ON TRANSMITTER POWER CONTROL FOR CELLULAR MOBILE RADIO NETWORKS

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Summary

Transmitter power control is a key technique that is used to mitigate interference, maintain required link QoS and enhance system capacity. This thesis is mainly aimed at studying various transmitter power control schemes for wireless cellular communication systems. The research work can be divided into two aspects: one involves the theories behind the feasibility of transmitter power control schemes and the other is focused on the proposal of novel transmitter power control schemes in relatively fast fading channels.

The problem of whether the required SIR thresholds are achievable in transmitter power control is first examined. It is well known that this problem is a very important premise to transmitter power control and has been examined mainly for interference-limited systems in previous research works. However, different rules are applied for homogeneous-SIR systems and heterogeneous-SIR systems. In this thesis, a unified framework and a more generalized theorem for these two cases are presented by defining the system gain matrix $\mathbf{W_S}$. It is shown that whether a SIR threshold vector is achievable for both cases is determined by the largest modulus eigenvalue of $\mathbf{W_S}$. The physical meanings of this unified framework are also examined and a systematic interpretation is given.

An optimal power control scheme aiming at achieving outage probability balancing in Rician/Rician fading channels is proposed and studied. A disadvantage of the traditional power control schemes is that the transmitter power levels used to be updated every time the state of the channel changes. In fast fading wireless communication channels where the channel gains change very rapidly, these

traditional power control schemes may fail. In contrast, by taking into account the statistical average of the channel variations and optimally controlling the transmitter powers to balance the probability of fading-induced outages, the newly proposed scheme can be implemented at a time scale much larger than the fading time scale. Hence, it is especially suitable to the scenarios where the fading changes so quickly that the feedback of the channel states information cannot keep up with the fading changes. The proposed power control scheme has been verified to be able to balance the outage probabilities of all the desired communication links well.

In addition, the previous studies in the area of transmitter power control are summarized and a comprehensive literature survey is proposed. The survey mainly generalizes the relevant research works from several aspects such as transmitter power control schemes categorization, basic power control algorithms and so on.

Finally, several open issues that are worth investigating in the future are proposed. The feasibility of combining other techniques such as multi-user detection, smart antennas and temporal & spatial signal processing with transmitter power control to further enhance the system capacity is discussed.

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List of Symbols

$\mathbf{0}$	Zero matrix or vector
$\mathbf{A}$	Square nonnegative irreducible matrix
$c_i(t)$	The base station to which the ith transmitter is assigned at the time moment t
$\mathbf{c}$	The base station allocation vector
d	Distance between a transmitter and a receiver
d_0	The reference distance for prediction of log-distance path loss
$E[\cdot]$	The expectation operation
$\left(\frac{E_b}{I_0}\right)_i$	Received bit energy to interference power spectral density ratio of the ith desired communication link from the transmitter i to the receiver i
F_{ij}	A complex Gaussian variable that models small scale fading from transmitter j to the receiver i, i.e., $F_{ij} \sim CN(m_{ij}, 2\sigma_{ij}^2)$, where CN denotes complex Gaussian distribution
G_{ij}	The link gain from transmitter j to receiver i which includes the effects of path loss, log-normal shadowing and small scale fading
$I_0(\cdot)$	Modified Bessel function of the first kind and zero-order
$\mathbf{I}$	The identity matrix
K	Rician factor of the Rician distribution

K_{ij} Ricean factor that models the Rician fading effect of the communication link from transmitter j to receiver i

L_{ij} Distance-dependent path loss from transmitter j to the receiver i

N The number of corresponding pairs of transmitters and receivers, i.e., the number of desired communication links in a cellular system

p_i The transmission power of the i th transmitter

$p_i^{\max}$ The maximum power limit of transmitter i

$p_i^{\min}$ The minimum power limit of transmitter i

$p_i(t)$ The transmission power of the i th transmitter at time moment t

$p_{ij}^{(r)}$ The received power at the receiver i from transmitter j

$p_j\left[\tau_j^i(t)\right]$ The most recent known value of the power of transmitter j to transmitter i at time moment t

P_i^{out} The outage probability experienced by the i th desired communication link between transmitter i to receiver i

$PL(d)$ The path loss for a given distance d

$\overline{PL}(d)$ The mean path loss for a given distance d

$\mathbf{p}$ The power vector for all the transmitters

$\mathbf{p}^{(0)}$ The initial transmitter power vector in the iterative distribute power update schemes

$\mathbf{p}(t)$ The transmission power vector at the time moment t

$\mathbf{p}_W^*$ The positive eigenvector of the normalized link gain matrix $\mathbf{W}$ that is corresponding to its maximum modulus eigenvalue

$\mathbf{p}_{\mathbf{W}_S}$ An eigenvector of the system gain matrix $\mathbf{W_S}$

$\mathbf{p}_{\mathbf{W_S}}^*$ The eigenvector corresponding to the positive maximum modulus eigenvalue of the system gain matrix $\mathbf{W_S}$

$\mathbf{R}$ A permutation matrix

s^2 Noncentrality of the Rician distributed variable

S_{ij} The log-normal shadowing of the communication link from transmitter j to receiver i

$SIRM_i$ The SIR margin of the ith desired communication link from the transmitter i to receiver i

$\mathbf{u}$ The SINR-embedded normalized noise vector

$\mathbf{W}$ The normalized link gain matrix

$\mathbf{W_S}$ The system gain matrix

$\mathbf{W_{ave}}$ The time average system gain matrix

X_σ Zero-mean Gaussian random variable (in dB) with variance σ (also in dB).

α Path loss exponent

β Processing gain of a spread system

γ_i The required SIR or SINR threshold of the ith desired communication link from the transmitter i to the receiver i

γ_W^* The largest achievable common SIR threshold for all the desired communication links in the SIR-balancing transmitter power control scheme

$\boldsymbol{\gamma}$ The required SIR or SINR threshold vector for all the desired communication links

η_i The noise power level at the i th receiver

λ_A An eigenvalue of the matrix $\mathbf{A}$

λ_A^* The maximum modulus eigenvalue of the matrix $\mathbf{A}$

λ_W^* The maximum modulus eigenvalue of the matrix $\mathbf{W}$

λ_{W_S} The maximum modulus eigenvalue of the the matrix $\mathbf{W}_\mathbf{S}$

$\Gamma_i(t)$ The received SIR or SINR at the i th receiver at the time moment t

$\Gamma_{li}(t)$ The received SIR or SINR of transmitter i at the l th base station receiver

Abbreviations

BS	Base Station
BER	Bit Error Rate
CPC	Central Power Control
DPC	Distributed Power Control
DS-CDMA	Direct Spreading Code Division Multiple Access
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
ISI	Inter Symbol Interference
MAI	Multiple Access Interference
ML	Maximum Likelihood
MMSE	Minimum Mean Squared Error
MPA	Minimum Power Assignment
MRC	Maximum Ratio Combination
MS	Mobile Station
PDF	Probability Density Function
PIC	Parallel Interference Cancellation
QoS	Quality of Service
Rx	Receiver
SIC	Successive Interference Cancellation
SINR	Signal to Interference and Noise Ratio
SIR	Signal to Interference Ratio

SRA	Stepwise Removal Algorithm
STD	Standard Deviation
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
Tx	Transmitter

Chapter 1

Introduction

1.1 Background

Establishment and reconfiguration of communication links, and maintenance of the required quality of service (QoS) for all the communication links are the main network control functions in both wireline and wireless communication systems. For wireline systems that are the main constitute of the early modern communications infrastructure, these functions are not very difficult to be realized due to the reliable connections and relatively stable channel conditions. However, in the past decade, wireless communication systems developed so rapidly that nowadays it could even compete with the wireline counterparts in terms of business volume.

Contrary to the stable environment of wireline networks, the wireless channel is highly erratic and stochastic due to the node mobility, interference and unpredictable signal propagation environment. Hence, to achieve the functions mentioned above in wireless networks, effective methodologies need to be carefully designed. And from our

point of view, transmitter power control is one of the useful methods to ensure link reliability.

The reason for this is quite straightforward. In a wireless communication system, by adjusting the transmitter power, a communication link will affect the amount of interferences received by the remaining links in the network and therefore affect the QoS of these links. At the same time, the communication link also receives information about the other links. Since the quality of a communication link in a network is affected by other remaining links, improper transmitter power of a communication link may degrade the performance of others, resulting in overall poor system performance. As a result, transmitter power control can be used to perform several important dynamic network operations such as communication link QoS maintenance, admission control, resource allocation and handoff [1].

With the rapid development of wireless communication, subscribers' requirements are no longer limited to the voice and low-rate data transmission. Most of the multimedia services supported by the wireline networks must also be accommodated in the future wireless communication networks. Therefore, increasing number of multimedia communication applications are driving the existing wireless communication systems to support higher rate transmission. This requires transmission bandwidth that is much larger than the coherent bandwidth of the wireless channel, which causes frequency selective fading.

Direct-spread code division multiple access (DS-CDMA) system enables all the users to share the entire transmission bandwidth by spreading a user's signal to bandwidth much larger than the user's information rate. By the means of RAKE receiver, DS-CDMA

can overcome the time-varying frequency selectivity more effectively than previous time division multiple access (TDMA) or frequency division multiple access (FDMA). Furthermore, DS-CDMA can flexibly support diverse and variable transmission rates by varying the processing gain. As a result, DS-CDMA has become a mainstream technology of 3G and 4G wireless communication systems.

Since DS-CDMA technique in the uplink allows all users to access the common bandwidth simultaneously but asynchronously, the timing offsets between signals are random. This makes it impossible to design the code waveforms to be completely orthogonal. Thus multiple access interference (MAI) is inevitable in DS-CDMA systems. And as the number of interferers increases, MAI could become very substantial and seriously affect the system performance. Accordingly, some techniques are needed to combat the interference and to optimize the performance of DS-CDMA communication systems. Because transmitter power control scheme can be designed to maintain the required QoS of each link by using the least possible power, obviously it can reduce the interference that is caused by all the other links to any given active communication link. Therefore, in addition to facilitate some fundamental network operations, transmitter power control plays a more significant role of suppressing interference in the 3G and 4G wireless communication systems which take DS-CDMA as their main air interface.

Because of its fundamental importance to the operation of wireless communication networks, transmitter power control is always a hot area in research and a lot of extensive works have been carried out in the past years. Based on these previous works, the main objective of this thesis is to study the transmitter power control schemes for wireless communication systems.

1.2 Objectives of This Thesis

This thesis is aimed to focus on the following aspects:

1) To present a unified framework for transmitter power control in cellular radio systems to study whether the required SIR thresholds are achievable in both homogeneous-SIR and heterogeneous-SIR systems.
2) To propose a novel transmitter power control scheme that is able to balance the outage probabilities of all the active communication links in a Rician/Rician wireless fading channels.
3) To review and summarize previous works on transmitter power control and present a comprehensive literature survey in this research area.
4) Highlight and discuss several open issues that are worthy to be looked into in the future.

1.3 Contributions of This Thesis

Many previously published research works have aimed at investigating the theoretical rationale behind transmitter power control. Research results show that the maximum achievable Signal-to-Interference Ratio (SIR) of all the active communication links and the corresponding transmitter power vector can be determined by the Perron-Frobenius Theorem. However, most of the researchers consider only the homogeneous-SIR systems and only pay attention to the heterogeneous-SIR systems until recently. With the increasing multimedia applications, future wireless communication systems should be able to accommodate diverse services such as voice, data, image and video transmissions. These different types of traffic have different QoS requirements and therefore the SIR

thresholds for different communication links are also often distinctive. So the solution to homogeneous-SIR systems is no longer appropriate and the previous research results cannot apply directly to the heterogeneous-SIR systems.

In order to solve this problem, a unified framework of the theory behind transmitter power control is proposed, which is suitable to both homogeneous-SIR and heterogeneous-SIR systems. The previous results can be successfully derived from the results of our framework. The physical meanings behind this unified framework are also discussed and interpreted in details. These works constitutes the first contribution of this thesis.

On the other hand, most of the traditional power control schemes are based on the observed and desired Signal-to-Interference-plus-Noise Ratio (SINR) or Signal-to Interference Ratio (SIR) at the receiver, and the knowledge of the link gains to update the transmitter power levels. Thus, the implicit assumption behind all these power control schemes is that the transmitter power updates are made every time the channel states change, i.e., whenever the channel gain of any link changes. However, in fast fading wireless communication channels where the channel states change so rapidly that the delay in feedback loop cannot be neglected, the traditional power control schemes will fail due to the reason that the feedback of channel information cannot keep up with the channel state variations and thus the information for accurately estimating the channel states and SINR or SIR levels is not available.

To overcome this disadvantage of the traditional power control method, a novel power control scheme with outage probability specifications is proposed in this thesis. Since the outage probability is only related to the average values of both the desired and

unwanted signal powers, this new power control scheme can be implemented with the knowledge of the statistical average of the channel fading, rather than the instantaneous fading conditions. Hence the transmitter power levels can be updated at a time scale much larger than the fading time scale. This constitutes the second contribution of this thesis.

Another contribution of this thesis is that an extensive literature survey is present to give a concise and schematic description of the relevant works in this field so far.

In addition, based on my own understanding and research experiences, several issues that are worthy to be studied in the future are highlighted. This may offer some helps to the researchers who are interested in the relevant area and is also one of the contributions of this thesis.

1.4 Organization of This Thesis

The rest of this thesis is organized as below:

In Chapter 2, the system and signal models used in this thesis is described. In addition, some basic definitions and preliminary knowledge that are required in the thesis are also introduced.

In Chapter 3, a literature survey on the study that has been so far performed in the area of transmitter power control is given. Three aspects are mainly discussed: the categorization of transmitter power control methods, the most classic power control algorithms and future development directions in this research area.

In Chapter 4, we present a unified framework and derive a generalized theorem on the problem of whether a SIR threshold vector is achievable in transmitter power control for both homogeneous-SIR and heterogeneous-SIR cellular systems. The results obtained

in this thesis can be seen as generalization of the previous works where the problem for both cases seems distinct from each other.

In Chapter 5, an optimal power control scheme based on outage-probability balancing for Rician/Rician wireless fading channels is presented. This scheme is more general than a proposed scheme in an early paper for Rayleigh/Rayleigh fading channels. It is shown that this power control scheme is more suitable to be used than traditional power control schemes when more frequent power control update is not possible or when the channel states vary so fast that the feedback of channel information cannot truly reflect the present channel state. Some design considerations related to this power control scheme are also discussed.

Subsequently, the proposal for possible future work in the area of transmitter power control is presented in Chapter 6 and several open issues worth looking into are highlighted and discussed.

Finally, a conclusion of this thesis is given in Chapter 7.

Chapter 2

System Model and Background

In this chapter, the system and channel model that are used in this thesis are presented. All the subsequent chapters are using this common model. Besides, some background and notations used in this thesis are also introduced.

2.1 System Model

Assume a cellular wireless communication system with N pairs of transmitters and receivers. Receiver i is meant to receive signal from transmitter i, that is, the link between transmitter i and receiver i is the desired communication link and therefore we call this communication link as the ith desired link in the system. The link from transmitter j to receiver i ($j \neq i$) is then the unwanted communication link, which will cause interference to the ith desired communication link. Hence, there are N desired communication links in the system and each desired communication link are subject to $(N-1)$ interference links.

In our system model, by transmitter and receiver, we do not necessarily mean N

different physical transmitters and receivers. For example, the receivers with different labels may refer to the same physical receiver with different frequency channels, codes or antenna beams. And the same rule also applies to the transmitters.

We further assume that the QoS of each desired communication link depends on the Signal to Interference and Noise power Ratio (SINR) requirement. Let p_i denote the transmission power of transmitter i, then $\mathbf{p} = [p_1 \cdots p_i \cdots p_N]^T$ denotes the transmitter power vector and $\mathbf{p} > \mathbf{0}$ means that each element of $\mathbf{p}$ is positive. G_{ij} denotes the link gain (which models the effects of path loss, log-normal shadowing and fast fading) from transmitter j to receiver i. Hence, $G_{ii}, i \in [1, N]$ corresponds to the desired communication links and $G_{ij}, j \neq i$ corresponds to the unwanted links (to make the system geometry and link gains more understandable, Fig. 2.1 and 2.2 are used to illustrate the uplink and downlink communication scenarios respectively). Let γ_i, $i \in [1, N]$ denote the required SINR threshold for each desired link and define the vector $\boldsymbol{\gamma} = [\gamma_1 \cdots \gamma_i \cdots \gamma_N]^T$ as the required SINR threshold vector for the system.

Using these notations, we can derive the received SINR level, Γ_i, for the desired link from transmitter i to receiver i as

$$\Gamma_i = \frac{p_i G_{ii}}{\sum_{j \neq i}^{N} p_j G_{ij} + \eta_i}, \quad i = 1, \cdots, N \tag{2.1}$$

where η_i denotes the noise power at receiver i. In order to satisfy the QoS requirement of each desired communication link, we have

$$\Gamma_i = \frac{p_i G_{ii}}{\sum_{j \neq i}^{N} p_j G_{ij} + \eta_i} \geq \gamma_i, \quad i = 1, \cdots, N \tag{2.2}$$

In some systems where the noise power level at the receiver of the desired link is negligible compared to the interference power levels from unwanted communication links, The QoS measurement for each desired communication link will mainly depend on the SIR, rather than SINR. We call such systems as interference-limited systems. Obviously, an interference-limited system is only an approximation to practical communication system. But due to its simplicity and the acceptable closeness to practical scenarios, this system model is widely used. For interference-limited systems, the received SIR level, Γ_i, for the desired link from transmitter i to receiver i is

$$\Gamma_i = \frac{p_i G_{ii}}{\sum_{j \neq i}^{N} p_j G_{ij}}, \quad i = 1, \cdots, N \tag{2.3}$$

where the noise power at receiver i is ignored. In order to fulfill the QoS requirements of each desired communication links, Γ_i should satisfy the following inequality

$$\Gamma_i = \frac{p_i G_{ii}}{\sum_{j \neq i}^{N} p_j G_{ij}} \geq \gamma_i, \quad i = 1, \cdots, N \tag{2.4}$$

here γ_i, $i \in [1, N]$ denote the required SIR thresholds for each desired communication link. For a non-spread system, γ_i is equivalent to the received bit energy to interference power spectral density ratio, $(E_b / I_0)_i$, which can be determined by the modulation used and the desired BER performance. For a spread system, $\gamma_i = 1/\beta \cdot (E_b / I_0)_i$ where β is the processing gain of the system. This is because the effect of spreading lowers the required SIR threshold at the expense of larger signal bandwidth being used.

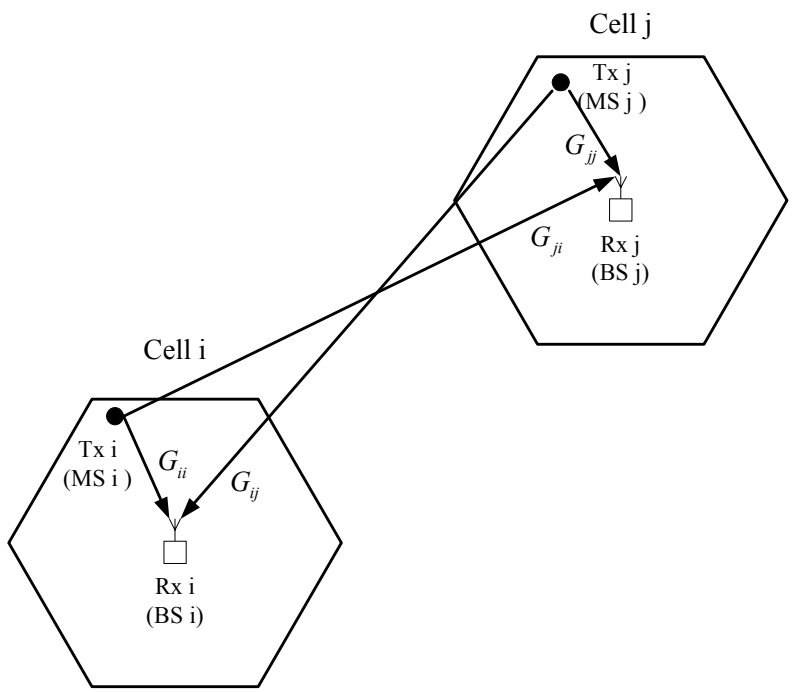

Fig. 2.1 System geometry and link gains for uplink communications

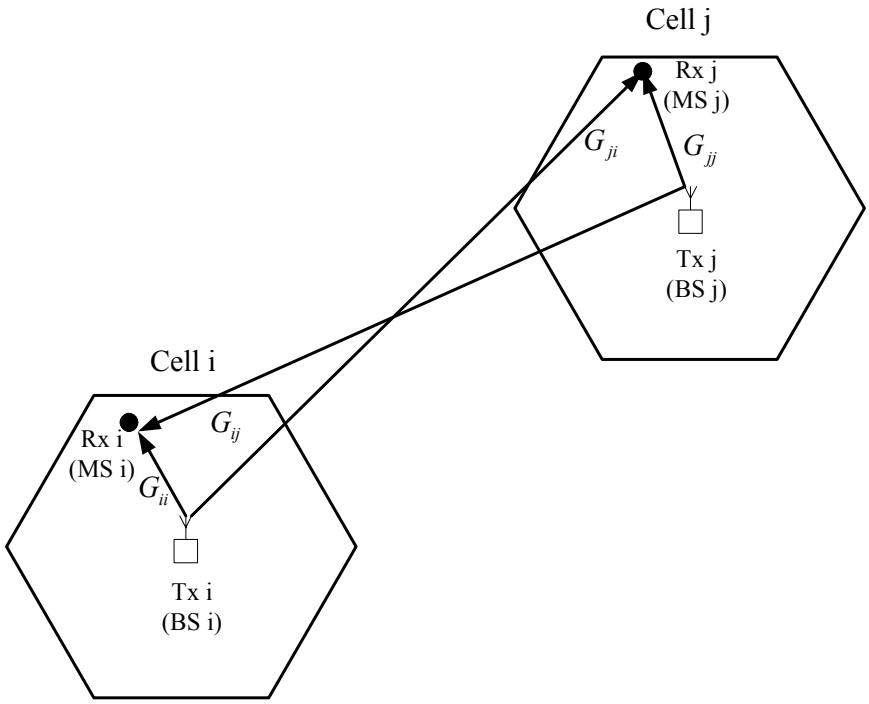

Fig. 2.2 System geometry and link gains for downlink communications

If the received SIR or SINR level of a desired communication link is lower than the required SIR or SINR threshold, that is, the inequality of (2.2) or (2.4) cannot be satisfied, this link experiences an outage event. In this case, the outage probability of the i th desired communication link is:

for interference-limited systems:

$$P_i^{out} = \Pr\left\{ p_i G_{ii} - \gamma_i \sum_{j \neq i}^{N} p_j G_{ij} < 0 \right\} \tag{2.5a}$$

for systems limited by both interference and noise:

$$P_i^{out} = \Pr\left\{ p_i G_{ii} - \gamma_i \sum_{j \neq i}^{N} p_j G_{ij} - \gamma_i \eta_i < 0 \right\} \tag{2.5b}$$

Apparently, the outage probability of a communication link in a certain time period refers to the ratio of the time during which the communication link experiences outage event to the total time span. Outage probability is also an important measure to evaluate the QoS of a given communication link.

Note that here the transmitter can either point to the mobile station for uplink (reverse link) case or the base station for downlink (forward link) case. And similarly, the receiver refers to the base station for uplink case and the mobile station for downlink case. Therefore, such a model provides a uniform framework for both uplink and downlink scenarios.

We now depict the channel model in details. In the above, the link gains $G_{ij}, i, j \in [1, N]$ includes all the effects of path loss, lognormal shadowing and fast fading. In order to ease the description on the theory to be presented in Chapter 5, different notations are needed to represent these three channel effects. Assume that

$L_{ij}, i, j \in [1, N]$ denote the path loss due to the distance between transmitter j and receiver i. Further assume that $S_{ij}, i, j \in [1, N]$ stands for the lognormal shadowing and the modulus of $F_{ij}, i, j \in [1, N]$ represent the fast fading envelope. Thus the link gains $G_{ij}, i, j \in [1, N]$ can be rewritten as

$$G_{ij} = L_{ij} S_{ij} \left| F_{ij} \right|^2, \quad i = 1, \cdots, N \quad \text{and} \quad j = 1, \cdots, N \tag{2.6}$$

Here F_{ij} is a complex Gaussian variable. If the fast fading follows Rayleigh distribution, its mean is zero, that is, $F_{ij} \sim CN(0, 2\sigma_{ij}^2)$. And if the fast fading follows Rician distribution, its mean is nonzero, i.e., $F_{ij} \sim CN(m_{ij}, 2\sigma_{ij}^2)$. Thus, the received power at the receiver i from transmitter j is

$$p_{ij}^{(r)} = p_{ij} G_{ij} = p_{ij} L_{ij} S_{ij} \left| F_{ij} \right|^2, \quad i = 1, \cdots, N \quad \text{and} \quad j = 1, \cdots, N \tag{2.7}$$

Path loss and lognormal shadowing model the large scale fading in wireless channels; fast fading effects model the small scale fading in wireless channels. In the Section 2.2 and 2.3, a brief introduction about both the large and small scale fading will be given.

2.2 Large Scale Fading in Mobile Radio Propagation

2.2.1 Path Loss

Many theoretical and measurement-based propagation models indicate that average received signal power level decreases logarithmically with distance in wireless mobile communication systems [5]. The average path loss for an arbitrary Tx-Rx (transmitter to receiver) separation is expressed as

$$\overline{PL}(d) \propto \left(\frac{d}{d_0} \right)^{\alpha} \tag{2.8}$$

or

$$\overline{PL}(d)[dB] = \overline{PL}(d_0) + 10\alpha \log\left(\frac{d}{d_0}\right) \tag{2.9}$$

where α is the path loss exponent that reflects the rate at which the path loss increases with the distance; d_0 is the reference distance which is determined by measurements; d is the Tx-Rx distance. And $\overline{PL}(d)$ denotes the ensemble average of all possible path loss values for a given separation distance d.

2.2.2 Log-normal Shadowing

Due to the fact that the surrounding environmental clutter may be vastly different at two different locations having the same Tx-Rx separation, the path loss of signal propagation between these two locations may also fluctuate around the average value predicted by equation (2.8). Measurements show that the path loss $PL(d)$ between any two locations that are separated by the distance d is random and distributed log-normally about the mean distance-dependent value [5]. That is

$$PL(d)[dB] = \overline{PL}(d) + X_\sigma = \overline{PL}(d_0) + 10\alpha \log\left(\frac{d}{d_0}\right) + X_\sigma \tag{2.10}$$

where X_σ is a zero-mean Gaussian distributed random variable (in dB) with variance σ (also in dB).

The above equation (2.10) describes the log-normal shadowing which implies that measured signal levels at a specific Tx-Rx distance have a normal Gaussian distribution about the distance-dependent mean of (2.8), where the measured signal power levels have values in dB units.

2.3 Small Scale Fading in Mobile Radio Propagation

2.3.1 Rayleigh Fading Distribution

It is well known that the envelope of the sum of two quadrature Gaussian noise signals obeys a Rayleigh distribution. That is, if X_1 and X_2 are zero-mean statistically independent Gaussian random variables and both have the common variance σ^2, i.e., $X_1 \sim N(0,\sigma^2)$ and $X_2 \sim N(0,\sigma^2)$; the square root of the sum of X_1 and X_2, i.e., $Y = \sqrt{X_1^2 + X_2^2}$, follows the Rayleigh distribution. The pdf of Y is given in [5,6] as the following:

$$p_Y(y) = \begin{cases} \dfrac{y}{\sigma^2} e^{-\frac{y^2}{2\sigma^2}} & y \geq 0 \\ 0 & y < 0 \end{cases} \tag{2.11}$$

In mobile radio channels, the Rayleigh distribution is commonly used to describe the statistical time varying nature of the received envelope of a flat fading signal, or the envelope of an individual multipath component.

When the system model in Section 2.1 is used to describe Rayleigh fading channels, the $|F_{ij}|$ in the equation (2.6) should follow the Rayleigh distribution and $|F_{ij}|^2$ should follow the central chi-square distribution with degree of freedom being 2, which is also known as the exponential distribution.

2.3.2 Rician Fading Distribution

When there is a dominant stationary (nonfading) signal component present, such as a line-of-sight propagation path, the small-scale fading envelope distribution is Rician. In such a situation, random multipath components arriving at different angles

are superimposed on a stationary dominant signal [5]. From the mathematical point of view [6], if X_1 and X_2 are two statistically independent random variables that have different means m_1 and m_2 and same variance σ^2, that is, $X_1 \sim N(m_1, \sigma^2)$ and $X_2 \sim N(m_2, \sigma^2)$; then the square root of sum of X_1 and X_2, $Y = \sqrt{X_1^2 + X_2^2}$, is a Rician distribution variable. Its pdf is

$$p_Y(y) = \begin{cases} \dfrac{y}{\sigma^2} e^{-\frac{y^2+s^2}{2\sigma^2}} I_0\left(\dfrac{ys}{\sigma^2}\right) & y \geq 0 \\ 0 & y < 0 \end{cases} \tag{2.12}$$

where $s^2 = m_1^2 + m_2^2$ is the noncentrality parameter of Rician distribution and its square root s denotes the peak amplitude of the dominant signal component. $I_0(\cdot)$ is the modified Bessel function of the first kind and zero-order.

In fact, Rician distribution is often described in terms of the Rician Factor K, which is defined as the ratio between the deterministic dominant component power and the diffused components power. It is given by

$$K = \frac{s^2}{2\sigma^2} \tag{2.13}$$

Rician Factor completely specifies the Rician distribution. As the dominant signal becomes weaker, the composite signal resembles a noise signal that has an envelope that is Rayleigh distributed. Thus, when the dominant component fades away, that is, when $K = 0$, the Rician distribution degenerates to a Rayleigh distribution.

For Rician fading channels, the $|F_{ij}|$ in our system model is a Rician distributed variable and $|F_{ij}|^2$ follows the noncentral chi-square distribution with degree of freedom being 2. The Rician factor for $|F_{ij}|$ is $K_{ij} = m_{ij}^2 / 2\sigma_{ij}^2$.

2.4 Homogeneous-SIR and Heterogeneous-SIR Communication Systems

In an interference-limited communication system, if the required SIR thresholds for all the links are identical to each other, it is a homogeneous-SIR system. If the required SIR thresholds for different communication links are not identical, it is a heterogeneous-SIR system.

In the early communication systems, the service that is catered for is mainly the voice, so the SIR thresholds for different links are usually the same and most of those systems are homogeneous-SIR systems. However, nowadays communication systems must accommodate diverse services such as voice, data and images, which naturally require different SIR thresholds. Therefore, a heterogeneous-SIR system is a more practical model for describing multimedia communication systems. Due to this reason, many previously research results based on homogeneous-SIR/SINR systems cannot directly apply to multimedia communication systems. So further works are needed to explore the heterogeneous multimedia systems.

2.5 Perron-Frobenius Theorem

Perron-Frobenius Theorem gives the important basis of transmission power control theory and therefore it is widely quoted in many classic papers. In order to make the subsequent interpretation more understandable, we summarize the theorem as the following.

Theorem 2.1 [2,3,4]: Let $\mathbf{A}$ be an $n \times n$ irreducible nonnegative matrix with eigenvalues $\{\lambda_A^i\}_{i=1}^n$, then

1 $\mathbf{A}$ has a positive real eigenvalue λ_A^* with $\lambda_A^* = \max_{1 \le i \le N} \{|\lambda_A^i|\}$;

2 λ_A^* above has an associated eigenvector $\mathbf{q}^*$ with strictly positive entries;

3 λ_A^* has algebraic multiplicity equal to 1;

4 All eigenvalues λ_A^i of $\mathbf{A}$ other than λ_A^* satisfy $|\lambda_A^i| < |\lambda_A^*|$ if and only if there is a positive integer k with all entries of $\mathbf{A}^k$ strictly positive;

5 If there exists a real number, μ, such that the inequality $\mu\mathbf{q} \ge \mathbf{A}\mathbf{q}$ has solutions for $\mathbf{q} \ge 0$, the minimum value of μ is λ_A^*;

6 If there exists a real number, μ, such that the inequality $\mu\mathbf{q} \le \mathbf{A}\mathbf{q}$ has solutions for $\mathbf{q} \ge 0$, the maximum value of μ is λ_A^*;

7 The matrix $\mathbf{A}$ cannot have two linearly independent nonnegative eigenvectors.

With the above properties, we can derive a lemma to supplement Perron-Frobenius Theorem.

Lemma 2.1: λ_A^* is the unique eigenvalue of $\mathbf{A}$ that has corresponding nonnegative eigenvectors.

Proof:

From Theorem 2.1-3, we know that λ_A^* is the simple root of the characteristic equation $|\lambda_A \mathbf{I} - \mathbf{A}| = 0$, hence the other eigenvalues of $\mathbf{A}$ are different from

λ_A^*. Since the eigenvectors corresponding to different eigenvalues are linearly independent, together with Theorem 2.1-7, we can conclude that only λ_A^* has corresponding nonnegative eigenvectors among all the eigenvalues of $\mathbf{A}$.

Perron-Frobenius Theorem is only applied to nonnegative irreducible matrix. Nonnegative matrix means that all elements of the matrix are equal to or greater than zero. The definition of irreducible matrix is as below.

A permutation matrix $\mathbf{R}$ is any matrix which can be created by rearranging the rows and/or columns of an identity matrix. Pre-multiplying a matrix $\mathbf{A}$ by a permutation matrix $\mathbf{R}$ results in a rearrangement of the rows of $\mathbf{A}$. Post-multiplying by $\mathbf{R}$ results in a rearrangement of the columns of $\mathbf{A}$. That is, if the permutation matrix $\mathbf{R}$ is obtained by swapping rows i and j of the $n \times n$ identity matrix $\mathbf{I_n}$, then rows i and j of $\mathbf{A}$ will be swapped in the product $\mathbf{RA}$, and columns i and j of $\mathbf{A}$ will be swapped in the product $\mathbf{AR}$.

A square nonnegative $n \times n$ matrix $\mathbf{A}$ is a reducible matrix if there exists a permutation matrix $\mathbf{R}$ such that

$$\mathbf{R}^T\mathbf{AR} = \begin{bmatrix} \{\mathbf{A_{11}}\}_{n_1 \times n_2} & \{\mathbf{A_{12}}\}_{n_1 \times n_3} \\ \mathbf{0} & \{\mathbf{A_{22}}\}_{n_4 \times n_3} \end{bmatrix} \tag{2.14}$$

where $\mathbf{A_{11}}$, $\mathbf{A_{12}}$ and $\mathbf{A_{22}}$ are non-zero matrices; and their dimensions should satisfy $n_1 + n_4 = n$ and $n_2 + n_3 = n$. Clearly $\mathbf{0}$ is a zero matrix with dimensions equal to $n_4 \times n_2$.

$\mathbf{A}$ is an irreducible matrix if it is not a reducible matrix.

2.6 Conclusions

The system model and some background of the works are presented in this chapter. Based on this knowledge, in the next chapter, an extensive literature survey on the previous research works on transmitter power control will be presented.

Chapter 3

Literature Survey

Due to its importance to the operation of wireless mobile communication systems, a lot of research works have been carried out in the area of transmitter power control scheme design. In order to be practical, the schemes must satisfy the following requirements [1]:

- Distributed: allowing autonomous execution at the node or link level, requiring minimal usage of network resources
- Simple: Suitable for real-time implementation with low strain on node and link computation resources
- Agile: able to fast track channel changes and adaptation to network stretching due to node mobility
- Scalable: to maintain high performance at various network scales of interest
- Robust: to adapt to diverse stressful contingencies, rather than stall and collapse

According to these design guidelines, many transmitter power control schemes and algorithms have been proposed. In the following, a comprehensive literature survey in this field will be present.

In Section 3.1 the categorization of power control schemes is first summarized. Then a survey of power control schemes is given in Section 3.2. Finally in Section 3.3 the future research directions in this field are described.

3.1 Categorization of Power Control Schemes

In general, the transmitter power control schemes can be classified into several groups according to different criteria:

(1) Open-Loop and Closed-Loop [7-10]

Open-loop power control requires the transmitter to measure communication quality and adjust its own transmission power accordingly. That is, a mobile station can determine its uplink transmission power according to its downlink-received SINR and a base station can update its downlink transmission power based on its received SINR in the uplink. Open-loop power control can achieve good results when both uplink and downlink communications undergo similar channel fading such as in systems operating with TDD mode. However, when the uplink and downlink channel conditions are not correlated, for example in the FDD systems, this method only gives some degrees of accuracy in average power levels on average, where only the effects of path loss and shadowing can be compensated because these two factors change relatively slowly and exhibit reciprocity in the uplink and downlink cases. To compensate the fast fading that is quite different for uplink and downlink in FDD systems and TDD systems with long dwell time, closed-loop power control must be used.

Closed-loop power control can be further classified as inner loop power control and outer loop power control. In inner loop power control, the quality measurements are done at the receiver and the results are then sent back to the transmitter such that it can adjust its transmission power. This method can achieve better performance than open-loop power control because the power levels are controlled according to the actual channel conditions. The outer loop power control functions at the receiver and aims to adjust the required SINR value that is used in the inner loop power control. The outer loop power control works in this way: the final quality of transmission can only be known after the decoding process and this final result is used to adjust the required SINR threshold for the inner loop power control. So any change in the outer loop will trigger the inner loop to respond accordingly.

(2) Deterministic and Stochastic [11]

Deterministic power control algorithms require accurate knowledge or perfect estimates of some deterministic quantities such as SIR, received interference power and so on. However, due to the randomness of multi-access interference, channel impairments and the ambient Gaussian noise, none of these quantities is easy to estimate perfectly. So in order to track the stochastic features of practical wireless communication systems, stochastic power control algorithms are proposed, where the deterministic variables are replaced by their random estimates. It is quite straightforward that these algorithms converge in a stochastic sense.

(3) Centralized and Distributed

Centralized power control (CPC) requires the knowledge of all the radio link gains in the system and therefore is not easy to implement. But CPC may help in designing

distributed power control (DPC) schemes. Moreover, if the feasible solution exists, CPC gives the optimal solution for the power control problem and this solution can become a performance measurement criterion for the distributed power control algorithms.

Contrast to CPC, in distributed power control schemes, each link measures autonomously its current SIR/SINR or received interference and link gain and then updates its transmission power based on these local measurements. Therefore, DPC is a more realistic and feasible power control scheme.

(4) Synchronous and Asynchronous [12,13]

Synchronous power control means that every user performs power adjustment simultaneously and users can access the most recent values of the power vector at each iteration step.

On the contrary, asynchronous power control allows some users to update transmission power faster and implement more iterations than others. Therefore, in asynchronous power control scheme, some users may need to execute power adjustments using the outdated information about the power vector.

5) Constrained and Unconstrained

According to whether transmitters are subject to maximum or minimum power constraints, power control schemes can be divided into constrained and unconstrained. In constrained power control, the range of adjusting the power levels cannot exceed the maximum and minimum limits.

3.2 A Survey of Power Control Schemes

3.2.1 SIR-Balancing Power Control Scheme

In [2,14,15], the SIR-balancing transmitter power control scheme is proposed for interference-limited systems, where the noise power satisfies $\eta_i = 0$ for all i. Thus the required QoS reduces to SIR thresholds, rather than the SINR thresholds.

The SIR-balancing transmitter power control scheme is devised to find a power vector $\mathbf{p} = \{p_i\}_{i=1}^{N}$ to achieve the same SIR at the receivers for all desired communication links. That is,

$$\Gamma_i = \frac{p_i G_{ii}}{\sum_{j \neq i}^{N} p_j G_{ij}} = \gamma \,,\ i = 1, \cdots, N \tag{3.1}$$

where we use γ to denote the achieved common SIR threshold for all the links.

That is

$$1/\gamma \cdot p_i = \sum_{j \neq i}^{N} \frac{G_{ij}}{G_{ii}} p_j \ \ ,\ i = 1, \cdots, N \tag{3.2}$$

We can express the above equations in matrix form as

$$1/\gamma \cdot \mathbf{p} = \mathbf{W}\,\mathbf{p} \tag{3.3}$$

where the matrix $\mathbf{W}$ is called as the normalized link gain matrix and its elements are

$$W_{ij} = \begin{cases} \dfrac{G_{ij}}{G_{ii}} & i \neq j \\ 0 & i = j \end{cases} \tag{3.4}$$

In order to solve the SIR-balancing power control problem, we need to use the Perron-Frobenius Theorem which we introduced in Chapter 2. But as we know, Perron-

Frobenius Theorem applies to nonnegative irreducible matrix; thus we first need to prove that the matrix $\mathbf{W}$ is an irreducible matrix.

Lemma 3.1: $\mathbf{W}$ is an irreducible nonnegative matrix [14].

Proof:

From the above description, the matrix $\mathbf{W}$ has all the elements on its main diagonal equal to 0 and all the other elements greater than 0. According to the definition of irreducible matrix in Section 2.3, the matrix $\mathbf{W}$ would be reducible only if it had at least one row with more than one zero element. So $\mathbf{W}$ is an irreducible nonnegative matrix.

With Lemma 3.1, we can see that Theorem 2.1 and Lemma 2.1 can be applied to the normalized link gain matrix $\mathbf{W}$. Hence, it is naturally concluded that the largest achievable SIR, γ_W^*, by all the desired communication links is equal to the reciprocal of the positive maximum modulus eigenvalue λ_W^* of the normalized link gain matrix $\mathbf{W}$, i.e., $\gamma_W^* = 1/\lambda_W^*$ and the transmitter power vector achieving this SIR threshold is the positive eigenvector $\mathbf{p}_\mathbf{W}^*$ corresponding to λ_W^*.

From the above, we know that the SIR-balancing transmitter power control belongs to the centralized power control methods and may not be applicable in practice; however, it is very classical and becomes an important basis for the later research work on power control.

3.2.2 Stepwise Removal Algorithm (SPA)

From the Section 3.2.1, we know that the largest achievable SIR in SIR-balancing power control scheme is determined by the normalized link gain matrix $\mathbf{W}$. However, there are cases when the required SIR threshold cannot be achieved. Then the problem in such cases is how to find the power vector to achieve the required SIR threshold. The stepwise removal algorithms proposed in papers [14,72] just aims to solve this problem.

In the stepwise removal algorithms, the first step is to check if the required SIR threshold is achievable for the original matrix $\mathbf{W}$. If not, we should try to remove one transmitter from the system, computing the eigenvalue of each reduced normalized link gain matrix until the SIR threshold can be fulfilled. This is the common rationale for all stepwise removal algorithms. But the criteria used to determine which transmitter should be removed may vary. In the following, we will introduce the different stepwise removal algorithms in [14] and [72] respectively.

A Stepwise Removal Algorithm I [14]

1) Determine the largest achievable SIR, γ_W^*, for the original normalized link gain matrix $\mathbf{W}$. Compare γ_W^* with the required SIR threshold γ, if $\gamma_W^* \geq \gamma$, use $\mathbf{p}_{\mathbf{W}}^*$ as the transmitter power vector and stop.

2) If $\gamma_W^* < \gamma$, remove the transmitter i for which the maximum of the row and column sums $r_i = \sum_{j=1}^{N} W_{ij}$ and $r_i^T = \sum_{j=1}^{N} W_{ji}$ is maximized and form the $(N-1)\times(N-1)$ submatrix $\mathbf{W}'$. Determine $\gamma_{W'}^*$ corresponding to $\mathbf{W}'$. If

$\gamma^*_{W'} \geq \gamma$, use the eigenvector $\mathbf{p}^*_{\mathbf{W}'}$ as the transmission power vector and stop. Otherwise repeat step 2 for the submatrix $\mathbf{W}'$.

In this algorithm, the row and column sums provide bounds on the dominant eigenvalue, λ^*_W, of the matrix $\mathbf{W}$. Therefore, this stepwise removal criterion seeks to maximize the lower bound for the largest achievable SIR, $\gamma^*_{W'}$, of the submatrix $\mathbf{W}'$.

B Stepwise Removal Algorithm II [72]

1) Determine the largest achievable SIR, γ^*_W, for the original normalized link gain matrix $\mathbf{W}$. Compare γ^*_W with the required SIR threshold γ, if $\gamma^*_W \geq \gamma$, use $\mathbf{p}^*_{\mathbf{W}}$ as the transmission power vector and stop.
2) If $\gamma^*_W < \gamma$, remove the transmitter i for which $\gamma^*_{W'}$ of the reduced submatrix $\mathbf{W}'$ is maximized. If this maximum $\gamma^*_{W'} \geq \gamma$, use the eigenvector $\mathbf{p}^*_{\mathbf{W}'}$ as the transmission power vector and stop. Otherwise repeat step 2 for the submatrix $\mathbf{W}'$.

This algorithm will be optimal at any removal step although the combination of the removal set may not be optimal.

3.2.3 Minimum Power Assignment (MPA) Scheme

3.2.3.1 For Fixed Base Station Assignment

A Centralized Scheme [1,16]

The minimum power assignment scheme aims to find a smallest possible transmitter power vector to fulfill the SINR requirements, hence the feasible power vector should satisfy (2.2) with equality, that is,

$$\Gamma_i = \frac{p_i G_{ii}}{\sum_{j \neq i}^{N} p_j G_{ij} + \eta_i} = \gamma_i, \; i = 1, \cdots, N \tag{3.5}$$

We can express the above equations in the form of matrix and vector as

$$(\mathbf{I} - \mathbf{W_S})\mathbf{p} = \mathbf{u} \tag{3.6}$$

where

$$\{W_S\}_{ij} = \begin{cases} \gamma_i \dfrac{G_{ij}}{G_{ii}} & i \neq j \\ 0 & i = j \end{cases} \tag{3.7}$$

and

$$\{u\}_i = \frac{\gamma_i \eta_i}{G_{ii}}, \quad i = 1, \cdots, N \tag{3.8}$$

If the inverse of the matrix $(\mathbf{I} - \mathbf{W_S})$ exists, that is, if there exists a feasible power vector as the solution to this power control problem, the optimal minimum power vector achieving the required SINR thresholds for all the links should be

$$\mathbf{p}^*_{\mathbf{W_s}} = (\mathbf{I} - \mathbf{W_S})^{-1}\mathbf{u} \tag{3.9}$$

B. Distributed Algorithm [8,16-19]

Based on above centralized algorithm, a distributed minimum power assignment scheme is proposed. The equation (3.6) is equivalent to

$$\mathbf{p} = \mathbf{W_S}\mathbf{p} + \mathbf{u} \tag{3.10}$$

Using iteration, we can rewrite (3.10) as

$$\mathbf{p}(t+1) = \mathbf{W_S}\mathbf{p}(t) + \mathbf{u}\,,\ t = 0,1,2,3\cdots \tag{3.11}$$

where t stands for the time moment at which the power vector is updated. Equation (3.11) can be expressed by a piece-wise form as

$$p_i(t+1) = \left(\gamma_i / G_{ii}\right)\left(\sum_{j\neq i}^{N} G_{ij} p_j(t) + \eta_i\right) = \frac{\gamma_i}{\Gamma_i(t)} p_i(t)\,,\ i = 1,\cdots,N \tag{3.12}$$

Equation (3.12) can be implemented in a distributed way, where $p_i(t)$ is the transmission power of the i th link at time t. Each link only needs to measure its current SINR, $\Gamma_i(t)$, in order to determine the power level at the next time, $(t+1)$. It has been proven that this distributed algorithm converges to the optimal minimum power vector $\mathbf{p}^*_{\mathbf{W_S}}$ that is given in (3.9) provided that the Centralized MPA Scheme has a solution.

3.2.3.2 For Joint Base Station Allocation

The transmitter power control schemes introduced above only consider the fixed link allocation. But as we point out in section 1.1 that transmitter power control is also an effective tool to realize some key network control operation such as resource allocation and handoff, so in [12,13,16,18] the minimum power assignment scheme is integrated with base station allocation, that is, a joint power control and base station allocation scheme.

Since here we take the base station allocation into account, we need to make some modifications to the system model in Section 2.1. We assume there are N mobiles and M base stations in the system. The transmitter power of mobile i is p_i and the link gain between transmitter i and base station l is G_{li}. In addition, η_l denotes the received noise power at the base station l and γ_i denotes the SINR threshold which has to be maintained to guarantee the QoS requirement of mobile i. We also define $c_i = l$, $l \in [1, M]$ to represent that mobile i is assigned to base l. A base station assignment is a vector $\mathbf{c} = [c_1, c_2 \cdots c_N]$ that specifies an assigned base station for each mobile.

The received SINR for mobile i at base station l should be

$$\Gamma_{li} = \frac{p_i G_{li}}{\sum_{j \neq i}^{N} p_j G_{lj} + \eta_l}, \; i = 1,2,\cdots,N \tag{3.13}$$

In order to satisfy the SINR requirement γ_i, we have

$$\Gamma_{li} = \frac{p_i G_{li}}{\sum_{j \neq i}^{N} p_j G_{lj} + \eta_l} \geq \gamma_i, \; i = 1,2,\cdots,N \tag{3.14}$$

To minimize the power level p_i of user i, the inequality (3.14) should be satisfied by equality, that is

$$p_i = \gamma_i \cdot \frac{\sum_{j \neq i}^{N} p_j G_{lj} + \eta_l}{G_{li}}, \; i = 1,2,\cdots,N \tag{3.15}$$

Thus, starting from time 0 with an arbitrary positive vector $\mathbf{p}^{(0)}$, the transmitter power at time $t+1$ is given by

$$p_i(t+1) = \min_{1 \le l \le M} \left(\frac{\gamma_i}{\Gamma_{li}(t)} p_i(t) \right), \; i = 1,2,\cdots,N \tag{3.16}$$

and the base station assignment for mobile i at time $t+1$ is

$$c_i(t+1) = \arg\min_{1 \le l \le M} \left(\frac{\gamma_i}{\Gamma_{li}(t)} p_i(t) \right), \; i = 1,2,\cdots,N \tag{3.17}$$

So mobile i is assigned to the base station $c_i(t+1)$ where the minimum power is needed to maintain the required SINR threshold. Note that this algorithm can be executed in a distributed manner because each link can autonomously measure its current SINR to compute its transmitter power and assigned base station in the next step. The convergence of the scheme has been proven in [12,13] under the premise that there exists a base station allocation vector $\mathbf{c}^*$ at which the fixed-link minimum power assignment scheme has a solution.

3.2.3.3 Other Extensions of Minimum Power Assignment Schemes

A. Asynchronous Minimum Power Assignment Scheme

Asynchronous communication is more realistic than the synchronous case especially for uplink communication. The reason is that for uplink case, it is not always possible for one mobile transmitter to get the latest power levels of other mobiles due to the limited channel resources, limited data access and processing speed. Hence in [13] the asynchronous minimum power assignment scheme is proposed.

The scheme allows some mobiles to perform power adjustments faster and implement more iterations than others and also allows mobiles to update the transmission power using outdated information about the interference caused by other users. Thus, we assume that mobile i may not have access to the most recent values of the components of

power vector $\mathbf{p}(t)$ and has outdated information about some other mobile transmitters' power levels. At time t, let $\tau_j^i(t)$ denote the most recent time for which p_j is known to mobile i, note that $0 \le \tau_j^i(t) \le t$. And hence $p_j\left[\tau_j^i(t)\right]$ denotes the most recent known value of p_j to mobile i. Thus, mobile transmitter i can update its power level and base station assignment using the power vector $\mathbf{p}\left[\tau^i(t)\right] = \left\{p_1\left[\tau_1^i(t)\right], p_2\left[\tau_2^i(t)\right] \cdots p_N\left[\tau_N^i(t)\right]\right\}^T$.

Let $T = \{0,1,2,\cdots\}$ denote a set of times at which one or more components $p_i(t)$ of $\mathbf{p}(t)$ are adjusted. Let T^i be the set of times when $p_i(t)$ is updated. Then at times $t \notin T^i$, $p_i(t)$ is unchanged. Thus, the asynchronous minimum power assignment and base station allocation scheme can be written as

$$p_i(t+1) = \begin{cases} \min\limits_{1 \le l \le M} \left\{ (\gamma_i / G_{li}) \left(\sum_{j \ne i}^{N} G_{lj} p_j\left(\tau_j^i(t)\right) \right) + \eta_l \right\} & t \in T^i \\ p_i(t) & t \notin T^i \end{cases} \tag{3.18}$$

$$c_i(t+1) = \begin{cases} \arg\min\limits_{1 \le l \le M} \left\{ (\gamma_i / G_{li}) \left(\sum_{j \ne i}^{N} G_{lj} p_j\left(\tau_j^i(t)\right) \right) + \eta_l \right\} & t \in T^i \\ c_i(t) & t \notin T^i \end{cases} \tag{3.19}$$

We assume that T^i is infinite and given any time t_0, there exists t_1 such that $\tau_j^i(t) \ge t_0$ for all $t \ge t_1$.

Convergence of asynchronous minimum power assignment scheme is proven in [13] and the convergence is guaranteed if there exists a fixed solution to the synchronous minimum power assignment scheme given in Section 3.2.3.2.

B. Constrained Minimum Power Assignment Scheme [13,20,21]

In real systems, transmitters are usually subject to either maximum or minimum power constraints. For simplicity, we take the fixed link assignment case as an example. And the same rule can be easily extended to the variable link assignment scenario.

Let $p_i^{\max}$ be the maximum power at which the transmitter i is allowed to transmit, and then we can get the power vector as

$$p_i(t+1) = \min\left\{p_i^{\max}, (\gamma_i / G_{ii})\left(\sum_{j\neq 1}^{N} G_{ij} p_j(t) + \eta_i\right)\right\} \tag{3.20}$$

Let $p_i^{\min}$ be the minimum power limit of transmitter i, and then the power vector can be updated as

$$p_i(t+1) = \max\left\{p_i^{\min}, (\gamma_i / G_{ii})\left(\sum_{j\neq i}^{N} G_{ij} p_j(t) + \eta_i\right)\right\} \tag{3.21}$$

Under this algorithm, transmitter i will transmit with its maximum power $p_i^{\max}$ when its SINR requirement needs a transmission power larger than $p_i^{\max}$; and transmitter i will transmit with its minimum power $p_i^{\min}$ when its SINR requirement needs a transmission power smaller than $p_i^{\min}$. The discussion about convergence of this algorithm can be found in [13].

3.3 Research Direction of Power Control

With the explosion of cellular networks in the 90's, transmitter power control becomes very important for improving spatial channel reuse and increasing network capacity since it is an effective tool to reduce the interference caused by one communication link to other links in the same system.

Early work aims at keeping the received power of the desired link at some constant level [22,23]. This scheme has the advantage that the requirements on the receiver dynamic range are smaller which results in better adjacent channel protection, but analytical investigation shows that the constant-received power control has only limited ability to reduce co-channel interference.

Then, SIR-balancing power control scheme is proposed in [2,14,15], which serves as a tool to derive upper bounds on the performance of power control schemes and lays the foundation for the later research. Based on previous research, the centralized minimum power assignment scheme is designed to find the minimum possible power level to maintain the required SINR threshold for each communication link [1,16]. After that, distributed minimum power assignment schemes are present in [8,16-19].

Besides the basic functions of link QoS maintenance and interference suppression, power control schemes are further designed to realize some key network operations such as resource allocation, handoff and admission control. In [12,13,16,18], the joint minimum power assignment and base station allocation scheme is introduced. Moreover, these joint schemes are extended to asynchronous communication case in [13] and constraint power control case in [13,20,21]. In addition, the admission control problem is also considered in [24-28] using the tool of power control.

Based on these previous works on transmitter power control, today's research is expanded to a wider area. According to an extensive literature survey, current research on transmitter power control is centered on the following scopes:

(1) Novel transmitter power control schemes with outage-probability specifications which are able to update the power levels on a much larger time scale compared

to the conventional power control algorithms by using statistical characteristics of the channel states [29];

(2) Transmitter power control schemes for the future multimedia wireless networks that support flexible information transport and heterogeneous QoS requirements [30-39];

(3) Integration of transmitter power control with other interference management techniques such as multi-user detection [40-49] and space-time signal processing based on the adaptive antenna array [50-60];

(4) Stochastic power control schemes which use random estimates of some quantities in power control process like SINR, received interference power and channel link gains, such that it can track the random features of practical wireless communication systems [11,61-63];

(5) Combination of the conventional power control schemes with some new factors and factors such grey theory, fuzzy theory and Kalman-filter [64-66].

In order to make the whole picture clearer, in Fig. 2.1 a chart is used to summarize the research scopes and directions in this area. This thesis focuses on the first two research scopes and the contributions will be presented in the next two chapters

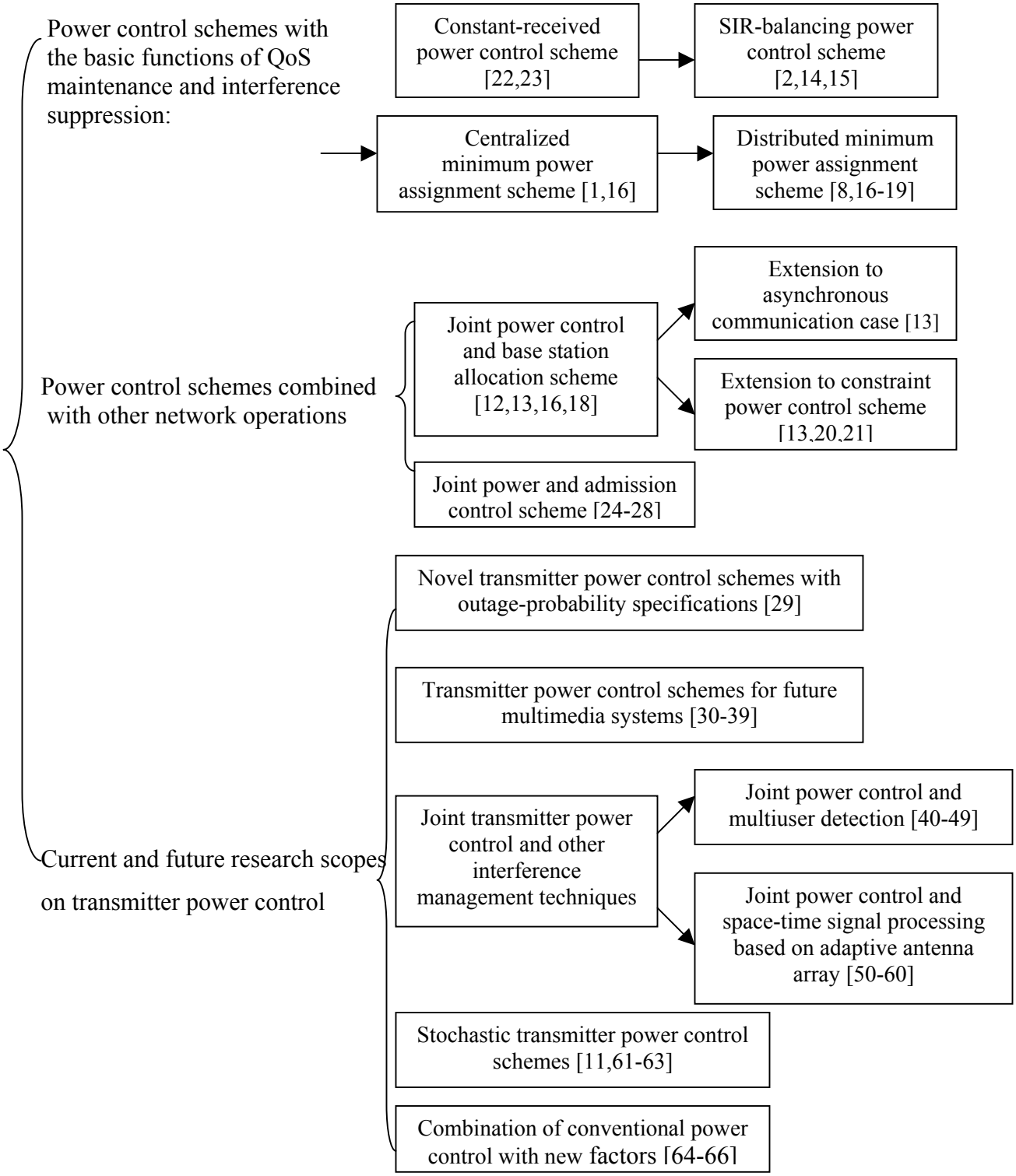

Fig. 3.1 Research scopes and directions in transmitter power control

3.4 Conclusions

In this chapter, previous relevant works on transmitter power control are reviewed and summarized in three aspects: categorization of transmitter power control methods, an extensive survey of the mainly used power control schemes and the possible research directions and scopes for this field in the future.

In the next two chapters, research works that are completed by the author of this thesis are presented.

Chapter 4

A Unified Framework for Transmitter Power Control in Cellular Radio Systems

In wireless cellular CDMA communication systems, interference can have significant negative impacts on both the system capacity and quality-of-service (QoS) if it is not properly dealt with. Power control is an effective technique to mitigate interference, maintain required link QoS and increase system capacity. Extensive research has been carried out on this subject. It is commonly assumed that the system is interference-limited, that is, the receiver noise level at the desired link is negligible compared to the interference from other unwanted links, such that QoS depends only on the signal-to-interference-power ratio (SIR). Based on such a system model, we aim to find the minimum possible transmitter power that can achieve the required SIR threshold. Obviously, it is desirable to be able to predict whether the required SIR threshold is achievable using the adopted power control technique because this is a very important premise to the problem of power control.

In this chapter, this problem is studied particularly. First, some of the findings in the previous relevant literature are summarized. Second, research results on this problem are presented and detailed discussion and interpretation are given.

4.1 Previous Works

The problem of whether a required SIR threshold is achievable has been investigated in earlier works for interference-limited systems. Sudheer A. Grandhi [2] and J. Zander [14,15] studied cellular communication systems with identical SIR threshold for each mobile in the so-called homogeneous-SIR systems. They found that the largest achievable SIR is equal to the reciprocal of the positive maximum modulus eigenvalue of the normalized link gain matrix.

A homogeneous-SIR system model is mainly suitable for networks that support only one class of service. Future cellular mobile radio systems have to support different classes of service with different SIR requirements. This prompted Wu to investigate cellular systems with different SIR thresholds, so-called heterogeneous-SIR systems in [67]. In order to make use of the results in [2,14,15], he used a margin parameter δ to reconstruct the required SIR threshold vector.

Looking at these works on transmitter power control, the solution to whether a SIR threshold vector is achievable for homogeneous-SIR cellular systems appears to be different from that for heterogeneous-SIR cellular systems. However, from these previous works, we found that for both homogeneous-SIR and heterogeneous-SIR cases, we can determine whether there exists an achievable SIR for a particular power control scheme by a unified criterion. In this paper, our main contribution is in presenting a unified framework on the power control systems for both homogeneous-SIR and heterogeneous-

SIR scenarios, and in deriving a generalized theorem to determine whether a SIR threshold vector is achievable for both cases. Therefore, our result is a generalization of the results reported in papers [2,14,15,67].

The system model used here is still the same one in Section 2.1, except that the QoS measurement criterion is the received SIR level for each desired communication link in interference-limited systems. In addition, some definitions to facilitate the later analysis and explanation are stated below.

- *Definition 1:* For two vectors $\mathbf{a} = [a_1 \cdots a_i \cdots a_N]^T$ and $\mathbf{b} = [b_1 \cdots b_i \cdots b_N]^T$ having the same dimension, $\mathbf{a} \le \mathbf{b}$ means $a_i \le b_i$ for every i and $\mathbf{a} > \mathbf{b}$ means $a_i > b_i$ for every i. The notation $\mathbf{p} > \mathbf{0}$ denotes that all elements of $\mathbf{p}$ are positive, where $\mathbf{0}$ is a vector with all elements equal to zero.
- *Definition 2*: The SIR threshold vector $\boldsymbol{\gamma} = [\gamma_1 \cdots \gamma_i \cdots \gamma_N]^T$ is achievable if there exists a power vector $\mathbf{p} \ge \mathbf{0}$ such that the received SIR level $\Gamma_i \ge \gamma_i$ for each desired communication link.

Based on the review of the previous relevant works, in the next section the unified framework on the power control schemes for both homogeneous-SIR and heterogeneous-SIR scenarios will be proposed and explained.

4.2 The Unified Framework

With the assumption that the systems is interference-limited and according to the inequality (2.4), the problem of transmitter power control is aimed at finding the positive power vector $\mathbf{p} = [p_1 \cdots p_i \cdots p_N]^T$ that satisfies

$$\Gamma_i = \frac{p_i G_{ii}}{\sum_{j \neq i}^{N} p_j G_{ij}} \geq \gamma_i, \; i = 1, \cdots, N \tag{4.1}$$

That is

$$p_i \geq \sum_{j \neq i}^{N} \gamma_i \frac{G_{ij}}{G_{ii}} p_j \;, \; i = 1, \cdots, N \tag{4.2}$$

We can express the above inequality in matrix form as

$$\mathbf{p} \geq \mathbf{W_S p} \tag{4.3}$$

where the matrix $\mathbf{W_S}$ is defined in (3.7).

In contrast with the normalized link gain matrix defined in [2,14,15], we shall call the matrix $\mathbf{W_S}$, which is the SIR-threshold-embedded normalized link gain matrix, as the system gain matrix. In a particular case where all services have the same SIR threshold, i.e $\gamma_i = \gamma \;\; \forall i$, we obtain

$$\{W_S\}_{ij} = \begin{cases} \gamma \cdot \dfrac{G_{ij}}{G_{ii}} & i \neq j \\ 0 & i = j \end{cases} \tag{4.4}$$

As expected, we can see that the homogeneous-SIR system is only a special case of the heterogeneous-SIR system.

In $\mathbf{W_S}$, the original normalized link gain matrix is "modified" by the SIR thresholds which could be identical for homogeneous-SIR systems or dissimilar for heterogeneous-SIR systems. Hence, this definition of system gain matrix provides us a unified framework on the formulation of power control problem for both homogeneous-SIR and heterogeneous-SIR systems.

Using Lemma 3.1 that is given in Section 3.2.1, we know that the system gain matrix $\mathbf{W_S}$ is an irreducible nonnegative matrix so that Theorem 2.1 and Lemma 2.1 can be applied to it.

According to the unified framework presented above, the power control problem for both homogeneous-SIR and heterogeneous-SIR systems can be expressed by a unified form of (4.3). Because of Lemma 2.1 and Theorem 2.1, the maximum modulus eigenvalue $\lambda^*_{W_S}$ of $\mathbf{W_S}$ is real, positive and it has an eigenvector $\mathbf{p}^*_{\mathbf{W_S}}$ with strictly positive entries. Thus we can introduce the following Proposition 4.1 and Proposition 4.2.

Proposition 4.1: Let $\lambda^*_{W_s}$ denote the maximum modulus eigenvalue of the system gain matrix $\mathbf{W_S}$. Then if $\lambda^*_{W_S} \le 1$, the required SIR threshold vector is achievable and the power vector achieving this SIR threshold vector is the positive eigenvector $\mathbf{p}^*_{\mathbf{W_S}}$ corresponding to $\lambda^*_{W_S}$.

Proof:

Since $\lambda^*_{W_s}$ is the maximum modulus eigenvalue of the matrix $\mathbf{W_S}$ and $\mathbf{p}^*_{\mathbf{W_S}} > \mathbf{0}$ is its corresponding positive eigenvector, we have

$$\lambda^*_{W_S}\mathbf{p}^*_{\mathbf{w_s}} = \mathbf{W_s}\mathbf{p}^*_{\mathbf{w_s}} \tag{4.5}$$

If $\lambda^*_{W_S} \le 1$, we get

$$\mathbf{p}^*_{\mathbf{w_s}} \ge \lambda^*_{W_S}\ \mathbf{p}^*_{\mathbf{w_s}} = \mathbf{W_s}\ \mathbf{p}^*_{\mathbf{w_s}} \tag{4.6}$$

From (4.3) we know the inequality (4.6) means that there exists a positive power vector $\mathbf{p}^*_{\mathbf{w_s}}$ satisfying $\Gamma_i \ge \gamma_i$ for all the mobiles, i.e., the SIR threshold vector is achievable.

Proposition 4.2: If a SIR threshold vector is achievable, we have $\lambda^*_{W_S} \le 1$.

Proof:

First assume that if the SIR threshold vector is achievable $\lambda^*_{W_S} > 1$.

Because the SIR threshold vector is achievable, we have $\mathbf{p} > 0$ such that $\mathbf{p} \ge \mathbf{W_s}\ \mathbf{p}$. That is, there exists a value of μ, for example $\mu = 1$, such that $\mu\,\mathbf{p} \ge \mathbf{W_s}\ \mathbf{p}$ has solutions for $\mathbf{p} > 0$. Since $\mu = 1 < \lambda^*_{W_S}$, which is obviously a contradiction against the Theorem 2.1-5, the assumption is wrong and Proposition 4.2 is proved.

With Proposition 4.2 and 4.3, we naturally get the following theorem 4.1.

Theorem 4.1: A SIR threshold vector is achievable if and only if $\lambda^*_{W_S} \le 1$.

Using the same proving method as the above, we can also conclude that

Theorem 4.2: A SIR threshold vector is not achievable if and only if $\lambda_{W_S}^* > 1$.

4.3 Previous Results Seen from the Unified Framework

We have seen that Proposition 4.1, Proposition 4.2 and Theorem 4.1 give the general rules to determine whether a SIR threshold vector is achievable for both homogeneous-SIR systems and heterogeneous-SIR systems. In this section we shall demonstrate that all the results in paper [2,14,15,67] can be derived from the above general rules.

4.3.1 Homogeneous-SIR Cellular Systems

For a homogeneous-SIR system, we can extract the SIR threshold from the system gain matrix $\mathbf{W_S}$, which can be rewritten as

$$\mathbf{W_S} = \gamma \mathbf{W} \tag{4.7}$$

where the entry of matrix $\mathbf{W}$ is

$$W_{ij} = \begin{cases} \dfrac{G_{ij}}{G_{ii}} & i \neq j \\ 0 & i = j \end{cases} \tag{4.8}$$

and this matrix $\mathbf{W}$ is defined as the normalized link gain matrix in [2,14,15]. According to the inequality (4.3), the problem of power control for this case becomes

$$\mathbf{p} \geq \gamma \mathbf{W} \mathbf{p} \tag{4.9}$$

If we let λ_W^* be the real, positive and maximum modulus eigenvalue of the matrix $\mathbf{W}$, and $\mathbf{p_W^*}$ be the positive eigenvector corresponding to λ_W^*, we have

$$\lambda_W^* \mathbf{p_W^*} = \mathbf{W} \mathbf{p_W^*} \tag{4.10}$$

Multiplying γ to both sides of (4.10), we get

$$\gamma\lambda_W^* \mathbf{p}_{\mathbf{W}}^* = \gamma \mathbf{W} \mathbf{p}_{\mathbf{W}}^* = \mathbf{W}_{\mathbf{S}}\, \mathbf{p}_{\mathbf{W}}^* \tag{4.11}$$

Thus $\gamma\lambda_W^*$ is a positive eigenvalue of $\mathbf{W}_{\mathbf{S}}$ and it has a corresponding positive eigenvector $\mathbf{p}_{\mathbf{W}}^*$. Because of Lemma 2.1, we can conclude that

$$\lambda_{W_S}^* = \gamma\lambda_W^* \quad \text{and} \quad \mathbf{p}_{\mathbf{W}_\mathbf{S}}^* = \mathbf{p}_{\mathbf{W}}^* \tag{4.12}$$

From Proposition 1, we know that the SIR threshold γ is achievable if $\lambda_{W_S}^* \le 1$. The power vector achieving γ is the positive eigenvector $\mathbf{p}_{\mathbf{W}_\mathbf{S}}^*$ of $\mathbf{W}_{\mathbf{S}}$ corresponding to $\lambda_{W_S}^*$. That is, if the SIR threshold $\gamma \le 1/\lambda_W^*$, it is achievable and the power vector achieving γ is the positive eigenvector $\mathbf{p}_{\mathbf{W}}^*$ of $\mathbf{W}$ corresponding to λ_W^*. This is just the result of paper [2,14,15].

4.3.2 Heterogeneous-SIR Cellular Systems

For a heterogeneous-SIR system, given a required SIR threshold vector $\boldsymbol{\gamma}$, the system gain matrix $\mathbf{W}_{\mathbf{S}}$ can be expressed as

$$\mathbf{W}_{\mathbf{S}} = \begin{pmatrix} \gamma_1 & & & \\ & \gamma_2 & & \\ & & \ddots & \\ & & & \gamma_N \end{pmatrix} \mathbf{W} \tag{4.13}$$

where $\{\gamma_i\}_{i=1}^N$ are the elements of the required SIR threshold vector $\boldsymbol{\gamma}$.

If we extract a common margin parameter δ from each element of $\boldsymbol{\gamma}$, we can rewrite $\boldsymbol{\gamma}$ as

$$\boldsymbol{\gamma} = \delta\, \boldsymbol{\gamma}^0 \tag{4.14}$$

where $\boldsymbol{\gamma}^0 = \{\gamma_i^0\}_{i=1}^N$. Thus $\mathbf{W}_{\mathbf{S}}$ becomes

$$\mathbf{W_S} = \delta \begin{pmatrix} \gamma_1^0 & & & \\ & \gamma_2^0 & & \\ & & \ddots & \\ & & & \gamma_N^0 \end{pmatrix} \mathbf{W} = \delta \mathbf{W}^0 \tag{4.15}$$

where $\mathbf{W}^0 = \left\{ \gamma_i^0 \cdot W_{ij} \right\}_{N \times N}$. Hence, the problem of power control becomes

$$\mathbf{p} \geq \delta \mathbf{W}^0 \mathbf{p} \tag{4.16}$$

Following the same analysis as for the above homogeneous-SIR systems,

$$\lambda_{W_S}^* = \delta \lambda_{W^0}^* \text{ and } \mathbf{p}_{\mathbf{W_S}}^* = \mathbf{p}_{\mathbf{W^0}}^* \tag{4.17}$$

where $\lambda_{W^0}^*$ is the real, positive and maximum modulus eigenvalue of the matrix $\mathbf{W}^0$ and $\mathbf{p}_{\mathbf{W^0}}^*$ is the positive eigenvector of $\mathbf{W}^0$ corresponding to $\lambda_{W^0}^*$.

From Proposition 4.1, if $\lambda_{W_S}^* \leq 1$, i.e., $\delta \leq 1 / \lambda_{W^0}^*$, the SIR threshold vector $\boldsymbol{\gamma}$ is achievable. That is, the largest value of the margin parameter is $\delta^* = 1 / \lambda_{W^o}^*$ and the largest achievable SIR threshold vector related to $\boldsymbol{\gamma}^0$ is $\boldsymbol{\gamma}_{\mathbf{W_S}}^* = \delta^* \boldsymbol{\gamma}^0$. This is the result in paper [67].

To summarize, we need not extract the SIR threshold γ (see (4.7)) for homogeneous-SIR systems or the margin parameter δ (see (4.14)) for heterogeneous-SIR systems in order to determine whether a SIR threshold vector is achievable. Instead, the unified rule in Section 4.2, which is derived from the system gain matrix $\mathbf{W_S}$, can be used to determine whether the required SIR threshold vector is achievable for cellular systems with either homogeneous SIR thresholds or heterogeneous SIR thresholds.

4.3.3 A Physical Interpretation on the Unified Framework

In this section, we further interpret the physical meaning of the unified framework. This provides the more practical and intuitive explanation behind the mathematical derivation and proof. We shall use a system with two users in Fig. 4.1 and Fig. 4.2 as an example to illustrate the physical interpretation about the unified theory.

In the system gain matrix $\mathbf{W_S}$, the normalized link gain is multiplied by the SIR threshold corresponding to each desired link, that is, $\{W_S\}_{ij} = \{\gamma_i \cdot W_{ij}\}$. We can view the SIR threshold γ_i (of the desired link from transmitter i to its receiver) as an additional gain factor to the gain, G_{ij} (of the unwanted link from transmitter j ($j \neq i$) to receiver i). Mathematically, we can use an equivalent link gain $G_{ij}^{'}$ to denote this effect, where $G_{ij}^{'} = \gamma_i G_{ij}$. (Or equivalently, the link gain of the desired link will be modified to $G_{ii}^{'} = \dfrac{G_{ii}}{\gamma_i}$). Therefore, the larger the required SIR threshold, the more is the equivalent amount of "interference" imposed on the gain G_{ii} of the desired link. In Table 4.1, We summarize how the system gain matrix $\mathbf{W_S}$, which combines link gains and the required SIR thresholds of the system, provides us with a unified framework to the problem.

In homogeneous-SIR systems, because the required SIR thresholds for all desired links are identical, which is γ, the gains of all the unwanted links are weighted equally according to $G_{ij}^{'} = \gamma G_{ij}$. Therefore the largest achievable homogeneous SIR threshold depends only on the normalized link gains. But in heterogeneous-SIR systems, the gains of all the unwanted links are weighted unequally according to $G_{ij}^{'} = \gamma_i G_{ij}$. So whether a

SIR threshold is achievable will depend not only on the link gains but also on the SIR thresholds of all desired system links.

Table 4.1: Physical interpretation on the unified framework

Original heterogeneous-SIR system		Equivalent homogeneous-SIR Systems	
Normalized link gain matrix	$\mathbf{W} = \{W_{ij}\}$	System gain matrix	$\mathbf{W_S} = \{\gamma_i W_{ij}\}$
Gain of the desired links	G_{ii} , $i = 1, \cdots, N$	Equivalent gain of the desired links	$G'_{ii} = G_{ii}$, $i = 1, \cdots, N$
Gain of the unwanted links	G_{ij} , $j \neq i$	Equivalent gain of the unwanted links	$G'_{ij} = \gamma_i G_{ij}$, $j \neq i$
SIR threshold at the receiver	γ_i , $i = 1, \cdots, N$	Equivalent SIR threshold at the receiver	$\gamma'_i = 1$, $i = 1, \cdots, N$

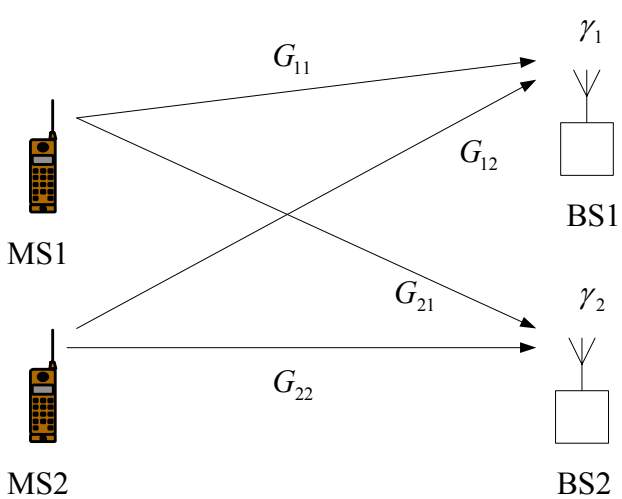

Fig. 4.1 Original model based on normalized link gain matrix W

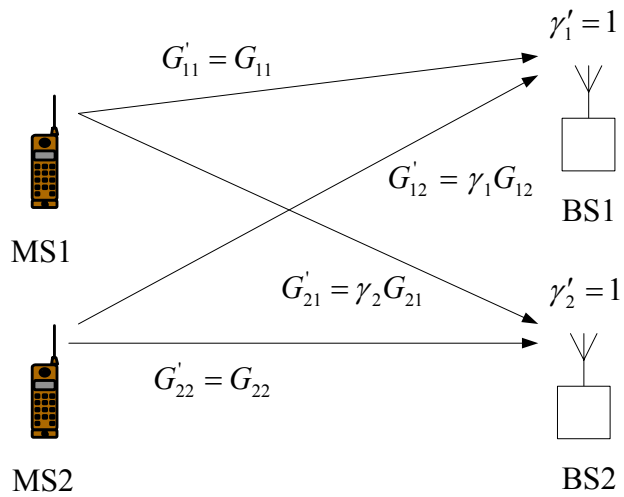

Fig. 4.2 Equivalent model based on system gain matrix $\mathbf{W_S}$

4.4 Notes on Achievable SIR for Heterogeneous-SIR Systems

In homogeneous SIR systems, once the maximum modulus eigenvalue λ_W^* of the normalized link gain matrix **W** is determined, the largest achievable SIR threshold of a homogeneous-SIR system is given by $\gamma_W^* = 1/\lambda_W^*$. However, so far there is no definite answer to the largest achievable SIR threshold vector for heterogeneous-SIR systems. Hence in this section, we highlight the conditions under which a given SIR threshold vector for the heterogeneous systems is achievable.

Proposition 4.3: If the SIR threshold vector for a heterogeneous system satisfies $\max_{1\le i\le N}[\gamma_i] \le \gamma_W^*$, then the maximum modulus eigenvalue of the system gain matrix satisfies $\lambda_{W_s}^* \le 1$, which means that the required SIR threshold vector, $\boldsymbol{\gamma}$, for the heterogeneous system is achievable.

Proof:

For a heterogeneous-SIR system with N users, let us assume that when $\max_{1\le i\le N}[\gamma_i] \le \gamma_W^*$, $\lambda_{W_S}^* > 1$.

$$\because \lambda_{W_S}^* \mathbf{p}_{\mathbf{w_s}}^* = \mathbf{W_S}\, \mathbf{p}_{\mathbf{w_s}}^* = \begin{pmatrix} \gamma_1 & & & & \\ & \ddots & & & \\ & & \gamma_i & & \\ & & & \ddots & \\ & & & & \gamma_N \end{pmatrix} \mathbf{W}\, \mathbf{p}_{\mathbf{w_s}}^* \tag{4.18}$$

$$\therefore \begin{cases} \dfrac{\lambda_{W_S}^*}{\gamma_1} p_{W_S 1}^* = \displaystyle\sum_{j\ne 1}^{N} \frac{G_{1j}}{G_{11}} p_{W_S j}^* \\ \vdots \\ \dfrac{\lambda_{W_S}^*}{\gamma_i} p_{W_S i}^* = \displaystyle\sum_{j\ne i}^{N} \frac{G_{ij}}{G_{ii}} p_{W_S j}^* \\ \vdots \\ \dfrac{\lambda_{W_S}^*}{\gamma_N} p_{W_S N}^* = \displaystyle\sum_{j\ne N}^{N} \frac{G_{Nj}}{G_{NN}} p_{W_S N}^* \end{cases} \tag{4.19}$$

Since $\lambda_{W_S}^* > 1$ and $\max_{1\le i\le N}[\gamma_i] \le \gamma_W^*$, we have $\dfrac{\lambda_{W_S}^*}{\gamma_i} > \dfrac{1}{\gamma_W^*}$ for all i. Let $\gamma_0 = \max_{1\le i\le N}\{\gamma_i\}$, then we have $\dfrac{\lambda_{W_S}^*}{\gamma_0} \le \dfrac{\lambda_{W_S}^*}{\gamma_i}$ for all i and $\dfrac{\lambda_{W_S}^*}{\gamma_0} > \dfrac{1}{\gamma_W^*}$. Thus we get

$$\begin{cases} \dfrac{\lambda_{W_S}^*}{\gamma_0} p_{W_S 1}^* \le \dfrac{\lambda_{W_S}^*}{\gamma_1} p_{W_S 1}^* = \displaystyle\sum_{j\ne 1}^{N} \frac{G_{1j}}{G_{11}} p_{W_S j}^* \\ \vdots \\ \dfrac{\lambda_{W_S}^*}{\gamma_0} p_{W_S i}^* \le \dfrac{\lambda_{W_S}^*}{\gamma_i} p_{W_S i}^* = \displaystyle\sum_{j\ne i}^{N} \frac{G_{ij}}{G_{ii}} p_{W_S j}^* \\ \vdots \\ \dfrac{\lambda_{W_S}^*}{\gamma_0} p_{W_S N}^* \le \dfrac{\lambda_{W_S}^*}{\gamma_N} p_{W_S N}^* = \displaystyle\sum_{j\ne N}^{N} \frac{G_{Nj}}{G_{NN}} p_{W_S N}^* \end{cases} \tag{4.20}$$

That is $\frac{\lambda_{W_S}^*}{\gamma_0}\mathbf{p}_{\mathbf{w}_s}^* \le \mathbf{W}\,\mathbf{p}_{\mathbf{w}_s}^*$. But since $\frac{\lambda_{W_S}^*}{\gamma_0} > \frac{1}{\gamma_W^*} = \lambda_W^*$, this result is in contradiction with Theorem 2.1-6. So the assumption $\lambda_{W_S}^* > 1$ is wrong. Hence, when $\max_{1\le i\le N}[\gamma_i] \le \gamma_W^*$, it implies $\lambda_{W_S}^* \le 1$. From Theorem 4.1, this means the SIR threshold vector $\boldsymbol{\gamma}$ is achievable.

Proposition 4.4: If $\min_{1\le i\le N}[\gamma_i] > \gamma_W^*$, then $\lambda_{W_S}^* > 1$, which means that this heterogeneous SIR threshold vector is not achievable.

Proof:

Assume that when $\min_{1\le i\le N}[\gamma_i] > \gamma_W^*$, $\lambda_{W_S}^* \le 1$. Since $\lambda_{W_S}^* \le 1$ and $\min_{1\le i\le N}[\gamma_i] > \gamma_W^*$, we have $\frac{\lambda_{W_S}^*}{\gamma_i} < \frac{1}{\gamma_W^*}$. Similar to the proof to Proposition 4.3, we can get $\frac{\lambda_{W_S}^*}{\gamma_0}\mathbf{p}_{\mathbf{w}_S}^* \ge \mathbf{W}\,\mathbf{p}_{\mathbf{w}_S}^*$ where $\gamma_0 = \min_{1\le i\le N}\{\gamma_i\}$ and $\frac{\lambda_{W_S}^*}{\gamma_0} < \frac{1}{\gamma_W^*} = \lambda_W^*$. This is in contradiction with Theorem 2.1-5. Hence, the assumption is not valid. Therefore, if $\min_{1\le i\le N}[\gamma_i] > \gamma_W^*$, then $\lambda_{W_S}^* > 1$. From Theorem 4.2, this means that the SIR threshold vector $\boldsymbol{\gamma}$ is not achievable.

With Proposition 4.3 and 4.4, the achievable SIR threshold vector of a given heterogeneous-SIR cellular system is related to its largest achievable homogeneous-SIR threshold, which is $\boldsymbol{\gamma}^* = \{\gamma_W^*\}_{i=1}^N$. When a heterogeneous SIR threshold requirement $\boldsymbol{\gamma}$ is

imposed on an originally homogeneous-SIR system, if $\boldsymbol{\gamma} \le \boldsymbol{\gamma}^*$, the heterogeneous SIR threshold $\boldsymbol{\gamma}$ is achievable by the system. If $\boldsymbol{\gamma} > \boldsymbol{\gamma}^*$, the heterogeneous SIR threshold $\boldsymbol{\gamma}$ is not achievable. However, if some elements of $\boldsymbol{\gamma}$ are bigger than γ_W^* and some elements of $\boldsymbol{\gamma}$ are smaller than γ_W^*, then there is not definite answer about whether such $\boldsymbol{\gamma}$ is achievable.

In the next section, an examples is given to illustrate the use of the above results.

4.5 An Illustration

We illustrate using an interference-limited CDMA network, but the theorem presented above is applicable for all types of networks. Let us consider a system consisting of three base stations, namely BS A, BS B, BS C, and four mobile users 1,2,3, and 4. The channel gains their communication links are given as follow:

i) User 1 to BS A = 1×10^{-4}, user 1 to BS B = 1×10^{-5}, user 1 to BS C=8×10^{-5};

ii) User 2 to BS A = 3×10^{-4}, user 2 to BS B = 1×10^{-4}, user 2 to BS C=3×10^{-5};

iii) User 3 to BS A = 8×10^{-5}, user 3 to BS B = 1.5×10^{-4}, user 3 to BS C=7×10^{-5};

iv) User 4 to BS A = 3×10^{-5}, user 4 to BS B = 3×10^{-5}, user 4 to BS C=5×10^{-4};

The CDMA processing gain is 8 and binary phase shift keying (BPSK) is used. Supposing there are three classes of services, so-called class I, II and III services, and each requires a target bit error rate (BER) performance of 10^{-4}, 10^{-3} and 10^{-2}, respectively. The respective target bit energy to interference power spectral density ratio (E_b/I_0) to achieve such BER performance are, respectively, given by 6.85 (= 8.4dB), 4.80 (= 6.8dB) and 2.65 (= 4.2dB). Equivalently, we can divide the target E_b/I_0 by the

processing gain to obtain the corresponding SIR thresholds γ_I = 0.86, γ_{II} = 0.60 and γ_{III} = 0.33, respectively, for class I, II and III services. The relation between the target E_b/I_0 and its corresponding SIR threshold is explained in Section 2.1.

We assume that the transmitter power of each user is controlled by the BS associated with the largest channel gain. Therefore, in this example, the transmitter power of mobile users 1 and 2 will be controlled by BS A, user 3 by BS B, and user 4 by BS C.

Therefore, the channel link gain matrix is given by

$$\mathbf{G} = \begin{bmatrix} 1\times10^{-4} & 3\times10^{-4} & 8\times10^{-5} & 3\times10^{-5} \\ 1\times10^{-4} & 3\times10^{-4} & 8\times10^{-5} & 3\times10^{-5} \\ 1\times10^{-5} & 1\times10^{-4} & 1.5\times10^{-4} & 3\times10^{-5} \\ 8\times10^{-5} & 3\times10^{-5} & 7\times10^{-5} & 5\times10^{-4} \end{bmatrix}$$

The normalized link gain matrix $\mathbf{W}$ (4.8) and system gain matrix $\mathbf{W_S}$ (4.13) can respectively be written as

$$\mathbf{W} = \begin{bmatrix} 0 & 3.0 & 0.8 & 0.3 \\ 0.333 & 0 & 0.267 & 0.1 \\ 0.0667 & 0.667 & 0 & 0.2 \\ 0.16 & 0.06 & 0.14 & 0 \end{bmatrix}$$

and

$$\mathbf{W_S} = \begin{bmatrix} 0 & 3\gamma_1 & 0.8\gamma_1 & 0.3\gamma_1 \\ 0.333\gamma_2 & 0 & 0.267\gamma_2 & 0.1\gamma_2 \\ 0.067\gamma_3 & 0.667\gamma_3 & 0 & 0.2\gamma_3 \\ 0.16\gamma_4 & 0.06\gamma_4 & 0.14\gamma_4 & 0 \end{bmatrix}$$

where $\gamma_i\,(i = 1,2,3,4)$ equals one of the values of $\gamma_I, \gamma_{II}, \gamma_{III}$, depending on the service class of user *i*.

Next, we shall list the following three cases separately.

Case (i) Homogeneous SIR Thresholds

Using the result in Section 4.3.1, since the real, positive and maximum modulus eigenvalue of **W** is given by $\lambda_W^* = 1.26$, the maximum SIR that the mobiles can achieve is $\gamma_W^* = 1/\lambda_W^* = 0.795$. Therefore, all four users can select either class II or class III service, whilst the SIR requirement for class I service is not achievable.

To look at the latter, let us consider the case where all four users select class I service, then $\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = \gamma_I = 0.86$, and the real, positive and maximum modulus eigenvalue of $\mathbf{W_S}$ is $\lambda_{W_S}^* = 1.26 > 1$. Based on our unified framework (see Theorem 4.2), we can see that such a system cannot be supported.

Case (ii) Heterogeneous SIR thresholds

Based on our unified framework, if user 1 and user 3 are using class I service, user 2 is using class II and user 4 is using class III service, we have $\lambda_{W_S}{}^* = 0.8982 < 1$. Therefore, such system can be supported and the optimal solution for transmitter power is given by the associated eigenvector $[0.935 \quad 0.255 \quad 0.237 \quad 0.073]$.

On the other hand, if users 1 and 2 are using class I service, while users 3 and 4 are using class II service, since $\lambda_{W_S}{}^* = 1.018 > 1$, we predict that these combination of users cannot be supported.

Case (iii)

As long as all the four users select either class II or class III services, their SIR requirements can always be met, regardless of the combination of their services. This

conclusion can be predicted using $\max(\gamma_{II}, \gamma_{III}) < \gamma_W^*$ by applying the Proposition 4.3. It is also not difficult to verify that by increasing the processing gain β to 9, we have $6.85/\beta < 0.795$, and therefore all service classes can be supported regardless of their combination.

4.6 Conclusions

In this chapter the SIR-based transmitter power control problem for cellular radio systems is studied. In contrast to the different rules for determining whether a SIR threshold is achievable for homogeneous-SIR and heterogeneous-SIR systems in earlier works, a unified framework and general theorem for both cases are presented by a definition of the system gain matrix $\mathbf{W_S}$ in which the target SIR is embedded. It is shown that a SIR threshold is achievable for both cases when $\lambda_{W_S}^* \leq 1$, where $\lambda_{W_S}^*$ is the largest modulus eigenvalue of $\mathbf{W_S}$. We have also highlighted the conditions under which a given SIR threshold vector is achievable for the heterogeneous-SIR system. These results show how the achievable heterogeneous SIR threshold of a cellular radio system is closely related to the maximum modulus eigenvalue λ_W^* of the normalized link gain matrix $\mathbf{W}$.

In the next chapter, a novel transmitter power control scheme with outage probability specifications will be proposed. Its advantages over the traditional transmitter power control algorithms are highlighted. Its validity and effectiveness are fully verified by simulation results.

Chapter 5

Power Control with Outage Probability Specifications in Rician Fading Channels

Traditional power control schemes are always based on the observed SINR at the receiver and the knowledge of the link gains to update the transmission power levels. Thus, the implicit assumption behind all these power control schemes is that the transmission power updates are made every time the channel state changes, i.e., whenever the gain of any link changes. However, in fast fading wireless communication channels where the fades fluctuate very frequently, this kind of power control may not be always practical. Take the uplink communications as an example, when the fast fading changes very quickly, the latest feedback channel states from the base station cannot keep up with the channel variations, i.e., when the mobile is to use the channel states feedback for the power control scheme, the actual channel gain has changed so rapidly that the information has become inaccurate. Under this circumstance, the traditional power control schemes fails.

In order to overcome the disadvantages of the early power control schemes, S. Kandukuri and S. Boyd proposed a novel power control scheme in [29]. Instead of tracking instantaneous SIR value of each desired transmitter/receiver pair, they took into account the statistical average of the SIR variation and optimally controlled the transmitter power to minimize the probability of fading-induced outage. Fading-induced outage means that outage occurs because of fading, and the log-normal shadowing and path loss are assumed to be constant between successive transmitter power update intervals. Because the outage probability could be reduced if each mobile has an extra margin above the required SIR threshold, they derived a tight upper and lower bounds of the outage probability as the function of the parameter, so-called Certainty Equivalent Margin. By maximizing the SIR margin, they obtained the optimal transmitter power to minimize the outage probability.

Compared to the conventional power control methods, the advantages of this algorithm are quite straightforward: Since the outage probability is only related to the average values of both the desired and unwanted signal powers, the transmitter power can be updated at a time scale much larger than the fading time scale. Moreover, this new power control scheme can be implemented more conveniently with the knowledge of the statistical average of the channel gains, rather than the instantaneous fading statistics.

However, in [29] Kandukuri and Boyd only dealt with the Rayleigh/Rayleigh wireless fading channel which is an appropriate channel model for macrocells (i.e., cells with diameter of 2 to 20 km) and has the nice property of being analyzed conveniently. However, with the fast growing number of users for mobile radio communications, many techniques are used to reduce the reuse distance to satisfy the demands for efficient use of

the limited frequency spectrum. Hence, except the macrocells, nowadays-cellular radio systems also include two other categories: microcells of 0.4 to 2 km diameter and picocells of 20 to 400 m diameter suited for indoors radio communications [68]. In the case of microcell or picocell systems, the interfering signals arrive from much shorter distances than those in macrocell systems. A LOS path always exists within the cells or between the co-channel cells. In these situations, very often the Rayleigh/Rayleigh fading model is no longer appropriate and will yield pessimistic results, which lead to an incorrect performance evaluation [69]. Therefore, Rician fading channel model should be adopted in order to describe more accurately the channel characteristics where the LOS path is present. Furthermore, Rician model will reduce to Rayleigh model when the LOS component does not exist. So Rician model is more general than Rayleigh model.

So based on the work of [29], in this chapter the Rician/Rician wireless fading channel where both desired signals and interference signals are subjected to Rician fading is considered and a power control scheme to balance the outage probabilities of all the desired links in a cellular system is proposed. It is shown that the algorithm of [29] is a special case of our power control scheme. Unlike the results reported in [29], in the system model of this chapter, the required SIR threshold for each desired link is not necessarily identical. That is, our power control scheme is general for both homogeneous-SIR systems as well as heterogeneous-SIR systems. Another contribution of the research works of this chapter is that computer simulation is used to prove the validity of this new power control scheme, which compensates for the lack of simulation results support in paper [29]. Besides, the minimum period of the power control cycle is also investigated, which has not been examined up till now.

This chapter is organized as follows: In Section 5.1, the system model used in this chapter is introduced. Then in Section 5.2, two concepts that are very important to the proposed power control scheme are explained and their relations are also interpreted. Subsequently, the proposed power control scheme is described in details in Section 5.3. Finally, in Section 5.4 simulation results are given and analyzed.

5.1 System and Channel Model

Let us assume that the system is interference-limited and follow the system and channel model that is described in Section 2.1. Since here we consider the Rician/Rcian wireless fading channels, the variable F_{ij} should be a nonzero mean complex Gaussian variable, i.e., $F_{ij} \sim CN(m_{ij}, 2\sigma_{ij}^2)$. Because we assume that the outage is only due to small scale fading, L_{ij} and S_{ij} introduced in Section 2.1 can be assumed to be constant between successive transmitter power updates. Therefore, our power control scheme will be implemented at a time scale over which these two factors are approximately constant, i.e., effects due to variation in the distance between transmitters and receivers as well as the log-normal shadowing are negligible. Thus, the received power at the receiver of transmitter i from transmitter j is

$$p_{ij}^{(r)} = p_j L_{ij} S_{ij} \left| F_{ij} \right|^2, \; i = 1, \cdots, N \text{ and } j = 1, \cdots, N \tag{5.1}$$

The mean value of $p_{ij}^{(r)}$ is

$$E\left[p_{ij}^{(r)}\right] = p_j L_{ij} S_{ij} \left(m_{ij}^2 + 2\sigma_{ij}^2\right) \tag{5.2}$$

where $E[\cdot]$ denotes the expectation operation. Let $K_{ij} = m_{ij}^2 / 2\sigma_{ij}^2$ denote the Rician factor of F_{ij} between transmitter j and receiver i, then equation (5.2) can be rewritten as

$$E\left[p_{ij}^{(r)}\right] = p_j \cdot Q_{ij} \cdot \left(1 + K_{ij}\right) \tag{5.3}$$

where

$$Q_{ij} = 2\sigma_{ij}^2 \cdot L_{ij} \cdot S_{ij} \tag{5.4}$$

Since the shadowing process changes very slowly in relative to the Rician fading process, the Q_{ij} can be considered as a constant within a relatively larger time scale, while during which the Rician fading process varies greatly. Because the power control scheme with outage probability specifications only takes into account the average values of both desired and interfering signal powers, our power control scheme is to be implemented for a time scale over which Q_{ij} is approximately constant, i.e., effects due to variation in the distances between transmitters and receivers as well as the log-normal shadowing are negligible. Therefore, the transmitted power is updated over a time scale much larger than the fading time scale.

5.2 Outage Probability And SIR Margin

5.2.1 Outage Probability as a Requirement for Power Control

Based on the system and channel model, $p_{ii}^{(r)}$ ($i = 1, \cdots, N$) denote the received desired signal powers and $p_{ij}^{(r)}$ ($j \neq i$) denote the received interfering signal powers. Let γ_i be the required SIR threshold of the desired link from transmitter i to receiver i. We assume that the quality of service is achieved when the SIR exceeds γ_i. Otherwise, the signal outage will occur when

$$\frac{p_{ii}^{(r)}}{\sum_{j\neq i}^{N} p_{ij}^{(r)}} < \gamma_i, \quad i = 1, \cdots, N \tag{5.5}$$

thus the outage event can be described as

$$p_{ii}^{r} - \gamma_i \sum_{j\neq i}^{N} p_{ij}^{r} < 0 \tag{5.6}$$

So the outage probability P_i^{out} of the i th transmitter/receiver pair is expressed by

$$P_i^{out} = \Pr\left\{ p_{ii}^{(r)} - \gamma_i \sum_{j\neq i}^{N} p_{ij}^{(r)} < 0 \right\} = \Pr\left\{ p_i L_{ii} S_{ii} \left|F_{ii}\right|^2 - \gamma_i \sum_{j\neq i}^{N} p_j L_{ij} S_{ij} \left|F_{ij}\right|^2 < 0 \right\} \tag{5.7}$$

Zhang gave the outage analysis of cellular systems for arbitrary lognormal shadowed Rician/Rician channels in [70,71]. Here we assume that the distance L_{ij} between transmitter j and receiver i and the lognormal shadowing process S_{ij} of this link can be considered as a constant over each power update interval and so is Q_{ij}. Thus with some corresponding transformation, the outage probability P_i^{out} for the i th desired communication link in our system and channel model is derived as

$$P_i^{out} = \frac{1}{2} - \frac{\exp\left(-\sum_{j=1}^{N} K_{ij} \right)}{\pi} \int_{-\infty}^{\infty} \mathrm{Im}\{ g_i(y) \cdot h_i(y) \} dy \tag{5.8}$$

The integrand factors $g_i(y)$ and $h_i(y)$ are defined by

$$g_i(y) = \Phi_i^{-1} \cdot \exp\left(K_{ii} \Phi_i^{-1} \right) \tag{5.9}$$

$$h_i(y) = \prod_{j\neq i}^{N} \Psi_{ij}^{-1} \cdot \exp\left(\sum_{j\neq i}^{N} K_{ij} \Psi_{ij}^{-1} \right) \tag{5.10}$$

where

$$\Phi_i = 1 - j \exp(y) \tag{5.11}$$

$$\Psi_{ij} = 1 + j\frac{\gamma_i p_j Q_{ij}}{p_i Q_{ii}} \exp(y) \tag{5.12}$$

Although the equation (5.8) has been derived, it is still unclear how the outage probability of a communication link in Rician/Rician fading channels is related to the power control problem. Moreover, no appropriate performance index that could link outage probability to power control has so far been proposed for Ricain/Rician fading channels. Our main contribution in this work is that we explore and explain these unknowns. Next, we present a new performance index, the so-called SIR margin, for power control in Rician channels. We also investigate the relationship between the outage probability given by (5.8) and the SIR margin before we propose the power control algorithm.

5.2.2 SIR Margin as a Performance Index for Power Control

With the outage probability specifications, instead of taking into account the instantaneous variation of both desired signal power and interference power, we only need to consider the statistical mean value of these random variables, we shall call average power in this chapter. According to equation (5.3), the average desired signal power at the receiver i is $p_i Q_{ii}(1+K_{ii})$, and the average interference power at the receiver i is $\sum_{j\neq i}^{N} p_j Q_{ij}(1+K_{ij})$. We define the average SIR at the i th receiver as

$$SIR_i^{ave} = \frac{p_i Q_{ii}(1+K_{ii})}{\sum_{j\neq i}^{N} p_j Q_{ij}(1+K_{ij})}, \quad i = 1, \cdots, N \tag{5.13}$$

For the reason that becomes evident shortly, by taking the required SIR threshold into account, we can further define a new performance index, so-called SIR margin ($SIRM_i$) for the i th transmitter/receiver pair as

$$SIRM_i = \frac{SIR_i^{ave}}{\gamma_i} = \frac{p_i Q_{ii}(1+K_{ii})}{\gamma_i \sum_{j \neq i}^{N} p_j Q_{ij}(1+K_{ij})}, \; i = 1, \cdots, N \tag{5.14}$$

which is the ratio of the average SIR to the required SIR threshold γ_i. The outage probability P_i^{out} of the i th transmitter/receiver pair is closely related with its SIR margin $SIRM_i$. When $SIRM_i$ is large, it means that the average SIR is more probable of being above the required SIR threshold and vice versa. Therefore, for a desired link with a large $SIRM_i$, its instantaneous signal-to-interference power ratio is less probable of falling below γ_i and therefore it experiences a smaller outage probability.

Next, we highlight and explain the relation between $SIRM_i$ and outage probability P_i^{out} for a system of multiple users in Rician fading channels.

5.2.3 Relation Between $SIRM_i$ and Outage Probability P_i^{out}

In this section, we will interpret the relation between $SIRM_i$ and outage probability P_i^{out}. First, let us consider a two-user cellular radio system. This two-user example may seem obvious to some readers. However, we think it is very useful for explaining the rationales behind the power control problem and our proposed algorithm in multi-user systems, which is to be presented in the next section. The SIR margins $SIRM_1$ and $SIRM_2$ for desired communication links 1 and 2 respectively are given by

$$SIRM_1 = \frac{p_1 Q_{11}(1+K_{11})}{\gamma_1 p_2 Q_{12}(1+K_{12})} \tag{5.15}$$

$$SIRM_2 = \frac{p_2 Q_{22}(1+K_{22})}{\gamma_2 p_1 Q_{21}(1+K_{21})} \tag{5.16}$$

The curves of P_1^{out} versus $SIRM_1$ and P_2^{out} versus $SIRM_2$ are plotted using (5.8) in Fig. 5.1 and Fig.5.2 respectively. These figures show the relation between SIR margin $SIRM_i$ and outage probability P_i^{out} for each desired communication link. As expected, P_i^{out} is monotonically decreasing with $SIRM_i$. That is, if we require a smaller P_i^{out}, the ith link should strive for a larger $SIRM_i$. However, no closed-form expression between $SIRM_i$ and P_i^{out} can be found.

However, according to equation (5.15) and (5.16), $SIRM_1$ and $SIRM_2$ are dependent on each other and are related by the power ratio p_1/p_2. A larger p_1/p_2 results in a larger $SIRM_1$ but a smaller $SIRM_2$. We plot the curve of $SIRM_2$ as the function of $SIRM_1$ in Fig. 5.3.

To have a small P_1^{out}, link 1 needs a large $SIRM_1$. But when $SIRM_1$ is large, $SIRM_2$ of link 2 is small and hence, P_2^{out} becomes large. Therefore, we cannot minimize P_1^{out} and P_2^{out} simultaneously and a compromise solution should be more feasible.

In Fig. 5.4, we evaluate the outage probabilities of link 1 and link 2 for a two-user system with $K_{11} = K_{22} = 5$ and $K_{12} = K_{21} = 2$. Note that both outage probability curves have $SIRM_1$ of link 1 as the horizontal axis. The relation between P_1^{out} and P_2^{out} can be seen clearly. Although we cannot minimize P_1^{out} and P_2^{out} at the same time, we can achieve outage probability balancing, $P_1^{out} = P_2^{out}$, by targeting $SIRM_1 = SIRM_2$. Note that

the two outage probabilities are equal for this particular example because we have chosen a particular setting where $(1+K_{11})/(1+K_{12}) = (1+K_{22})/(1+K_{21})$. In general, $(1+K_{11})/(1+K_{12}) \neq (1+K_{22})/(1+K_{21})$, and therefore P_1^{out} is not exactly equal to P_2^{out} when $SIRM_1 = SIRM_2$, but the difference between the two values is very small.

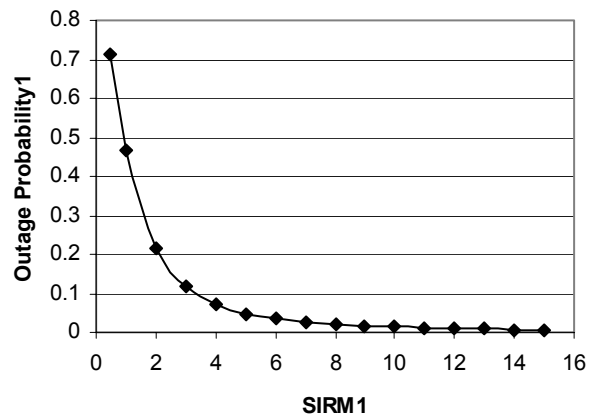

Fig. 5.1 Outage probability P_1^{out} versus $SIRM_1$ for user 1 with $K_{11} = 5, K_{12} = 2$

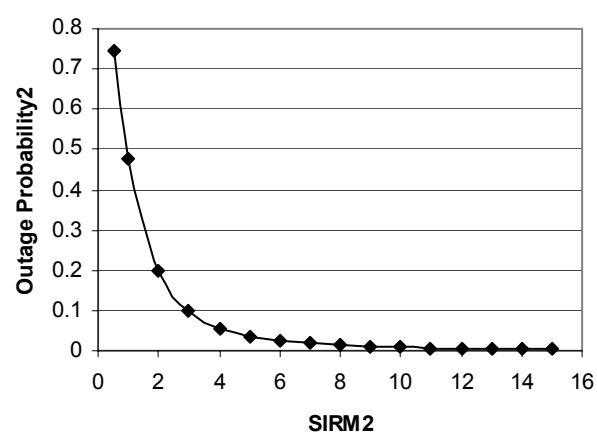

Fig. 5.2 Outage probability P_2^{out} versus $SIRM_2$ for user 2 with $K_{22} = 6, K_{21} = 3$

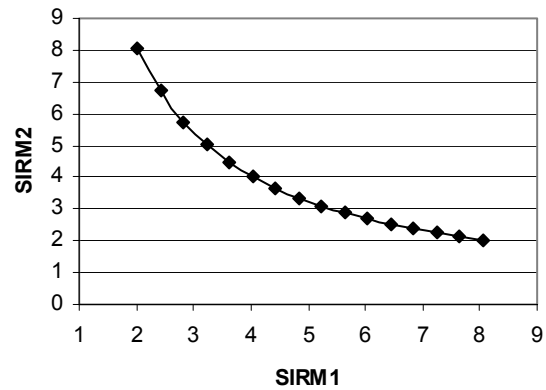

Fig. 5.3 $SIRM_2$ **versus** $SIRM_1$ **with** $\gamma_1 = \gamma_2$, $G_{11}/G_{12} = G_{22}/G_{21}$, $\sigma_{11}^2 = \sigma_{22}^2 = \sigma_{12}^2 = \sigma_{21}^2$ and $(1+K_{11})/(1+K_{12}) = (1+K_{22})/(1+K_{21})$

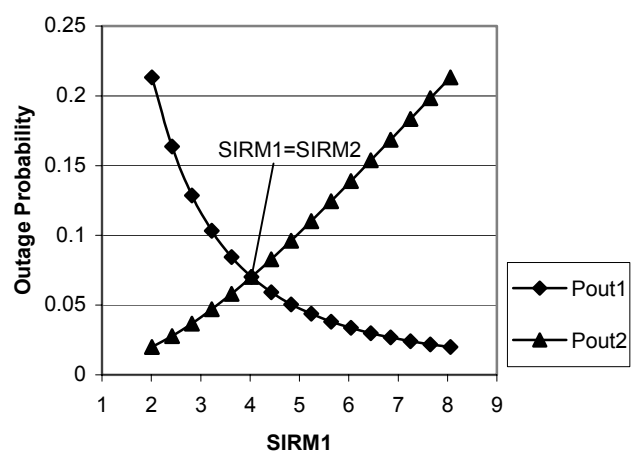

Fig. 5.4 Outage probability P_1^{out} **and** P_2^{out} **versus** $SIRM_1$ **for a system of two users with** $(1+K_{11})/(1+K_{12}) = (1+K_{22})/(1+K_{21})$

5.3 Proposed Power Control Scheme

Now we further extend the above idea to the general case of N pairs of transmitter/receiver in cellular radio system. Since the outage probability P_i^{out} of the link between transmitter i and its corresponding receiver is monotonically decreasing with $SIRM_i$, if we require a smaller P_i^{out}, we need to increase $SIRM_i$. However, when $SIRM_i$ is increased, the interference to the receiver j ($j \neq i$) caused by transmitter i will also be increased. This results in a smaller $SIRM_j$ ($j \neq i$) and therefore a larger outage probability P_j^{out} ($j \neq i$) for link j. Strictly speaking for such a system, it is impossible to maximize all the $SIRM_i$ $(i = 1, \cdots, N)$ simultaneously; in other words, the outage probability P_i^{out} $(i = 1, \cdots, N)$ cannot be minimized simultaneously. However, we can make the outage probabilities of all the desired links be approximately equal by targeting $SIRM_1 = \cdots = SIRM_N$. We want to highlight that the above rationale and conclusion hold for either Rician, Rayleigh fading or lognormal shadowing channels, regardless of the statistical distributions of the desired signal and interference. In contrast, the work in [29] presented only somehow limited viewpoint and discussion for Rayleigh fading channels. Furthermore, this rationale holds for both homogeneous-SIR and heterogeneous-SIR systems. The simulation results in Section 5.4 will verify our conclusions.

Based on our arguments in Section 5.2.3, we now propose a power control scheme to equalize the SIR margins of all the desired communication links for Rician/Rician fading channels, such that the outage probabilities of all these links are approximately equal. As far as outage probability is concerned, this power control scheme is optimal in being fair

to all desired transmitter/receiver pairs. We use the following objective function and constraints to solve the transmitting power p_i for all desired links

$$SIRM_i = \frac{p_i Q_{ii}(1+K_{ii})}{\gamma_i \sum_{j \neq i}^{N} p_j Q_{ij}(1+K_{ij})} = \nu$$

$$\text{subject to } p_i > 0, \; i = 1, \cdots, N \tag{5.17}$$

where ν is an optimal value to which the SIR margin of all the desired transmitter/receiver links are equal. Substituting the variable $\tau = 1/\nu$, we can rewrite the proposed algorithm in the form of matrices and vectors as

$$\tau \mathbf{p} = \mathbf{W}_{\mathbf{ave}} \mathbf{p}$$

$$\text{subject to } p_i > 0, \; i = 1, \cdots, N \tag{5.18}$$

where the matrix $\mathbf{W}_{\mathbf{ave}}$ consists of elements

$$\{W_{ave}\}_{ij} = \begin{cases} \dfrac{\gamma_i Q_{ij}(1+K_{ij})}{Q_{ii}(1+K_{ii})} & i \neq j \\ 0 & i = j \end{cases} \tag{5.19}$$

and

$$\mathbf{p} = [p_1, \cdots, p_N]^T \tag{5.20}$$

Equation (5.18) is recognized as an eigenvalue problem for the matrix $\mathbf{W}_{\mathbf{ave}}$ with all nonnegative entries. According to the Perron-Frobenius theory, the optimal value ν is unique and equal to the reciprocal of the maximum modulus eigenvalue $\lambda^*_{W_{ave}}$ of the matrix $\mathbf{W}_{\mathbf{ave}}$, and the optimal transmitter power vector is the positive eigenvector $\mathbf{p}^*_{\mathbf{W}_{\mathbf{ave}}}$ of the matrix $\mathbf{W}_{\mathbf{ave}}$ corresponding to $\lambda^*_{W_{ave}}$.

It is interesting to note that (5.18) is in a familiar form as in the case of SIR balancing [2,14]. However, it can be interpreted in a more general perspective, and therefore provides us a more general theory than all previous results. Since the matrix $\mathbf{W}_{\mathbf{ave}}$ in (5.18) is a function of the Rician factor K_{ij}, the proposed algorithm actually has taken into account the fading statistics of the Rician fading. In other words, (5.18) corresponds to a power control algorithm that takes into consideration the line-of-sight (LOS) components (through K_{ij}) as well as the diffused components (through Q_{ij}) of the received powers of all the links. An implication of the above finding is: even when all users have identical average power, the distribution of total average power among the LOS and the diffused components still constitutes another important factor, which determines the level of power to be transmitted for maintaining a required outage probability. From this viewpoint, our result in (5.18) is more general than former formulation in [2,14] and other similar works, where only fixed channel gains are considered.

For the special case of $K_{ij} = 0$ for all i and j, the matrix $\mathbf{W}_{\mathbf{ave}}$ includes the average power, $p_j Q_{ij}$, of the Rayleigh fading and reduces to exactly the same form as [29]. Hence, our power control scheme is more general than that of [29], which is presented for Rayleigh/Rayleigh fading channels.

5.4 Simulation Results

In this section, we will use simulation results to verify that our proposed power control scheme can balance the outage probabilities of all the desired communication links well in interference-limited wireless Rician/Rician fading systems. In addition, we

will also give some simulation results of the scheme proposed in [29] for Rayleigh/Rayleigh fading channels, since in that paper Kandukuri and Boyd only made the theoretical derivation.

5.4.1 Simulation Model

In our simulation, we adopt a microcellular system with a square grid of 9 cells as shown in Fig 5.5. There is one base station at the center of each cell. Without loss of generality, we assume that the smallest distance between adjacent base stations is unity. A frequency reuse of one is assumed.

In the simulation, we consider the uplink communication and assume that there are 7 cochannel users. These users are uniformly distributed in the cell area and they will be located in 7 different cells. Base station selection is assumed, that is, each user will be assigned to the nearest base station, i.e., the base station associated with the smallest path loss attenuation.

For all the simulation results, we assume that the path loss attenuation factor is 4 and the spread of log-normal shadowing is 4 dB. The notation t is used to denote the common SIR margin achieved by all the desired communication links.

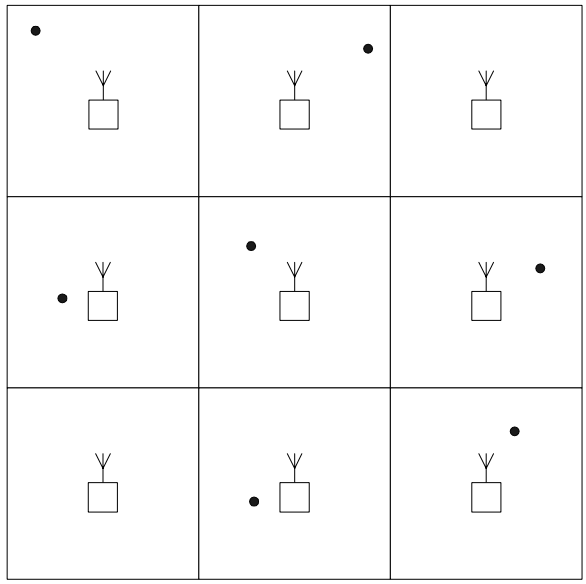

Fig. 5.5 Simulation model for a cellular system

5.4.2 Discussions

In Table 5.1, we assume that all the desired and unwanted communication links are subject to Rician fading. We consider the homogeneous-SIR scenario as well as the heterogeneous-SIR scenario. For both cases, we assume that the Rician factor K_{ii} of the desired links is 5 and the Rician factor $K_{ij}\,(j \neq i)$ of the unwanted links is 2.

In Table 5.2, we assume that all the desired and interfering communication links are subject to Rayleigh fading. We also simulate both the homogeneous-SIR systems and the heterogeneous-SIR systems.

The time average values of the different fast fading channels in Table 5.1 and 5.2 are obtained by calculating the mean of 10000 fast fading samples. We then use the mean value in the power control scheme (5.17) and (5.18) to obtain the simulation results.

The results in Table 5.1 and 5.2 show that the proposed power control scheme with outage specifications can properly balance the outage probabilities of all the desired communication links in either Rician/Rician or Rayleigh/Rayleigh fading channels, for both cases when the required SIR thresholds are homogeneous or heterogeneous. It is also shown that the larger the common achieved SIR margin, the smaller the outage probabilities.

Another phenomenon that is worthy to be noted is that even when the commonly achieved SIR margin in Rayleigh/Rayleigh fading channels is higher than that in Rician/Rician fading channels, the outage probabilities in the former case are still much larger than those in the latter scenario. The reason for this is that in Rician fading channels, the power link gain includes both line-of-sight (LOS) components and diffused components. Thus even if the overall link gains are similar in Rician/Rician and Rayleigh/Rayleigh fading channels, the LOS components in Rician/Rician channels make significant difference between outage probabilities experienced by all desired links in both scenarios. This explains our argument in Section 5.3, that is, the distribution of total average power among the LOS and the diffused components constitutes an important factor, which determines the channel conditions and therefore determines the achieved outage probabilities.

In addition to the above simulation results, we also study how the number of fast fading samples that are used to estimate the time average link gains will affect the efficiency of the proposed power control scheme. The simulation results are listed in Table 5.3 and 5.4. For Table 5.3, we assume Rician/Rician fading channels and the required SIR thresholds of all the desired communication links are identical ($\gamma = 7dB$).

For Table 5.4, we consider a heterogeneous-SIR system in Rayleigh/Rayleigh fading channels ($\gamma_{1,2,3,4,5,6,7} = 5,6,7,8,9,10,11dB$).

In our proposed power control scheme, during the period between two successive transmission power updates, the distance-dependent path loss and log-normal shadowing are assumed to be constant. Hence, the statistics of the link gains are mainly determined by the fast fading. Since fast fading is a random process, it is very important to select the appropriate number of samples to estimate its average value. And this will greatly affects the effectiveness of the proposed power control scheme. When the size of sample block is too small, the average link gains are not accurately estimated; as a result the proposed power control scheme cannot balance the outage probabilities of all the desired communication links well. Only when the size of sample block is large enough, the average link gains can be accurately estimated such that the proposed power control scheme can balance the outage probabilities well.

The simulation results in Table 5.3 and 5.4 illustrate the above arguments. It can be seen that when the size of sample block is small, the standard deviation (STD) value of the outage probabilities achieved by the proposed power control scheme are large. With the increase of the sample block size, the STD value also becomes small, i.e., the outage probabilities of different desired communication links are getting closer. In other words, the power control scheme can properly balance the outage probabilities when sufficiently larger sample block size is used to estimate the statistical average of the link gains.

The data in Table 5.3 and 5.4 are further plotted in Fig. 5.6 and 5.7. From these two figures, it is obvious that the data points that represent the outage probabilities of all the

desired communication links distribute around their mean value more closely with the increase of the size of sample blocks.

Table 5.1 Outage probabilities in Rician/Rician fading channels

P_i^{out}	$\gamma = 7dB$		$\gamma_{1,2,3,4,5,6,7} = 5,6,7,8,9,10,11dB$	
	$\nu = 4.5787$	$\nu = 8.4063$	$\nu = 2.8388$	$\nu = 5.4040$
P_1^{out}	0.0516	0.0172	0.1261	0.0386
P_2^{out}	0.0547	0.0175	0.1093	0.0388
P_3^{out}	0.0511	0.0154	0.1289	0.0405
P_4^{out}	0.0488	0.0142	0.1058	0.0355
P_5^{out}	0.0442	0.0183	0.1237	0.0293
P_6^{out}	0.0451	0.0183	0.1158	0.0361
P_7^{out}	0.0421	0.0178	0.1243	0.0315

Table 5.2 Outage probabilities in Rayleigh/Rayleigh Fading Channels

P_i^{out}	$\gamma = 7dB$		$\gamma_{1,2,3,4,5,6,7} = 5,6,7,8,9,10,11dB$	
	$\nu = 4.6621$	$\nu = 8.9013$	$\nu = 4.0355$	$\nu = 7.0981$
P_1^{out}	0.1814	0.1063	0.2137	0.1226
P_2^{out}	0.1746	0.1080	0.2081	0.1219
P_3^{out}	0.1948	0.1007	0.2122	0.1242
P_4^{out}	0.1881	0.1003	0.2106	0.1243
P_5^{out}	0.1822	0.1073	0.219	0.1305
P_6^{out}	0.1869	0.1026	0.2104	0.1274
P_7^{out}	0.1827	0.1038	0.2193	0.1287

Table 5.3 Comparisons between outage probabilities for different sample block sizes in Rician/Rician fading channels

Index of Results	1	2	3	4	5	6
Sample Block Size	100	200	300	400	500	800
SIRM	6.6718	6.7185	6.6537	6.5547	6.5696	6.7460
Outage 1	0.0200	0.0200	0.0333	0.0400	0.0380	0.0325
Outage 2	0.0400	0.0350	0.0333	0.0275	0.0260	0.0187
Outage 3	0.0300	0.0200	0.0267	0.0275	0.0300	0.0275
Outage 4	0.0100	0.0200	0.0200	0.0225	0.0200	0.0187
Outage 5	0.0300	0.0200	0.0267	0.0225	0.0200	0.0200
Outage 6	0.0300	0.0350	0.0367	0.0275	0.0260	0.0275
Outage 7	0.0100	0.0200	0.0167	0.0250	0.0260	0.0213
Mean	0.0243	0.0243	0.0276	0.0275	0.0266	0.0238
Std	0.0113	0.0073	0.0074	0.0060	0.0062	0.0054
Index of Results	7	8	9	10	11	
Sample Block Size	1000	3000	5000	10000	20000	
SIRM	6.7654	6.7186	6.7172	6.7374	6.7416	
Outage 1	0.0310	0.0237	0.0222	0.0234	0.0239	
Outage 2	0.0220	0.0243	0.0244	0.0230	0.0236	
Outage 3	0.0310	0.0273	0.0230	0.0208	0.0216	
Outage 4	0.0200	0.0207	0.0222	0.0249	0.0230	
Outage 5	0.0200	0.0210	0.0216	0.0221	0.0214	
Outage 6	0.0230	0.0233	0.0264	0.0249	0.0240	
Outage 7	0.0220	0.0197	0.0214	0.0221	0.0223	
Mean	0.0241	0.0229	0.0230	0.0230	0.0228	
Std	0.0048	0.0026	0.0018	0.0015	0.0011	

Note: Outage i *(*$i = 1 \cdots 7$*) means the outage probability of the* i *th desired communication link*

Table 5.4 Comparisons between outage probabilities for different sample block sizes in Rayleigh/Rayleigh fading channels

Index of Results	1	2	3	4	5	6
Sample Block Size	50	100	200	300	400	500
SIRM	8.5754	6.9156	6.8204	6.9056	7.3085	7.2482
Outage 1	0.2000	0.2200	0.2000	0.1667	0.1575	0.1460
Outage 2	0.1200	0.1400	0.1350	0.1167	0.1125	0.1180
Outage 3	0.0800	0.1000	0.1150	0.1100	0.1225	0.1160
Outage 4	0.1200	0.1300	0.1350	0.1233	0.1150	0.1120
Outage 5	0.1400	0.1600	0.1300	0.1300	0.1375	0.1420
Outage 6	0.0600	0.1500	0.1350	0.1467	0.1350	0.1320
Outage 7	0.0800	0.1300	0.1250	0.1133	0.1125	0.1120
Mean	0.1143	0.1471	0.1393	0.1295	0.1275	0.1254
Std	0.0472	0.0373	0.0278	0.0205	0.0168	0.0144
Index of Results	7	8	9	10	11	12
Sample Block Size	1000	2000	5000	10000	20000	30000
SIRM	7.2732	7.1528	7.1624	7.0981	7.0971	7.0969
Outage 1	0.1270	0.1265	0.1230	0.1226	0.1216	0.1236
Outage 2	0.1120	0.1200	0.1204	0.1219	0.1234	0.1246
Outage 3	0.1190	0.1210	0.1188	0.1242	0.1242	0.1238
Outage 4	0.1220	0.1230	0.1218	0.1243	0.1229	0.1235
Outage 5	0.1390	0.1325	0.1306	0.1305	0.1303	0.1291
Outage 6	0.1470	0.1365	0.1282	0.1274	0.1252	0.1268
Outage 7	0.1290	0.1310	0.1276	0.1287	0.1289	0.1280
Mean	0.1279	0.1272	0.1243	0.1257	0.1252	0.1256
Std	0.0120	0.0063	0.0045	0.0032	0.0032	0.0023

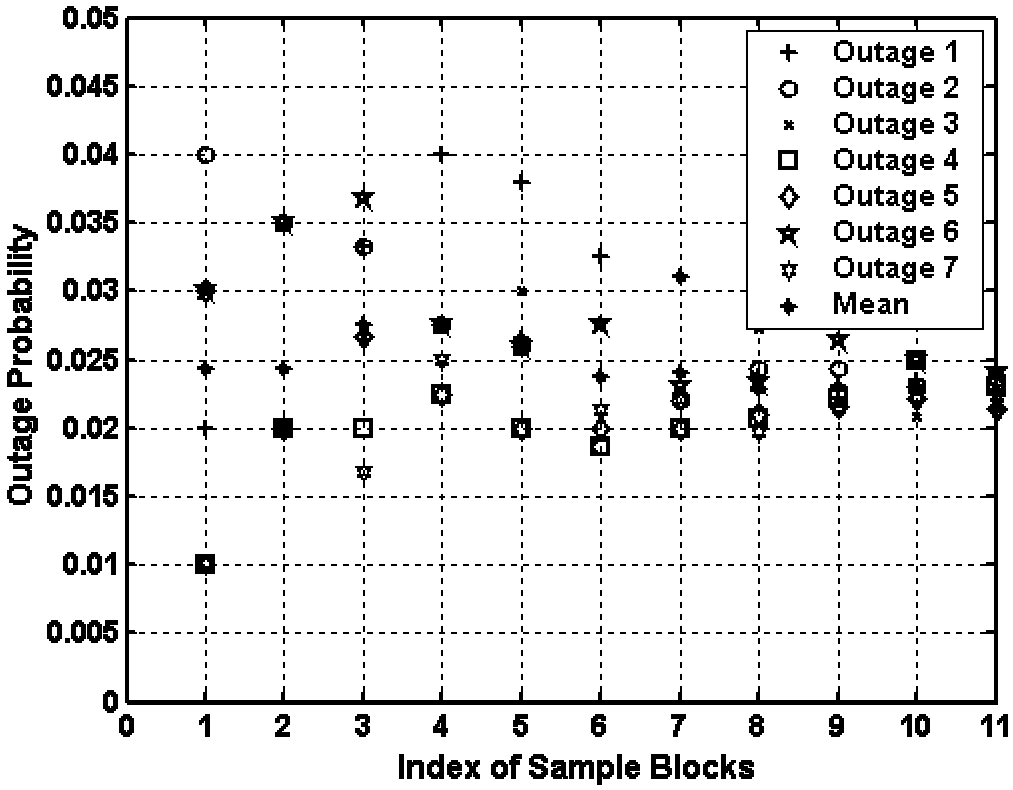

Fig. 5.6 Comparisons of outage probabilities for different sample block sizes in Rician/Rician fading channels

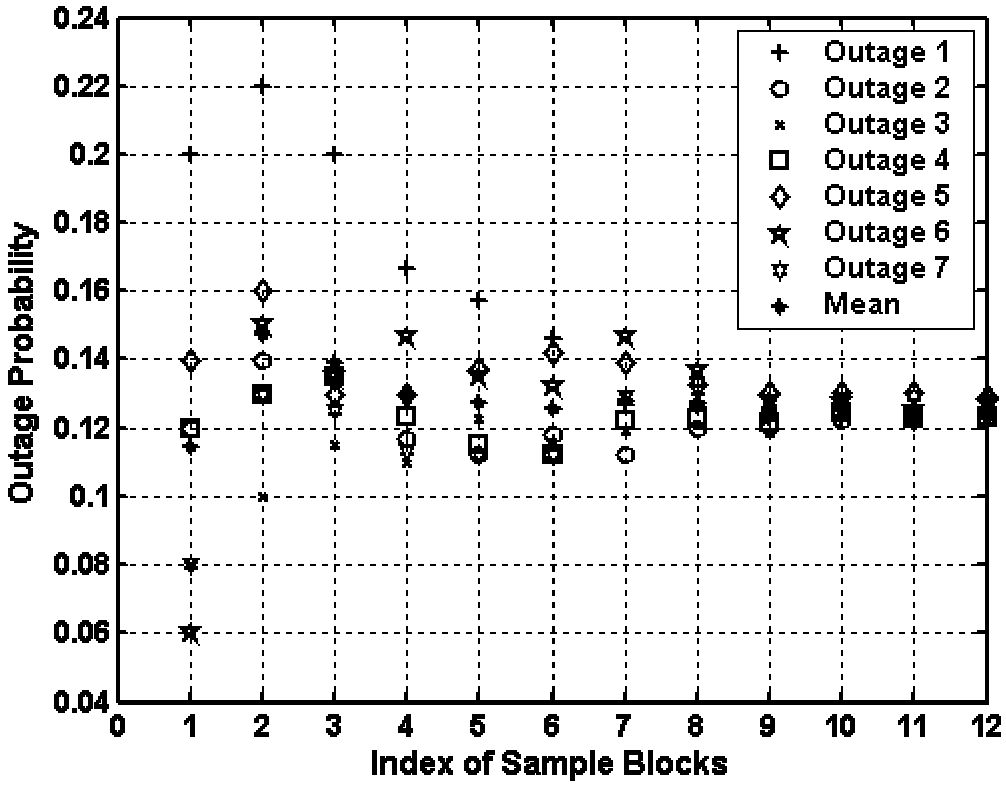

Fig. 5.7 Comparisons of outage probabilities for different sample block sizes in Rayleigh/Rayleigh fading channels

5.5 Conclusions

In this chapter, we present an optimal outage-probability-balancing power control scheme for interference-limited Rician/Rician wireless fading cellular radio systems by equalizing the newly defined performance index, the so-called SIR margin of each desired communication link. Our scheme not only includes the power control scheme in paper [29] as a special case but also suitable for both homogeneous-SIR and heterogeneous-SIR cellular radio systems. Simulation results show that the optimal power control scheme can really achieve the objective of balancing the outage probabilities of all the desired communication links in the system such that they are approximately equal.

In addition, we also discuss the relationship between the size of sample block and the efficiency of the proposed power control scheme. Simulation results indicate that only when the size of sample block is large enough, the average link gains can be accurately estimated so that the power control scheme can properly balance the outage probabilities of all the desired communication links.

Based on previous works in the area of transmitter power control as well as my own understanding and perception, a proposal for future research is put forward in the next chapter. Several issues that are worthy of further study are highlighted.

Chapter 6

Proposal for Future Works

If we look back at the previous research work, it is not difficult to find that most of the research was carried out only from the viewpoint of power control and did not jointly consider other factors in wireless cellular systems. However, power control is not the only way to combat interference and enhance the system capacity. Many other techniques such as multi-user detection and space-time signal processing based on the adaptive antenna array have been exploited to achieve the same goal and further improve the system performance. Moreover, future cellular DS-CDMA systems must be able to support diverse services that will require different data rates and QoS requirements. Hence, for the future research works in transmission power control, three topics are worthy to be studied:

- Joint power control and multi-user detection
- Joint power control and space-time signal processing based on adaptive antenna arrays

- Power control for multi-rate multimedia transmission

The results presented in Chapter 4 and 5 are general and do not apply to CDMA networks only. For CDMA networks, there will be more room to improve the transmitter power control algorithms. In this chapter , research works related to the above topics as well as improvement that need to be done are first discussed. Then research focuses and issues worth further studying in future are highlighted and interpreted.

6.1 Joint Power Control and Multi-User Detection

As has been emphasized in Chapter 1, DS-CDMA systems are "interference-limited" and Multiple Access Interference (MAI) is a main factor limiting the system performance and capacity. In conventional DS-CDMA systems, a receiver receives a signal composed of the sum of all users' signals, which overlap in time and frequency. And a particular user's signal is detected by correlating the entire received signal with that user's code waveform. This kind of conventional detector is often referred to as the matched filter detector. The basic concept behind the matched filter detector is that the detection of the desired users can be protected against MAI by the inherent interference suppression capability of CDMA, measured by the processing gain. It is obvious that the matched filter detector only treats MAI as the equivalent noise and uses a single-user detection strategy in which each user is detected separately without regard for other users. However, the inherent interference suppression due to the processing gain is not unlimited. When MAI is substantial, it will cause serious degradation of performance. Even if the number of users is not large, some users may also suffer from the near-far effect, which is another key limit to DS-CDMA systems.

Although MAI brings a lot of negative impacts to DS-CDMA systems, it can also be overcome. Multi-user detection just uses the information about multiple users to better detect each individual user. Compared to the conventional single-user receiver, the multi-user detection is a much better detection strategy, which has the potential to provide significant additional benefits for DS-CDMA systems such as significant improvement in capacity, more efficient uplink spectrum and power utilization and reduced precision requirements for power control.

Because the complexity of the optimal multi-user detector, maximum-likelihood sequence (MLS) detector, exponentially grows with the number of users, and furthermore requires knowledge of the received signal amplitudes and phases, MLS detector is not feasible. Hence, up till now many suboptimal multi-user detector solutions have been proposed. Most of the proposed detectors fall into the following two categories: linear multi-user detectors and subtractive interference cancellation detectors. The two main kinds of linear multi-user detectors are decorrelating detector and minimum mean-squared error (MMSE) detector. And subtractive interference cancellation detectors include successive interference cancellation (SIC) detector, parallel interference cancellation (PIC) detector and decision-feedback detector.

6.1.1 Related Research Works

Although multi-user detection receivers suffer less from MAI and near-far problems, adaptive power control is still necessary for some reasons. Firstly, it can compensate for signal fluctuation due to the motion of the mobile; Secondly, the actual amount of power needed to achieve the required performance is also a function of code correlation; Thirdly, it is necessary to conserve the battery power; Finally, multiuser detection can only be

employed for users with known codes and the other interfering users with unknown codes are treated as noise; hence, the amount of interference caused by these users is in terms of their power levels, just as with single–user receivers.

Due to the above reasons, some research work has been carried out in the area of joint power control and multi-user detection. The combination of power control with the linear decorrelator detector is considered in [40]; while in [41,42], different power control schemes combined with linear MMSE detectors are discussed. However, the linear multi-user detectors need to compute the inverse of the correlation matrix which makes it difficult to be implemented in practice. In contrast to this, the subtractive interference cancellation usually has a lower complexity. Hence, more attention is put on the power control schemes integrated with subtractive interference cancellation detectors.

In papers [43-47], the joint power control and SIC scheme is studied. The authors rank the users in descending order of channel gains in [43,45] and find that under closed loop power control, this order of ranking is optimal in minimizing the total transmission power of the system. Kim and Bambos rank users in descending order of data rate for multirate CDMA systems in [47]. The underlying motivation for doing so is that high-rate users have high signal powers; hence they should be cancelled first. In paper [44,46], the estimation errors of interference at every stage of SIC are considered in the power control scheme. It is shown that the estimation errors can be manageable if the power control scheme takes the estimation errors into account.

In [48,49], joint power control and PIC schemes are examined. Because PIC is to cancel all the interference out from a particular user's signal at one time, its performance is very sensitive to the reliability of interference estimation. If the detector reproduces the

interference erroneously, then subtracting it from the received signal will increase the interference level. Due to this reason, in [48] the algorithm does a partial MAI cancellation at each stage, with the amount of cancellation increasing for each successive stage. This is because that the tentative decisions of the earlier stages are less reliable than those of the later stages. By doing this, huge gains are obtained over the standard "brute force" PIC detector. Based on this PIC detection, Wu and Wang propose a corresponding power control scheme in [49] and achieve superior performance to some existing approaches.

6.1.2 Research Issues for Future Works

So far much research has been carried out developing signal processing algorithms for multi-user detection without considering the issue of transmitter power control. The subject of joint power control and multi-user detection is relatively new and there are still many open questions to be studied. This relatively new research subject can be a focus of the future work and emphasis can be centered on the following issues:

1) How to better solve the problem of signal estimation errors?

The related research work can be found in [44] and [46]; however, the required SIR threshold is assumed to be identical for every user in [44] and [46]. Besides, there is another impractical assumption in [46] that the amount of the estimation error is the same for every user. Hence, the problem of estimation error in SIC has not been completely solved and needs extensive research in the future work.

2) How to exploit time diversity in multipath fading channels?

Existing multi-user detection schemes seldom consider the multipath fading in channels; however, in DS-CDMA systems the chip duration is usually small enough for resolving the individual multipath components. Hence, it provides inherent time diversity. So new power control schemes could be developed jointly with multi-user detection and conventional RAKE receiver.

3) How to integrate power control with multi-user detection for future multi-rate multimedia cellular systems?

Most of the existing joint power control and multi-user detection schemes do not consider the real multimedia systems which must accommodate service types with heterogeneous-QoS requirements and diverse, variable data rates. However, multiple service types result in more challenges for the design of joint power control and multi-user detection schemes. This is because the interference levels that users of various service types can tolerate are different; and moreover, the interference levels caused by distinct service types are also different. Therefore, joint power control and multi-user detection schemes for multi-rate multimedia systems should be a subject worth studying in the future work.

6.2 Joint Power Control and Space-Time Signal Processing Based on Adaptive Antenna Array

Adaptive antenna array offers spatial diversity that can be exploited to achieve better system capacity and performance. According to the published literatures, the spatial signal processing methods based on antenna arrays roughly fall into two types: spatial diversity combining and beamforming. The rationale behind the spatial diversity combining is that

the signals received from different antenna elements whose spatial separation is larger than the coherence distance will undergo independent channel fading, therefore provides the spatial diversity and can be combined to better detect the desired signal. Beamforming is to produce a desirable beam pattern that receive signals radiating from some specific directions and attenuate signals from other direction of no interest. Accordingly, the main difference between spatial diversity combining and beamforming is that spatial diversity combining does not exploit the information of signals' direction of departure or direction of arrival while beamforming does.

The spatial diversity combining approach that can give the best performance among all possible linear combiners is the maximal ratio combining (MRC), which is to weight the outputs of each antenna of the array appropriately and then sum them up to maximize the SINR at the output. In addition to MRC, there are other linear combining methods like selection combining and so on.

Antenna array beamforming can be classified into transmitter beamforming and receiver beamforming. Transmitter beamforming can adjust the beam pattern of the array to minimize the induced interference to undesired receivers to improve the downlink capacity. Receiver beamforming is that an antenna array with properly assigned weights can form an antenna beam pattern that suppress the antenna gain toward the directions of the interferers while keeping a constant gain toward its desired signal. However, transmitter beamforming and receiver beamforming are different in nature. Receiver beamforming can be implemented independently at each receiver without affecting the performance of the other links, while transmitter beamforming will change the

interference to all other receivers. As a result, transmitter beamforming has to be done jointly in the entire network.

In addition to the application in space domain, adaptive antenna array can also perform in the time domain. In fact, based on adaptive antenna arrays there are many kinds of space-time signal processing methods, which are usually resulted from the flexible combination between antenna array technique and the time-domain signal processing techniques such as multi-user detection, RAKE receiver, inter-symbol-interference (ISI) equalization and so on. For example, the dual space-time signal processing can be performed to combat both MAI and ISI by using a tapped-delay-line filter at each antenna element. Compared to the single time-domain signal processing techniques, spatial and temporal signal processing based on adaptive antenna arrays promises more significant improvement of system performance. Therefore, adaptive antenna has become a breakthrough technique for 3G of wireless personal communications.

6.2.1 Related Research Works

Due to the importance of adaptive antenna technique, comprehensive research has been done and a review in this area can be found in paper [50-53]. In addition, there are also many papers [54-60] focusing on the joint power control and adaptive antenna array.

In [54] Gerlach and Paulraj present a power control method integrated with the base station transmitter beamforming in the downlink case by exploiting the subspace structure existing in the spatial channel. And for the mobile they only consider a single omnidirectional antenna. Although they consider the multipath fading in their channel model, they do not use RAKE receivers at the mobiles.

In [55] joint power control and receiver beamforming is studied; an iterative algorithm iss proposed to jointly update the transmission powers and the beamformer weights and the convergence of this algorithm is theoretically analyzed. Joint power control and beamforming schemes are proposed for cellular systems where adaptive arrays are used only at base stations for both uplink and downlink in paper [56]. For both cases, transmission powers and corresponding transmitter or receiver beamformer weight vectors are calculated jointly. Similar to [54], RAKE receiver is not considered for the multipath fading channel in both [55] and [56].

In [57] Liang *et al.* discuss the problem of joint power control and base station antenna array beamforming in a multipath fading channel. Although RAKE receivers are used in this paper, they are only applied at the mobile stations for the downlink communication and not integrated with adaptive antenna array. Unlike other papers where only either transmitter or receiver beamforming is taken into account, in [58] joint power control and beamforming problem is studied in wireless networks where both transmitters and receivers have adaptive antenna arrays.

To summarize, in [54]-[58], only space-domain signal processing is operated at the antenna array. More comprehensive research on dual space-time domain signal processing is performed in [59] and [60]. In [59] Yener *et al.* combine the three basic interference management approaches, transmit power control, multiuser detection and receiver antenna array beamforming to increase the uplink capacity of DS-CDMA systems. However, their approach is proposed only for a single path channel. In contrast to all the above papers where beamforming is chosen as the space-domain signal processing approach, Zhang *et al.* use spatial diversity combining at the antenna array in [60]. And they also apply a

MMSE filter to each antenna element to perform time-domain signal processing before the spatial diversity combiner.

6.2.2 Research Issues for Future Works

Although some works have been carried out to integrate transmitter power control and space-time signal processing based on adaptive antenna arrays, there are still many open issues remain unanswered, and more extensive research is needed in this area. Possible research issues are highlighted in the following:

1) How to exploit both space-domain and time-domain adaptive signal processing in the joint power control and antenna array scheme?

From the above description about the previous work, it can be seen that most of the early works only consider joint power control and antenna-array-based spatial signal processing. However, significant saving in total transmission power is possible if signal processing in both domains is utilized. Hence, this problem could be one of the focuses in the future research. This subject could be studied from the following two aspects:

a) Propose appropriate schemes to combine power control with antenna array and RAKE receiver. As we know, adaptive antenna array offers the spatial diversity in multipath fading channels and RAKE receiver uses the time diversity in multipath signals. Thus space-time signal processing based on these two factors can be performed to make better use of the information in multipath signals.

b) Develop appropriate algorithms to integrate power control, multiuser detector and adaptive antenna array. The dual-domain signal processing based on multiuser detection and antenna array could enable us to fully exploit the

information about multiple users so as to achieve better performance in suppressing MAI, which will also benefit transmission power control.

2) How to apply the joint power control and antenna-array-based space-time signal processing schemes to multimedia DS-CDMA systems?

Most of the early works in this area either assume that the required QoS for different users are identical or ignore the fact that the data rates in a multimedia system are diverse and variable. So previously proposed methods cannot be used in multimedia DS-CDMA systems directly and the above features of multimedia systems must be taken into consideration when designing the joint schemes.

3) How to design better joint power control and space-time signal processing schemes based on adaptive antenna array for the downlink scenarios?

In early works [56,57], the downlink transmitter beamforming weights are generated by constructing a virtual uplink network whose channel responses are similar to those of the downlink. This method is feasible for a TDD system where the transmit and receive channels are reciprocal. However, in a FDD system or a TDD system with large dwell time, the uplink and downlink channels are not reciprocal. Hence, channel probing must be done at the mobile and a feedback channel is needed to transmit the measurement results to the base station. In such a case, the proposed joint scheme in [56,57] must be implemented in a centralized way using the global channel information. But this makes the algorithm not feasible in a practical system. Therefore, in-depth research is needed for the downlink communication scenarios.

6.3 Conclusions

In this chapter, the proposal for future works is presented, which mainly focuses on two subjects: firstly, joint power control and multi-user detection; and secondly, joint power control and space-time signal processing based on adaptive antenna array. For each subject, major related research works are first reviewed and summarized. And then issues that are worthy of being studied in future work are highlighted and interpreted.

Chapter 7

Conclusions

The completed research works by the author have been presented in the above chapters. In this chapter, conclusions of this thesis are given.

Many of previously published research works are aimed to investigate the problem of whether the required SIR thresholds are achievable for transmitter power control. However, the research results show that the solution to this issue appears to be different between homogeneous-SIR and heterogeneous-SIR cellular systems. In order to solve this problem, a unified framework for both homogeneous-SIR and heterogeneous-SIR cases is proposed by defining a SIR-embedded system gain matrix $\mathbf{W_S}$ in Chapter 4. It is proved that regardless of whether the SIR requirements are homogeneous or heterogeneous, the SIR threshold vector is achievable if and only if the maximum modulus eigenvalue $\lambda^*_{W_S}$ of $\mathbf{W_S}$ satisfies $\lambda^*_{W_S} \le 1$. Furthermore, if $\lambda^*_{W_S} \le 1$, the eigenvector $\mathbf{p}^*_{\mathbf{W_S}}$ of $\mathbf{W_S}$ that is corresponding to $\lambda^*_{W_S}$ is the power vector that can achieve the required SIR threshold vector.

So far there is no definite answer to the largest achievable SIR threshold vector for heterogeneous-SIR systems. In Section 4.4, the conditions under which a given SIR threshold vector for the heterogeneous systems is achievable are highlighted. It is found that the achievable SIR threshold vector of a given heterogeneous-SIR cellular system is related to its largest achievable homogeneous-SIR threshold, which is $\boldsymbol{\gamma}^* = \{\gamma_W^*\}_{i=1}^N$. When a heterogeneous SIR threshold requirement $\boldsymbol{\gamma}$ is imposed on an originally homogeneous-SIR system, if $\boldsymbol{\gamma} \le \boldsymbol{\gamma}^*$, the heterogeneous SIR threshold $\boldsymbol{\gamma}$ is achievable by the system. If $\boldsymbol{\gamma} > \boldsymbol{\gamma}^*$, the heterogeneous SIR threshold $\boldsymbol{\gamma}$ is not achievable.

The above results are about the rationale behind transmitter power control schemes. Besides, a novel power control scheme is also proposed to integrate with outage probability specifications in Chapter 5. By defining a new performance index of SIR margin for each desired communication link, the proposed scheme takes into account the statistics of the channel variations and controls the transmitter powers to properly balance the outage probabilities of all the desired communication links. This scheme can be implemented at a time scale much larger than the fading time scale and is especially suitable for the scenarios where the traditional power control schemes may fail, that is, when the fast fading changes so quickly that the feedback of the fading states cannot keep up with the fading changes.

In addition to the theoretical derivation, simulation results have also been presented. The data in Table 5.1 and 5.2 verify that the proposed power control scheme is able to properly balance the outage probabilities of all the desired communication

links in both homogeneous-SIR and heterogeneous-SIR systems. Furthermore, by comparing the simulation results for Rayleigh and Rician fading channels, it is obvious that even when the commonly achieved SIR margin in Rayleigh fading channels is higher than that in Rician fading channels, the outage probabilities in the former case are still much larger than those in the latter case. This illustrates our arguments that the distribution of total average power between the LOS and the diffused components constitutes an important factor that determines the channel conditions and therefore determines the achieved outage probabilities.

In the proposed power control scheme, during the period between two successive transmitter power updates, the distance-dependent path loss and log-normal shadowing are assumed to be constant. As a result, the statistics of the link gains are mainly determined by the fast fading. Hence, the problem of how the selected number of samples to estimate the channel state statistics will affect the effectiveness of the power control scheme is examined by simulation. It is shown in Table 5.3 & 5.4 and Fig. 5.6 & 5.7 that when the selected number is too small, the proposed scheme cannot balance the outage probabilities well due to the reason that the average link gains cannot be accurately estimated. Only when the size of sample block is large enough such that the average link gains can be accurately estimated, the proposed power control scheme can properly balance the outage probabilities.

Most of the previous research works were carried out only from the view of power control and did not consider other factors in wireless cellular systems. Actually, many other techniques such as multi-user detection and space-time signal processing

have also been exploited to combat interference and enlarge the system capacity. Therefore, in Chapter 6 the feasibility of combining power control and other techniques to further enhance the system performance is analyzed. Several open issues that are worth investigating in the future are proposed and discussed.

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