the highest occupancy rate, the efficiency of the system is approximately the same as systems with the other two codes. Table 5-2 shows the performance of the same channel codes if the channel states are estimated from the sixteen received symbols in each transmitted slot. The efficiency of the system implementing the rate-1/4 code drops about 26% due to errors in estimating the channel state estimates at low SIR. The efficiency for the rate-1/2 and rate-3/4 codes remain about the same.

Table 5-1: Coded FH-CDMA system with P_{block} = 1% and P_b=0.001 and perfect channel state information.

Code Rate	SIR [dB]	M/N	Occupancy Rate	Efficiency
1/4	3.0	21/23	0.91	0.23
1/2	7.5	13/23	0.50	0.25
3/4	12.5	9/23	0.34	0.26

Table 5-2: Coded FH-CDMA system with P_{block} = 1% and P_b=0.001 and estimated channel state information.

Code Rate	SIR [dB]	M/N	Occupancy Rate	Efficiency
1/4	4.0	18/23	0.68	0.17
1/2	8.0	12/23	0.48	0.24
3/4	12.5	9/23	0.32	0.24

The results from Table 5-2 are compared to a similar FH-CDMA system in which users transmit in every slot of their hopping patterns and power control is performed so that the received power for every user in every slot is the same. For the equal received power system with the same rate-1/2 32-state convolutional code and decoding depth of 19, the efficiency is 20% assuming the receivers have channel state information. Interference avoidance by choosing M out of every N slots to transmit and be maximized by choosing the appropriate code rate and the ratio M/N jointly.

It is difficult to predict what kind of SIR distribution a code can overcome in the M slots used while protecting against Rayleigh fading. To reduce simulation time, an SIR threshold, γ_{th}, is picked for each code. Simulations have been performed to make sure that the users with this SIR in every slot have P_b at least one magnitude less than the desired P_b. A new user would try to obtain SIR equal to γ_{th} in M out of every N slots in its hopping pattern. If it cannot achieve γ_{th} in M slots, the user then lowers its desired SIR until a feasible power vector can be found. Error simulation is then performed for the users who cannot achieve the SIR threshold in M out of every N slots. The occupancy rate obtained by this simulation is a lower bound for the maximum occupancy rate/efficiency possible. It is possible to increase the capacity of the system by lowering the SIR of some slots for the users who can maintain SIR at the SIR threshold in all slots transmitted.

In our simulations, P_{block} is set at 1%. Fading is assumed to be the same in every slot, but independent from hop to hop. Interleaving across each slot is needed to decorrelate the symbols to maximize the gain achievable by the channel code. To provide selection diversity, each user has two receiving antennae, each receiving a copy of the transmitted signal through an independently fading channel. In Table 5-1, the efficiencies for three convolutional codes are shown assuming the receivers have perfect channel state information. All three convolutional codes have 32-states and have the best distance property for their rate and number of states [45]. The decoding depth is 19 for all three codes. It is found that these codes do not perform much better with larger decoding depth. The SIR listed is the SIR threshold, γ_{th}, that guarantees P_b to be below the desired value of 0.001. N is 23 and M is selected to maximize the highest to protect the signals from fading. The interference avoidance technique only allows the users to transmit in the M favorable slots that the users can achieve good signal quality on the average. It does not change fast enough to account for fading conditions.

Simulations are performed for the reverse link of a nineteen-cell outdoor system. Users are assigned orthogonal hopping patterns so that they encounter a different set of interferers at every slot. We assume that propagation loss follows the fourth order distance law and that shadowing can be modeled by a lognormal distribution with standard deviation of 8 dB. Since we are interested in error rate analysis, static simulations are performed to reduce simulation time. In static simulations, one user is added at a time until the desired P_{block} can no longer be sustained. These simulations are different from the dynamic simulations performed in the earlier chapters where the arrivals of users follow a Poisson distribution and the service time is i.i.d. and exponentially distributed.

In our simulations, we assume the users are communicating in Rayleigh-faded channels. The effect of fading is mitigated by the channel code with interleaving and diversity techniques. Besides protecting the signal from fading and noise, the channel code can also average out the different interference environment each user faces in the M slots chosen to increase the system capacity. It allows users who are unable to sustain good SIR in all of the M transmitted slots into the system.

We define occupancy rate as the product of the fraction of the hopping patterns used and the ratio of M/N. It is a measure of the channel usage or capacity. We also define an information throughput measure, *efficiency*, as the number of bits per second per hertz that can be communicated reliably in the system. In an M/N CDMA-FH system, efficiency is equal to the product of the code rate and the occupancy rate for a probability of bit error, P_b, distribution required by the users and a specific P_{block}. It can of an *M/N* system with a simple convolutional code in the outdoor environment. We then describe a proposed a simple pragmatic trellis coded modulation (TCM) technique for the variable bit allocation system to simplify the decoder structure. In Section 5.2, we study the effects of dynamic range limitation and present the simulation results for both an outdoor *M/N* system and an indoor variable bit allocation system.

5.1 Channel Coding

Channel coding is an important part of wireless systems. In addition to protect the signals from fading and noise, it can be used to average out the different interference levels in the transmitted slots. This section is divided into two parts. We first present simulation results of an *M/N* outdoor wireless system with simple convolutional codes. We then discuss a simple coding scheme that can be used for to reduce the complexity of the variable bit rate transmitter and receiver.

5.1.1 *M/N* Outdoor Systems

In the outdoor environment, the channels often changes quickly. We allow each user the flexibility to transmit in M favorable slots out of every N $(M \leq N)$ so that the users can avoid sharing a channel with large interferers. This interference avoidance technique has been shown to increase the system capacity in Chapter 3. We assume that the phase of the received signal does not undergo significant changes between adjacent symbols. Differential quadrature phase-shift keying (DQPSK), which encodes information in the form of the change in the phases between two consecutive received symbols, is chosen as the modulation scheme. We also assume that the users cannot rearrange which of the M out of every N slots to transmit fast enough to avoid temporarily deeply faded channels. It is up to the error correcting code and interleaving

Chapter 5

IMPLEMENTATION ISSUES OF FH-CDMA SYSTEMS

In previous chapters, we examined the effects of dynamically assigning power and channels by applying the concept of interference avoidance and averaging for FH-CDMA wireless systems. We assumed that there existed some error correcting codes that can ensure satisfactory signal quality if the average SIR among the slots used is above an SIR threshold. We also studied the effects of variable bit allocation in an indoor environment. In this chapter, we study the effects of practical forward error correcting codes on interference averaging and system capacity. We also look at the problem of dynamic power limitation as each user has a fixed minimum and maximum transmitted power. These constraints on transmitted power can affect the system capacity as users may not be able to transmit large enough power to sustain the signal-to-interference ratio (SIR) they desire.

This chapter is divided into two sections. Section 5.1 presents simulation results antenna arrays, channel probing, and distributed power control. Better channel models are needed to capture the dynamics of the wireless channels as fading may be correlated between adjacent frequency bins. As the demand for more flexible wireless system continues to grow, better mixed-traffic models are needed for wireless systems that support a combination of voice, video, and data. With these models, the variable bit allocation algorithms can further maximize the channel throughput according to the traffic statistics. These and many other interesting problems faced by the system designers of FH-CDMA wireless systems make this an exciting research field with very high potential rewards.

system. Since high capacity wireless systems are interference limited, reduction in interference directly leads to increased capacity.

We have proposed several techniques for performing interference avoidance in FH-CDMA wireless systems. A user can probe the slots in the assigned hopping pattern and avoid large interferers by transmitting only in the M favorable slots out of every N. Simulations show that this interference avoidance technique along with randomization of the interferers the users encounter in every hop can significantly raise the system capacity. If the channels vary slowly as in some indoor channels, users can adjust the bit rate by transmitting more information in the slots with low interference and little or no information in the slots that are congested. This additional flexibility of varying bit rates can further increase the system capacity by more than 50% over an equivalent M/N system.

In this thesis, we focus our attention on slow-hopped CDMA systems. While it is arguable which of the multiple access techniques is the most suitable for wireless communications, all of the algorithms and concepts described in this thesis can be applied to all wireless systems regardless of the multiple access protocols used. The general idea of the increased flexibility to allow users to adapt to the changes in channel conditions and avoid large interferers should still increase the system capacity the wireless systems with different access protocols. The amount of improvement, however, is yet to be shown.

There are many other challenging problems that many researchers are currently examining for FH-CDMA wireless systems besides channel resource allocation. Synchronization and phase acquisition at every hop are very difficult problems as channels may undergo drastic changes from hop to hop. There is also the problem of interactions between different adaptive algorithms like adaptive

Chapter 6

CONCLUSION

With limited spectrum and difficult propagation conditions, channel resource allocation is an important part of designing a high capacity wireless communication system. The key feature among the channel resource allocation algorithms proposed in this thesis is the increased flexibility of the wireless system. With the increased flexibility, the systems can dynamically assign power and channels to users according to their propagation and interference condition. The channel resources can be used more efficiently as users adapt to the changes in channel conditions and try to minimize the system interference.

All of the proposed algorithms can be performed in a distributed fashion. No communication between any pair of users sharing the same channels is necessary. Only coordination between each transmitter-receiver pair is needed. The algorithms implement the concept of interference avoidance via the increased flexibility. Users selectively transmit in the slots so that they can avoid sharing the channels with large interferers and do not induce large interference among all of the users in the is equal to *det(G)*. We can then expand C_{iN}.

$$det(D) = \sum_{i=1}^{N-1} (-1)^{N+i} h_{1i} det\left(\begin{bmatrix} G_i \\ h_2^T \end{bmatrix}\right) + d_{NN} det(G)$$

where G_i is the matrix G with the *i-th* row removed. Now, expand the determinant in the summation along the last row

$$det(D) = \sum_{i=1}^{N-1} (-1)^{N+i} h_{1i} \sum_{j=1}^{N-1} (-1)^{N-1+j} h_{2j} det(G_{ij}) + d_{NN} det(G)$$

where G_{ij} is the matrix G with the *i-th* row and *j-th* column removed.

$$det(D) = d_{NN} det(G) - \sum_{i=1}^{N-1} \sum_{j=1}^{N-1} (-1)^{i+j} h_{1i} det(G_{ij}) h_{2j}$$

The double summation term is equal to $h_2^T adj(G) h_1$. (QED)

Appendix A

Proof of Lemma 3.0

Lemma 3.0: For an $N \times N$ square matrix *D*,

$$D = \begin{bmatrix} G & h_1 \\ h_2^T & d_{NN} \end{bmatrix}$$

where G is an $(N-1) \times (N-1)$ matrix, $h_1^T = [h_{1i}]$ where $1 \le i \le N-1$, and $h_2^T = [h_{2i}]$ where $1 \le i \le N-1$. Determinant of *D* is

$$det(D) = d_{NN} det(G) - h_2^T adj(G) h_1$$

where *adj(G)* is the adjoint of *G* which is defined as the transpose of the cofactor matrix of *G*. The cofactor matrix of *G* is an $(N-1) \times (N-1)$ matrix with the *(i, j)-th* element defined as the determinant of *G* with the *i-th* row and *j-th* column removed.

Proof:

We expand the determinant of *D* by the *N*-th column

$$det(D) = \sum_{i=1}^{N} (-1)^{N+i} d_{iN} C_{iN} = \sum_{i=1}^{N-1} (-1)^{N+i} d_{iN} C_{iN} + d_{NN} C_{NN}$$

where C_{iN} is the (*i*,*N*)-*th* entry of the cofactor matrix of *D*. d_{iN} is equal to h_{1i}, and C_{NN}

involved in the quadratic terms $\gamma_i \times P_j$ in vector notation. Let

$$x = [P_1, P_2, \ldots, P_{i-1}, P_{i+1}, \ldots, P_B, \gamma_i]^T$$

We then put the sum of the quadratic terms $\gamma_i \sum_{j \neq i} P_j Z_{ij}$ in matrix notation as $x^T A x$. A in symmetric form is equal to

$$\begin{bmatrix} 0 & 0 & \ldots & 0 & \frac{Z_{i1}}{2} \\ 0 & 0 & \ldots & 0 & \frac{Z_{i2}}{2} \\ . & . & . & . & . \\ 0 & 0 & \ldots & 0 & \frac{Z_{iB}}{2} \\ \frac{Z_{i1}}{2} & \frac{Z_{i2}}{2} & \ldots & \frac{Z_{iB}}{2} & 0 \end{bmatrix}$$

In other words, A is a symmetric $B \times B$ matrix with all elements in the first $(B-1)$ rows and $(B-1)$ columns equal to zero. The j-th entry for the B-th row or column is equal to $Z_{ij} / 2$ for $1 \leq j < i$ and $Z_{i(j+1)} / 2$ for $i \leq j < B$. $A_{B \times B} = 0$.

From [51], ignoring the linear terms, $-P_i + \gamma_i \tilde{n}_i$, the feasible region for $x^T A x \leq 0$ is non-convex if A is not positive semi-definite. The eigenvalues of the matrix A are $(B-2)$ zeros and $\pm\sqrt{\sum_{j \neq i} (Z_{ij}/2)^2}$. Matrix A is thus not positive definite. This, along with the other $(B-1)$ non-convex feasible regions for each inequality, makes the optimization problem to *NP*-hard.

Appendix B

Proof of Bit Allocation Problem is *NP*-Hard

Here, we show another way to prove the bit allocation problem is *NP*-hard. We, again, assume that there are B users in the system. Each has a different desired SIR, γ_i, such that the inequality

$$\frac{P_i G_{ii}}{\sum_{j \neq i} P_j G_{ij} + n_i} \geq \gamma_i$$

holds for $1 \leq i \leq B$.

Multiplying the denominator on both side and dividing both side by G_{ii}, we have

$$\gamma_i \sum_{j \neq i} P_j Z_{ij} - P_i + \gamma_i \tilde{n}_i \leq 0$$

where Z_{ij} is equal to G_{ij} / G_{ii} and $\tilde{n}_i$ is equal to n_i / G_{ii}. In the above equation, the transmitted power, P_j, and desired SIR, γ_i, are unknowns. The equation is thus a quadratic equation of the variables P_j, $1 \leq j \leq B$, and γ_i. We now put the variables 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 and the background noise.

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

Soft decoding: The decoder uses the unquantized samples output from the demodulator to recover the information sequence.

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 without wires.

intervals in time to overcome burst errors.

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 are available to the system.

Medium: A substance regarded as the means of signal transmission.

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

Multilevel trellis coded modulation: A modified trellis coded modulation where the uncoded bits are coded often with an error correcting code that explore the geometric properties of the signal constellations.

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 when radio signals reach the receiving antenna by two or more paths.

Multiple-Access: A sharing scheme that enables dispersed users to simultaneously access a common channel resource.

Network: An organization of terminals capable of intercommunication.

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

Parity-check code: A simple forward error correcting block code of rate (N,N-1). It adds a parity bit at the end of (N-1) information bits so that the N-bit block would have even number of ones. This code can be decoded using a simple two-state trellis decoder.

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

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 used to minimize the effects of fading wherein the same information signal is transmitted and received simultaneously on two or more independent carrier frequencies.

Frequency hop (FH): A spread spectrum technique in which the available channel bandwidth is subdivided into a large number of frequency slots. Each user is assigned a hopping pattern which specifies the sequences of slots a user would use. Frequency hopped can be categorized into slow frequency hop systems where there are more than information symbols per hop and fast frequency systems where one information symbol interval is greater than a hop duration.

In any signaling interval, the transmitted signal occupies one or more of the available frequency slots.

Frequency reuse: The scheme of assigning different frequencies to adjacent cells so that users communicating at the same frequency would not be too close to one another.

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.

Integrated services digital network (ISDN): An integrated digital network which can establish connection for data and telephony services using the same transmission equipment.

Interference: Undesired signals generated by other users in the communication channel.

Interleaving: A method of spacing successive symbols of a given codeword at wide

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.

Convolutional codes: A type of code in which output sequence consists of a selected set of linear combinations of the input sequence.

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 hop (FH).

Differential quadrature phase-shift keying (DQPSK): A digital modulation scheme that uses the phase changes of multiples of ninety degrees or $\pi/2$ from the previous symbol to carry two bits of information.

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

Diversity: The reception of different versions of the same information, each with independent fading levels.

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): The scheme of allocating channel resources to the user depending on the channel condition and the availability of the channel resource.

Dynamic channel and power allocation (DPCA): The scheme 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.

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.

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.)
UCLA	University of California, Los Angeles

C.2 Definitions

Baud: The unit of number of bits per symbol.

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

BCH Codes: A large class of cyclic block codes that include both binary and nonbinary alphabets.

Block codes: A type of error correcting code of fixed length N. These N symbols represents K symbols of information and (N - K) parity or redundancy symbols where $N \geq K$.

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: An allocation of the physical (frequency and time) resources of a transmission medium for communications.

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
PBX	Private branch exchange
PC	Power control
PCN	Personal Communications Network (Europe)
PCS	Personal Communications Services (U. S.)
PN	Pseudo-noise
PDC	Personal Digital Cellular (Japan)
PSTN	Public Switched Telephone Network
QAM	Quadrature amplitude modulation
QOS	Quality of service

Appendix C

Glossary

C.1 List of Acronyms and Abbreviations

AMPS	Advanced Mobile Phone Service
AWGN	Additive white Gaussian noise
BER	Bit error rate
CDMA	Code division multiple access
DCA	Dynamic channel allocation
DECT	Digital European Cordless Telecommunications
DPCA	Dynamic power and channel allocation
DQPSK	Differential quadrature phase-shift keying
DS	Direct sequence
FCC	Federal Communications Commission (U. S.)
FDMA	Frequency division multiple access
FEC	Forward error correction
FH	Frequency hop
GSM	Groupe Spécial Mobile or Global System for Mobile Communication

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