CHAPTER ONE

INTRODUCTION

A graphical display of the dissertation layout is shown in Figure. 1.1. An introduction to Spread Spectrum cellular communication systems is presented in section 1.1. A literature survey is described in section 1.2. Basic definitions and operating principles of PC problems are presented in section 1.2.2; The importance of PC algorithms in multi-media systems is described in section 1.2.3. The limitations of current PC algorithms is described in 1.3. An outline of the goals of this dissertation is presented in section 1.4. Specific contributions of this dissertation are listed in section 1.5 and its layout is described in section 1.6.

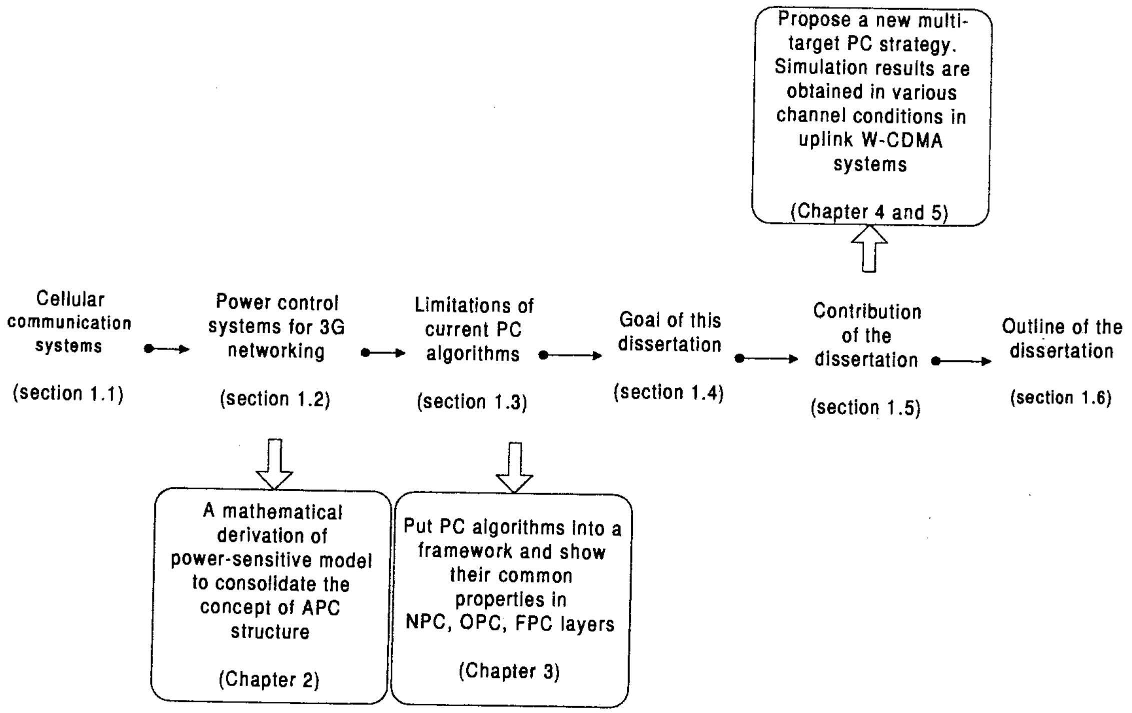


FIGURE 1.1: Overview of chapter 1

1.1 CELLULAR COMMUNICATION SYSTEMS

Because of the strong demand for personal communication systems and services, wireless networking is fast becoming a major component of today's communication infrastructure. In terms of business volume, wireless networking could even become a serious challenge to wireline networking, provided it can be extended, as traditional wireline networks have been, to multi-media and high-speed data applications.

First and second-generation cellular systems were designed primarily for voice communication, and provide data services only at relatively low rates. Third-generation systems recently introduced, are designed for multi-media communication. In the future, person-to-person communication will be enhanced with high quality images and video and access to information and services on public and private networks. For a communication system to be competitive it must have a high throughput, as well as integration of services including telephony, data, video and IP, and also interworking between different wireless networks [Figure 1.2].

However, to extend wireless communication systems to multi-media services, a broader frequency bandwidth is required which, given the lack of spectrum availability, is a major problem, especially in metropolitan areas. One solution is to use wideband code-division multiple-access (W-CDMA) technology. Over the past several years, it has been shown that W-CDMA is a viable alternative to both frequency-division multiple-access (FDMA) and time-division multiple-access (TDMA) technologies and has, in fact, emerged as the dominant next-generation wireless communication system worldwide.

Its specification has been created in 3GPP (the 3^{rd} Generation Partnership Project), which is a joint project of standardization bodies from Europe, Japan, Korea, the USA and China. Within 3GPP, W-CDMA is called UTRA (Universal Terrestrial Radio Access) FDD (Frequency Division Duplex) and TDD (Time Division Duplex). This dissertation focuses on the W-CDMA FDD technology because the uplink of a cellular network is, in general, the capacity limiting factor. The use of W-CDMA technology has been extensively researched and developed [4, 18, 28, 45, 58, 76, 81, 83, 86].

1.1.1 Advantages Of W-CDMA Technology

Even though the W-CDMA technology is not superior under all conditions to conventional multiple access in commercial wireless communication systems, it is the characteristics of spread-spectrum (SS) waveforms and sharing resources that give W-CDMA certain

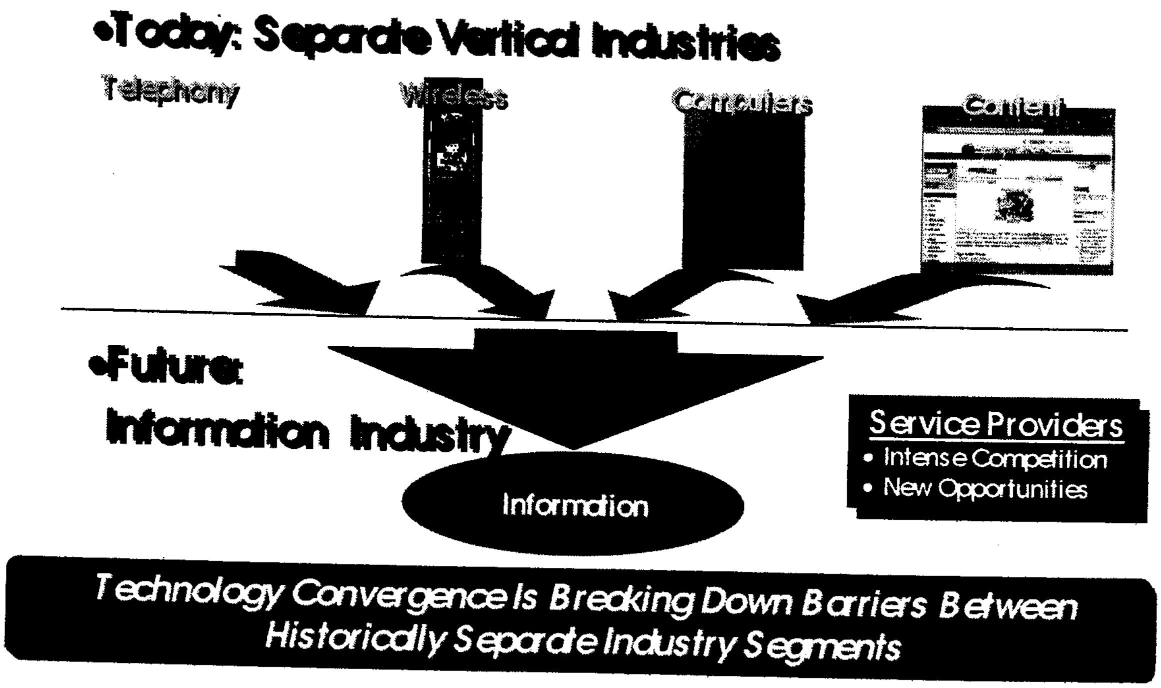


FIGURE 1.2: Technology convergence is breaking down barriers between historically separate industry segments

advantages.

It is well known that SS waveforms are effective in mitigating multipath fading, which can be attributed to its wider bandwidth which introduces frequency diversity. For the same reason, W-CDMA is also useful in mitigating interference. Medard [125] has determined that it is the uncertainty in estimating the time-varying wireless channels that degrades cellular capacity, not its time-varying nature. This coarse acquisition inadequacy has been investigated and it has been shown that wideband spreading waveforms provide better performance in a time-varying wireless channel than narrowband waveforms [64, 65]: a wideband digital waveform received at the base station has multiple correct paths, and the likelihood of observing a correct path during the search process is increased compared to what it would be for narrowband. Also, Rappaport [81] has shown that the accuracy of power measurement can be improved with an increase in spreading bandwidth because narrowband waveforms experience more attenuation due to multipath fading than W-CDMA does. Perfect acquisition and tracking of the spreading sequence described in the literature is usually assumed if pilot channels are associated with each data channel.

Furthermore, the characteristic of sharing resources providing a N=1 frequency re-use factor, allows a network to be built within a single frequency channel. Thus, three advantages of this characteristic are that it: allows a flexible number of users in a given channel; is capable of providing multi-media services to handsets and provides potentially higher radio capacity. W-CDMA can also enhance efforts in space-time processes and radio resource management due to its frequency diversity feature.

1.1.2 Disadvantages Of W-CDMA Technology

Second-generation cellular systems were developed for voice transport at a time when 75% of traffic in the world was voice. Consequently, these systems were optimized to offer telephone and low-date rate services. However, since FDMA/TDMA cellular systems require preliminary radio planning, advanced quality-of-service (QoS) mechanisms are not necessary, because the frequency re-use factor, N, of these systems is greater than one. The impact of the Internet has led to a dramatic growth in data traffic and multi-media services for W-CDMA cellular systems where different bandwidth and QoS requirements become essential.

However, because the entire transmission bandwidth is shared amongst all users at all times, this implies that the system capacity is very much dependent on multiple-access interference (MAI) which may be characterized as any combination of spectrum sharing interference signals, self-jamming by delayed signals, and inter-cell interference signals. The transmitted power and power distribution must be carefully planned and controlled if optimal system performance and maximal traffic capacity are to be achieved.

The disadvantages of W-CDMA are summarized below:

- CDMA is interference- and resources-limited: the number of users that can be accommodated within the same frequency band with acceptable performance, is determined by the total interference power of all users, taken as a whole, generated at the base station.

- The near-far effect: those W-CDMA transmitters that are closer to the receiver will cause overwhelming interference by saturating the receiver front-end to the detriment of the weaker signals received, which will be regarded as interference and treated as such. Power control (PC) or interference cancellation techniques become essential.

- Channel impairment: the wireless channel may be highly erratic and essentially stochastic in the presence of mobility. Most researchers have applied statistical techniques to describe signal variations in cellular mobile environments. Online link QoS monitoring mechanisms and online resource and interference management are required to ensure QoS to subscribers.

Thus, a resource management structure with online link QoS monitoring, online resource and interference management, and QoS assurance for adaptation to changes induced by mobility, channel impairment and traffic demand are necessary in W-CDMA systems and also need to be integrated at all layers. W-CDMA systems are considered as a design of power management wireless network architecture that aims to provide, maintain and guarantee different QoS classes.

1.2 POWER CONTROL SYSTEMS FOR 3G NETWORKING

Many novel solutions, including interference cancellation [84], coding [126], modulation [127], resource management [39, 80] and access methodologies [83] have been proposed, studied and implemented to guarantee QoS and also to maximize W-CDMA system capacity. Amongst other solutions, adaptive power control (APC) algorithms can provide, maintain and control QoS in a state-of-the-art system architecture. In our view, power is the central mechanism for W-CDMA systems because power is shared amongst all users and it can easily be measured, controlled and managed in multi-layered operations.

There are three basic time-scales for QoS management in multi-media networks [39]:

- Each time a call is requested, call-admission control determines whether or not the new call can be accepted while guaranteeing the QoS of established calls. The call-admission control function computes and allocates an equivalent bandwidth for the duration of the call, which is typically minutes for voice calls or hours for Internet Protocol (IP) sessions.

- Monitoring, scheduling and control mechanisms come into operation each time a number of packets are sent and/or received, typically within microseconds. Monitoring mechanisms are algorithms that police the negotiated QoS to subscribers. Scheduling algorithms decide when and which packet to send first.

- Fast Power Control (FPC) mechanisms come into operation each time a packet is sent and/or received, typically within nanoseconds. PC algorithms increase or decrease the transmitting power level.

The current literature on PC techniques can also be divided into three categories: network-layer PC (NPC), outer-loop PC (OPC) and fast PC (FPC), as shown in Figure 1.3.

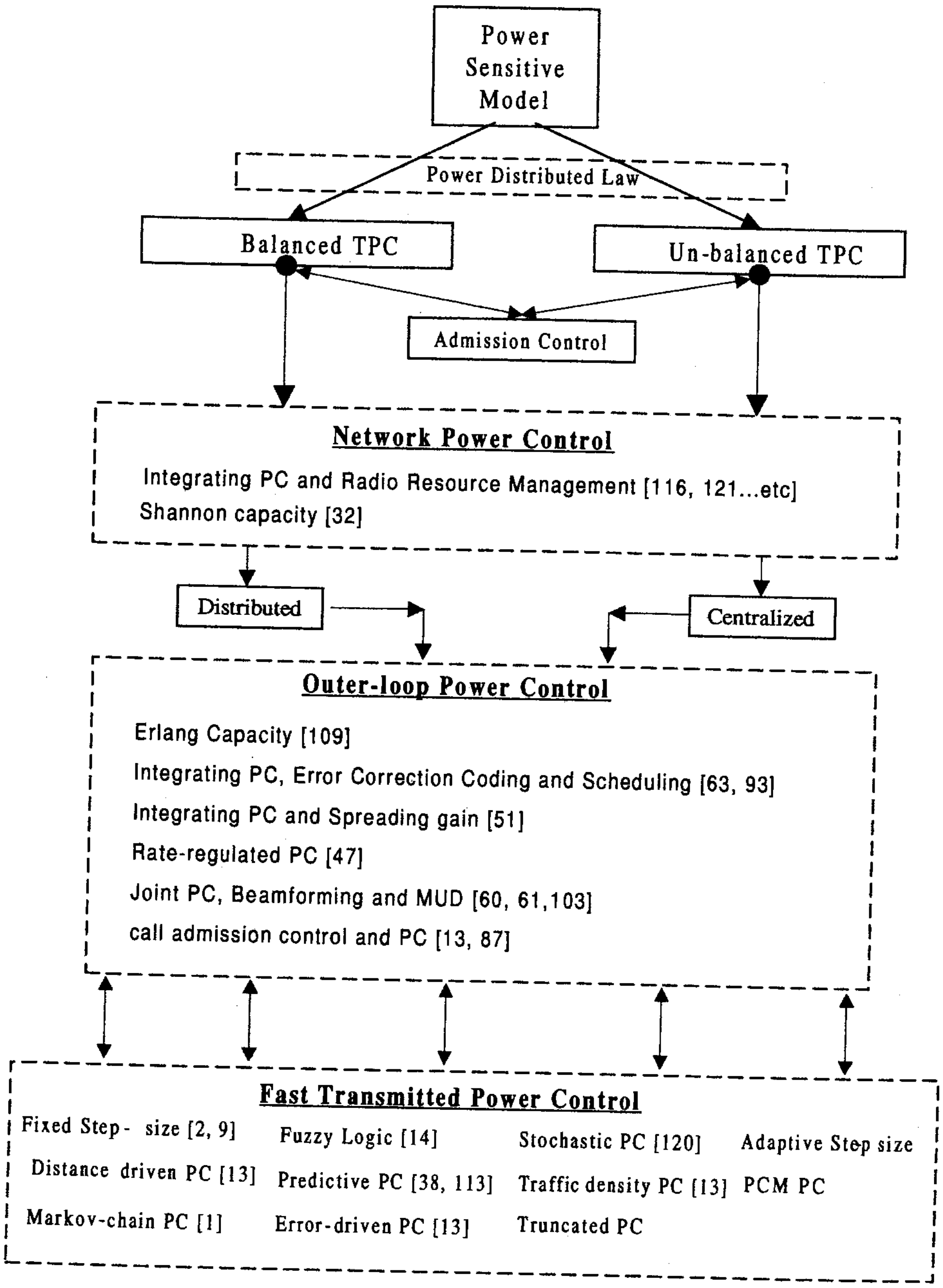


FIGURE 1.3: Overview on research background in PC algorithms

1.2.1 Research Background on APC Algorithms

First-generation Bell mobile systems used in New York city in the 1970s could only support a maximum of twelve simultaneous calls over a thousand square miles [81]. The cellular concept was a major breakthrough in solving the problem of spectral congestion and user capacity. Since then, the system capacity and the cellular system design of FDMA/TDMA schemes have been based on the frequency re-use concept: the multiple access methodology assigns time or frequency slots to users. The vital operation for interference avoidance in these conventional systems is through intelligent allocation, re-use of channels throughout a coverage region as well as by using appropriate handoff strategies. Conventional PC algorithms for FDMA/TDMA were designed to combat co-channel interference and multipath fading only.

A linear receiver structure is sufficient to deliver these services, since the system resources occupied by a handset is generally proportional to the transmission rate and the received power level. The larger the received power from a handset at the base station, the larger the proportion of the system capacity occupied by the handset.

Although SS technology has many advantages over TDMA and FDMA, the two most significant disadvantages are *self jamming* and the *near-far effect*. Traditionally, PC was the only solution for combatting the near-far effect in CDMA systems, by periodically instructing the mobile units to adjust their transmitter power so that all signals are received at the base station at roughly the same strength or same Signal to Interference and Noise Ratio (SINR) level. Much of the current literature on PC algorithms is devoted to this type of receiver structure [9,28,58,81]. If the power is adjusted according to the received strength, it is called strength-based; if the power is adjusted according to the received SINR, it is called SINR-based. Examples include fixed-step size PC [2,9], adaptive step-size PC [15], fuzzy logic PC [14], truncated PC [12,85], traffic density PC, stochastic PC [119], error-driven PC, predictive PC [59,110,112] and Markov-chain PC [1]. In this dissertation, we propose a new unbalanced SINR-based closed-loop FPC algorithms using frequency-multiplexed pilot symbols on the uplink of W-CDMA mobile radio channel.

However, non-linear receiver system means that the interference level is not linearly proportional to transmitted power and data rate, and is called the *near-far resistance* technologies. This technology can efficiently support different bit-error-rate (BER) and QoS performances for multi-media 3G systems. Therefore, conventional FPC algorithms for voice-only cellular systems cannot be directly applied to multi-media 3G cellular systems. Instead, with a complementary APC structure, the scarce radio resources will be optimally utilized, multi-media QoS will be guaranteed and system capacity will be maximized.

The inevitable trend of PC algorithms is toward OPC. Interest in state-of-the-art power-sensitive systems based on radio-resource management has recently increased. This OPC algorithms aim to monitor, schedule and control scarce resources and ensure BER on active links. Aein [6] initially introduced the OPC concept based on *carrier-to-interference ratio balancing* (CIR) for centralized satellite communication systems: if the power is adjusted by a central controller it is called centralized OPC, if the power is adjusted according to local SINR measurements, it is called distributed OPC. Zander [122] introduced a power-distributed law algorithm for centralized and/or distributed systems using Pareto's optimal solution to overcome the problem of interference management. Grandhi [30], Ren [82], Zander [121] and Wu [113] have contributed to the development of optimal centralized OPC algorithms, but centralized OPC algorithms require central controllers and due to their computational complexity, centralized algorithms are impractical. Grandhi *et. al.* [31], Foschini [23], Mitra [67], Lee [56], Kim [46] and Chong [17] have contributed the development of distributed OPC algorithms.

Yates [116,117] has extended these algorithms and formulated a general OPC framework, further identifying common properties and limitations of the interference constraints that may permit a general proof for synchronous/asynchronous convergence properties for PC algorithms.

The growing interest in the use of APC has also sparked the creation of novel applications in other areas too, including, W-CDMA receivers with error correction coding and scheduling [62,91], beamforming [40,60], multi-user detection [61], admission-control [39,51], hand-offs [32,42], rate-regulation [44,47] and many others.

The prime focus of this dissertation is a systematic examination of current APC algorithms, and on the formulation of a novel framework of APC algorithms. There has been little research devoted to the implementation of APC algorithms based on the iterative receiver.

An overview of the most important definitions used in the design and analysis of APC systems in this dissertation are presented below.

1.2.2 Advantages of APC Structure

Outage probability and the degree of user satisfaction provide the basis for a comparison of the performance of cellular technology [87]. Many definitions of outage probability and degree of user satisfaction have been proposed in the literature. Because the capacity of

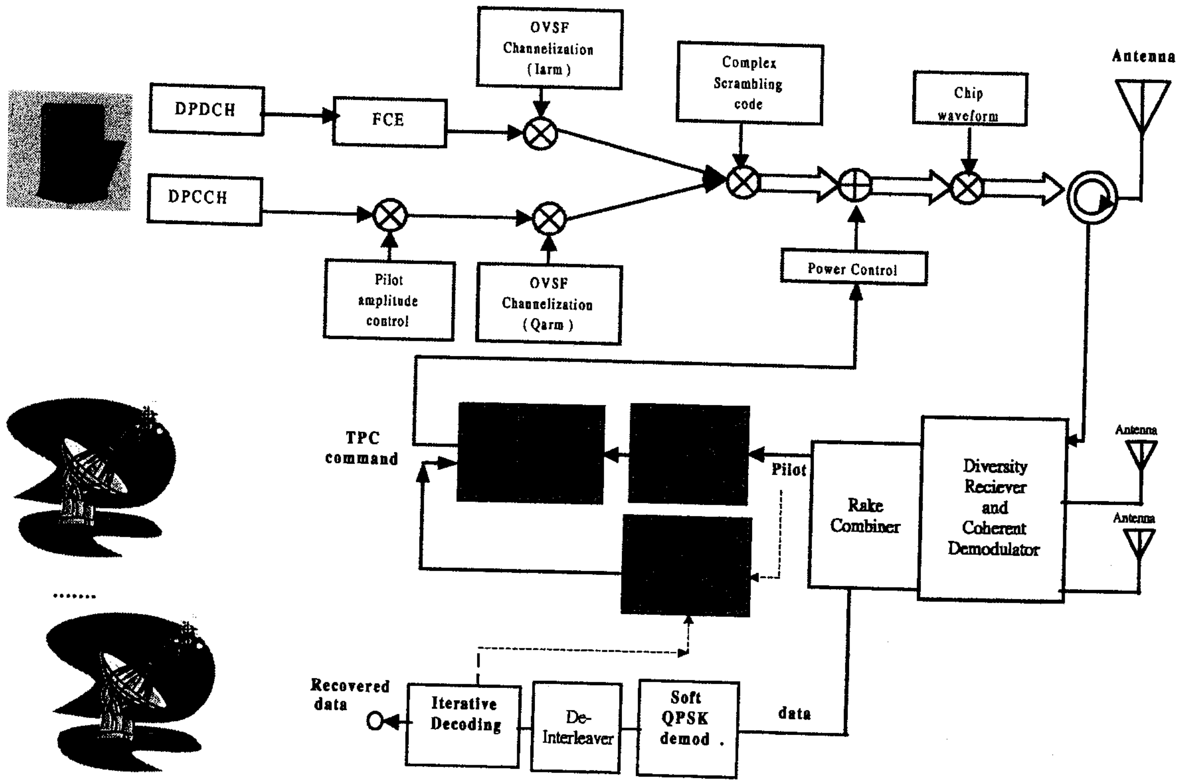


FIGURE 1.4: Three-level optimization hierarchy: user, intracell and intercell levels

W-CDMA technology relies on MAI and traffic-demand parameters, we have included these parameters in our definition of outage probability to evaluate APC performance.

Definition 1: Cellular System Capacity

The cellular system capacity of a W-CDMA system is defined as the maximum number of services under current power distribution law that can be delivered with acceptable QoS to subscribers.

Mathematically, cellular system capacity is defined by outage probability as:

$$P_r\left[\left(\frac{E_b}{I_o}\right)_i \geq \gamma_i\right] = P_r\left[\frac{h_{ik}P_i}{\sum_{j\neq i}^{N} h_{jk}P_j + \delta^2 W}\frac{W}{R_i} \geq \gamma_i\right] \qquad (1.1)$$

where $\left(\frac{E_b}{I_o}\right)_i$ denotes the received SINR for user i and γ_i the desired SINR for user i. Thus, the formula, $P_r\left[\left(\frac{E_b}{I_o}\right)_i \geq \gamma_i\right]$, where $Pr(x)$ is the probability that event x is true and γ^* denotes the pre-determined SINR required to ensure adequate received SINR. The derivation and the definition of notations of this outage probability formula can be find in Chapter 2.

This outage probability formula can be represented as the system capacity for W-CDMA systems and is calculated as the outage probability of d as the outage probability of received SINR values are greater than the desired SINR values.

It is assumed that the desired BER values can be converted to the desired SINR. Since the basic time-scale of QoS management increases from nanoseconds to milliseconds, the assumption of the conversion from BER to SINR becoming statistically invalid. The received SINR values are calculated after the RAKE receiver shown in Figure 1.4, and represented as

$$\frac{h_{ik}P_i}{\sum_{j\neq i}^{N} h_{jk}P_j + \delta^2 W}\frac{W}{R_i} \geq \gamma_i \tag{1.2}$$

where h_{ik} is the link gain between user i and base station k, P_i is the transmitted power of user i at iteration n, R_i is the desired date rate for user i and W, the spreading bandwidth, is assumed fixed in W-CDMA systems. FPC algorithms trigger the transmitted power (P_i) of all users and attempt to stabilize the received SINR at the base station. However, if the transmitted power of one user is increased without considering the MAI level to other users, a positive feedback may occur and an equilibrium state for the power vector will never be reached.

Therefore, MAI

$$\sum_{j\neq i}^{N} h_{jk}P_j + \delta^2 W \tag{1.3}$$

is the major limitation for the determination of outage probability, P_r [Figure 1.5].

Definition 2: A Power-Sensitive Model

A W-CDMA system is a power-sensitive model in which a set of factors, including the orthogonal factor (ρ) after de-spreading, the transmitted power (P_i) of all-users, the link gain (h_{jk}), the traffic demand (Γ_i) and processing gain, will influence the received SINR levels.

Interference-based radio resource management (RRM) is the terminology used by Holma & Toskala [39]. The RRM mechanism consists of handoff, PC, admission-control, load control and scheduling. These functionalities operate at different time-scales. In our view, APC is of fundamental importance to the operation of RRM mechanisms for a number of reasons. Firstly, the power is a shared resource amongst users and the W-CDMA network is a collection of interference links: by controlling the transmitted power, the total MAI can be reduced to a minimum. Secondly, the W-CDMA network is a management of resources: by re-allocating transmitted power and power budget at user and inter-cell

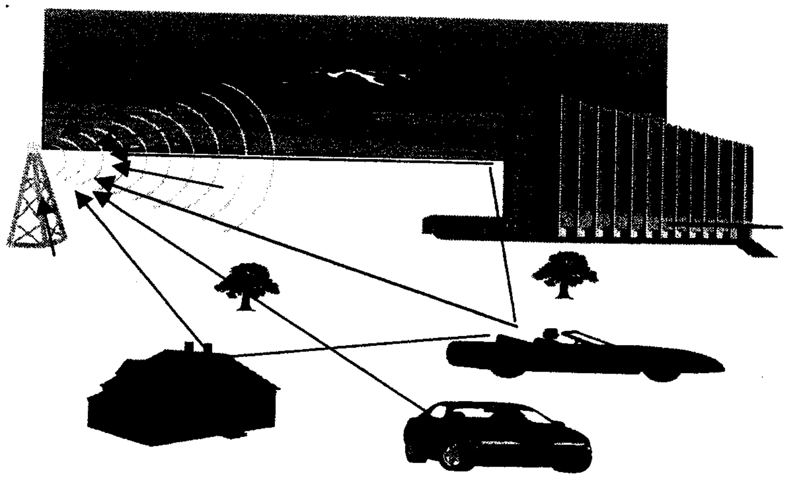


FIGURE 1.5: The potential system capacity is affected mainly by both the short-term and the local-mean statistics of SINR

levels, respectively, the outage probability of the resource can be minimized. Thirdly, the advantages of the APC structure have proven its online QoS monitoring ability, interference management ability, resources management ability and QoS maintenance ability through co-working with other RRM mechanisms.

Definition 3: The centralized strategy of W-CDMA systems

The centralized strategy of interference-based RRM mechanisms, which aim to guarantee QoS, to maintain the planned coverage area and to offer high capacity, is an adaptive power control structure.

Despite the question whether FPC algorithms are necessary and sufficient for unbalanced SINR services if interference cancellation techniques are deployed, APC provides QoS monitoring ability and interference management in a state-of-the-art multi-layered operation. However, these techniques are supplementary mechanisms for RRM systems.

1.2.3 A QoS-based APC Structure

Thus far we have shown that modern wireless-access communication systems are required to supply a number of different services to users in a number of different environments, and that APC techniques may meet these requirements. The APC algorithms for use in multi-media applications are defined as follows:

Definition 4: QoS-based APC structures

A QoS-based APC structure consists of an array of temporally distributed elements, each element in the array receiving the estimated SINR values from each handset. The outputs of each element are adaptively adjusted and calculated based on optimization objectives to determine an optimal power-distribution law for the next time-interval.

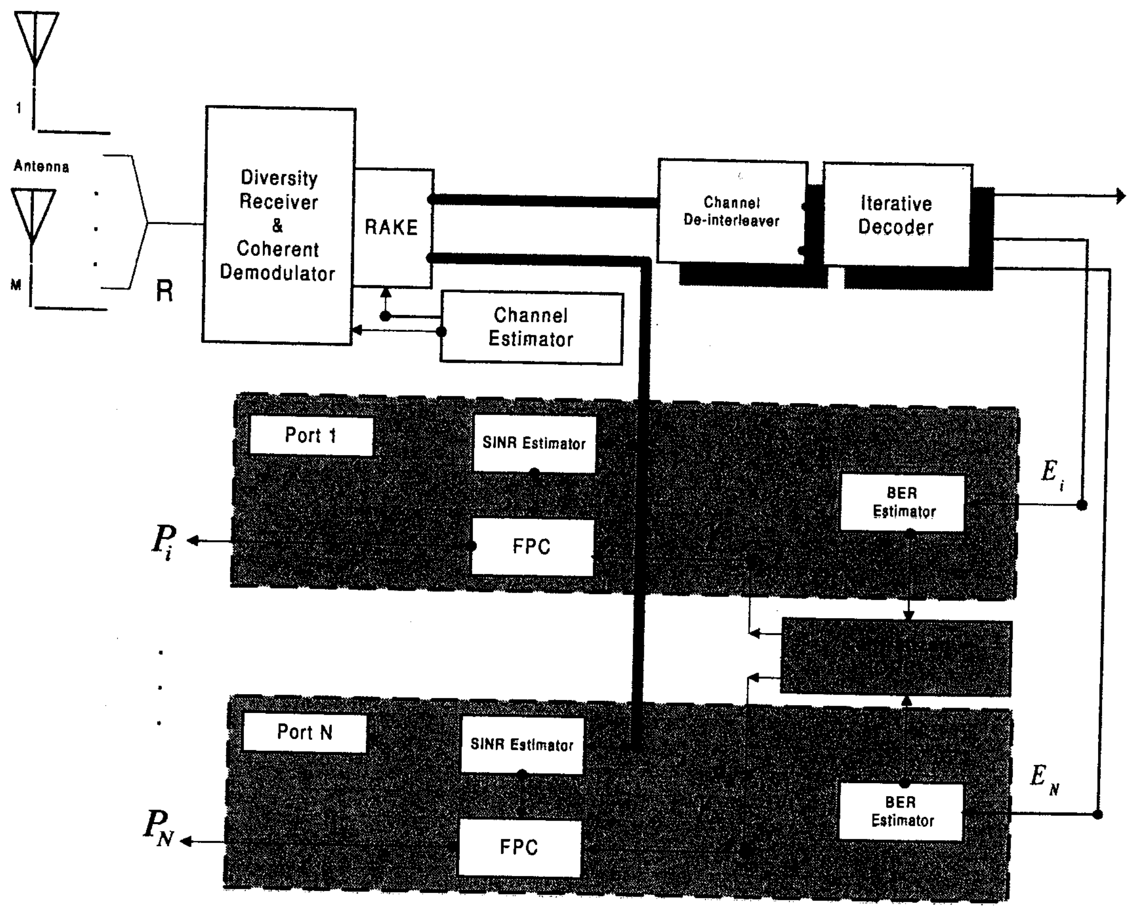


FIGURE 1.6: A QoS-based APC with centralized OPC and N output ports

An N-element, QoS-based, APC structure with a centralized processor that meets the optimization criteria of the power-distribution law for each active user with desired SINR (γ_N^*) is shown in Figure 1.6. The set of SINR measure operations required to track the variation of received signals is measured by SINR estimator after the RAKE receiver. Typically, the estimated SINRs of an APC are measured every 0.625 ms to compensate for the fast and slow channel impairments. The estimated BERs (E_N) of an APC are measured every fourth iteration of iterative decoding to compensate for a slow and erratic prediction of BER estimator. The OPC algorithm is needed to keep the quality of communication at the required level by setting the target for the FPC algorithm.

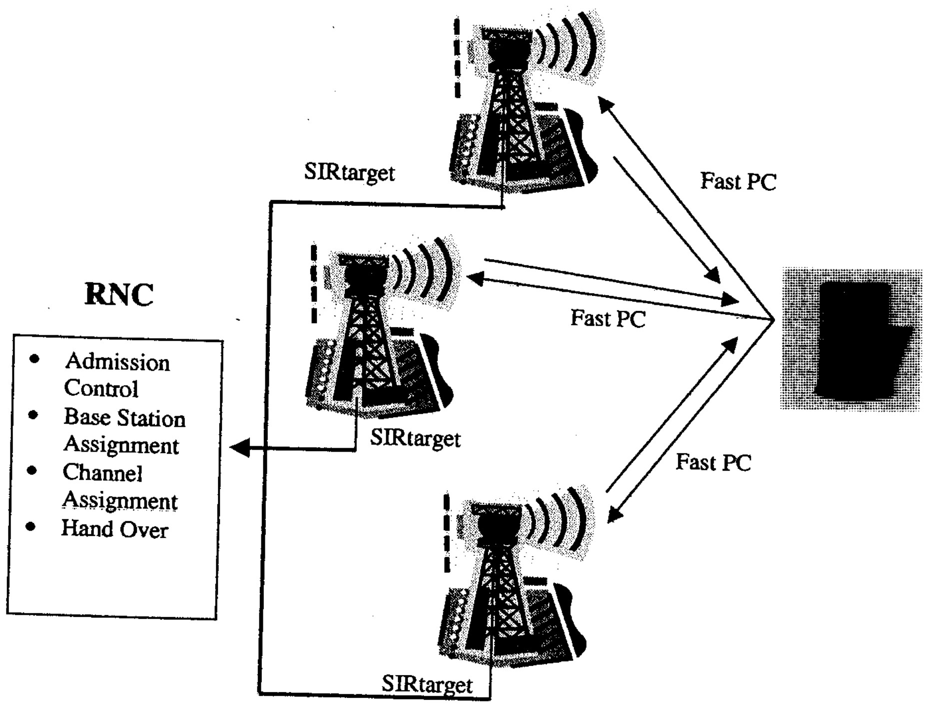


FIGURE 1.7: Radio resource management procedure

The details of operations of APC algorithms in a W-CDMA environment are described below.

Definition 5: A Radio Resource Management Procedure

The RRM mechanism consists of admission-control, base station assignment, channel assignment, scheduling, OPC, load control, FPC and handoffs.

Figure 1.7 shows a typical RRM procedure. When a new call arrives, a new call-admission procedure is invoked. If the air-interface loading exceeds system capacity, the coverage area of the cell is reduced below the planned value, and the QoS of current connections cannot be guaranteed. Admission control accepts or rejects a request to establish a radio-access bearer in the radio-access network. Several admission-control schemes have been suggested [39]. However, the use of the total power received by the base station is the primary uplink admission-control decision criterion and is called power-budge based admission-control strategy in our study of APC frameworks in Chapter 3, the objective of power budge being to minimize inter-cell interference.

The new call is then assigned to a base station and allocated to a channel subject for

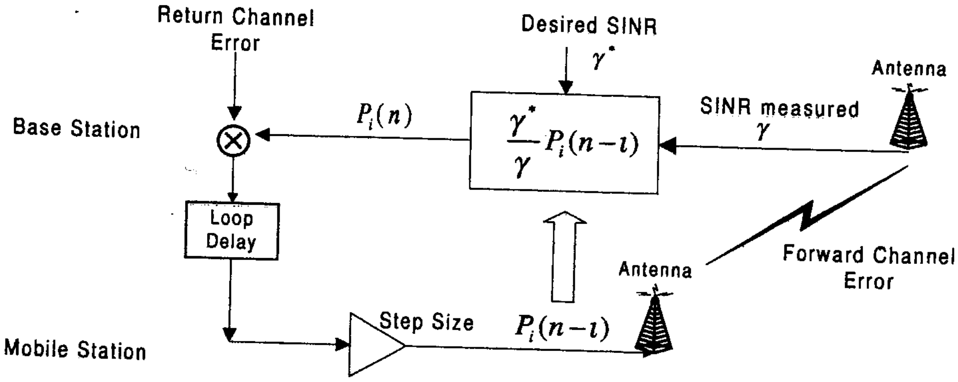


FIGURE 1.8: Traditional closed-loop FPC configuration

an admission check. Yates and Hanly [33, 115] utilized the advantage of soft-handoff of W-CDMA systems and studied an integrated PC and base station assignment. Other schemes such as fixed base station assignment [66, 78], minimal power assignment [33, 115] and diversity power assignment [36, 65] were also investigated, studied and implemented.

If the new call is successfully allocated to a channel, the radio-network centre (RNC) will assign a pre-determined SINR value γ^* to the new call and the transmitted power $P_i(n)$ is adjusted constantly by the FPC algorithm, to ensure that the pre-determined SINR value is preserved. Conventional FPC algorithms use closed-loop or open-loop mechanisms to control the transmitted power based on either strength-based or SINR-based measurements at the base station. Studies on FPC algorithms are reviewed in [85].

A block diagram of a traditional closed-loop FPC system in shown in Figure 1.8. Initially, a base station receives and resolves the multipath signals in slot-based duration. It is then possible for the base station to estimate the received SINR from the received pilot symbols. Based on the estimated SINR, the base station then determines a PC command for the next slot and sends it back to the mobile station. The mobile then determines its step-size after receiving the command. The factors that affect the determination of its step-size are: loop delay; allocated bits for FPC; processing delay; steady state error; rate of fading and number of active users [85]. However, increasing or decreasing the power is always done in a balanced manner, meaning that the power increment command is the same for both increasing and decreasing the power level. However, in practice, the power signal fades more quickly than it rises. This phenomenon can also be observed from the typical Rayleigh and Ricean fading distributions. [100]. This dissertation proposes an unbalanced, FPC algorithm, which is aimed to have faster rising time, less error distribution and better steady-state error [see section 4.3.1 for details].

During the call, the OPC is required to keep the quality of communication at the specified level, by setting the target for the FPC algorithm. Conventional OPC algorithms use joint PC with adaptive antenna techniques [60, 61, 120], multi-user detection techniques [103], coding techniques [3, 40, 62, 92, 124], rate-regulation techniques [41, 44, 47, 72, 128], and base-station assignment [115, 121, 129]. OPC algorithms can use either Pareto optimization or linear-programming optimization to find an optimal power-distribution vector in either centralized or distributed manner to minimize the intra-cell interference. However, the definition of QoS of each service is solely specified by the BER or frame-error-rate (FER) instead of the measured SINR. Strictly speaking, the SINR cannot represent the BER performance due to time-varying environments. since it is difficult to measure the BER, we prefer to apply an FER measurement based on iterative decoding for OPC, because the extrinsic information carry the confidence level corresponding to the current received signals. Adachi [3] has studied the application of an iterative receiver with power control algorithms, which we have extended and applied to a centralized, QoS-based, OPC algorithm:

Equation (1.1) can be rearranged and represented as:

$$\mathrm{P}_i \geq \frac{\gamma_i \mathrm{R}_i}{u_{ik}(\mathbf{P})\mathrm{W}} \tag{1.4}$$

The expression for the received SINR of each user is given by:

$$\frac{h_{ik}P_i}{\sum_{j\neq i}^{N} h_{jk}P_j + \delta^2 W}\frac{W}{R_i} \geq \gamma_i \tag{1.5}$$

with power constraint ($0 < P_i \leq P_{\max_i}$) and rate ($R_i \geq r_i$) where $i = 1, ...N$

Let

$$\Gamma_i = \frac{1}{W}R_i\gamma_i \tag{1.6}$$

be the *normalized* traffic demand of user i. The linear programming optimization problem for the OPC algorithm is described as follows:

$$\begin{aligned} &\min_{\mathrm{P}} \sum_{i=1}^{N} P_i \\ &subject..to \quad P_i \geq \frac{\Gamma_i}{\mu_{ik}(P)} \\ &..... \quad 0 \leq P_i \leq P_{\max} \\ &..... \quad \Gamma_i \geq \Gamma_{\min} \end{aligned} \tag{1.7}$$

The aim is to find a minimum power vector, $\bar{\mathrm{P}}$, such that all the active links are compliant with power constraints, $P_{\max}$, traffic-demand constraint, $\Gamma_{\min}$, and interference constraint, $\frac{\Gamma_i}{\mu_{ik}(P)}$, in both linear and non-linear receiver systems.

It is shown that the traditional Pareto optimal OPC algorithm cannot be directly applied in the simulation. Instead, SINR-unbalanced APC algorithms, which aim to find a power-distribution law that meets the QoS requirements, can improve the BER stability in multi-media W-CDMA systems with Doppler spreading.

If there is no success and handoff criteria are met, the handoff algorithm will assign a new base station and channel to the link. The handoff algorithms in the literature use pilot channel SINR as the handoff measurement quantity [39, 42, 81, 109].

1.3 LIMITATIONS OF CURRENT APC ALGORITHMS

We have identified two major deficiencies in the practical implementation of APC algorithms in power-sensitive networks. One deficiency stems from the fact that the principles of APC and resource management have not yet been integrated into multi-rate W-CDMA systems. Even though a large number of algorithms and hybrid structures have been developed, it would seem, from a survey of the literature, that there is no common framework for a systematic evaluation on subject comparison of different paradigms.

Definition 6: A Power Control Framework

A power control framework consists of a state-of-the-art power-sensitive system. This framework aims to compare different algorithms systematically.

The solution to this problem is, therefore, to introduce a general and mathematically tractable power-sensitive model to identify factors that may influence the capacity of W-CDMA systems. Specifically, three main areas of influence can be identified, namely, multi-access interference, the propagation path of the signal, and the traffic demand required by each subscriber [see Chapter 2 for details].

Since W-CDMA is a power management network architecture design, and there are three basic time-scales for QoS management. An APC framework with three basic time-scales is also proposed. Three layers of operation, dependent on their specific time-scale and optimization objectives, are shown as the interference management (FPC algorithms), the service management (OPC algorithms) and network management (NPC algorithms) [see Chapter 3 for details].

The second deficiency is that the performance and usefulness of APC algorithms are often not adequately compared in a Turbo-coded, RAKE combining and multi-media, uplink, W-CDMA simulation platform with a statistically valid method. The solution is to program a Monte Carlo computer simulation in a Turbo-coded, RAKE-combining uplink W-CDMA cellular environment with a Rayleigh fading channel impairment. The radio-channel models are described in terms of frequency-selective Rayleigh fading: indoor-office, outdoor and pedestrian, and vehicular environments, which are defined in the UMTS forum.

The ultimate goals of this computer simulation package are to compare balanced, step-size, FPC algorithms with our newly proposed, unbalanced scheme, based on BER performance and outage probability with different numbers of multipath components, Doppler spread, the number of receiver antennae and various coding schemes.

The simulation results show that unbalanced FPC algorithms can provide better BER performance and SINR outage probability by about 3dB under the different radio-propagation channels. The centralized QoS-based OPC algorithm can also provide better BER tracking ability and reduce intra-cell interference.

1.4 RATIONALE AND AIMS OF THE DISSERTATION

This research was prompted by ongoing research on multi-media W-CDMA technology, originally at the Alcatel Research Unit for Wireless Access (ARUWA) Laboratory and later in the Centre for Radio and Digital Communication (CRDC) in the Department of Electrical, Electronic and Computer Engineering (University of Pretoria, South Africa). The RRM algorithms based on APC algorithms have received considerable attention recently [13, 29, 33, 44, 47, 61, 87]. More specifically, a study of adaptive antenna arrays, PC, resource-management techniques and iterative receiver structures is undertaken in CRDC. The main focus of this centre is to develop a comprehensive iterative receiver with system implementation of an integrated hybrid adaptive antenna array, PC, and MUD receiver structure.

The aims of this dissertation are as follows:

- to establish a general and mathematically tractable power-sensitive model for multi-media W-CDMA cellular systems;
- to establish a general framework structure for APC algorithms in multi-media, W-CDMA cellular systems;
- to propose new QoS-based APC algorithms based on the framework structure established above;

- to program an ARUWA 3G CDMA simulation package using Matlab software, to provide a statistically valid simulation for uplink multi-media, UMTS/UTRA mobile environments;
- to evaluate the performance of different FPC techniques under different conditions by means of Monte Carlo techniques;

In order to accomplish these objectives, the following items have been considered in detail:

- Power-sensitive model:
  - the influence of MAI and channel effects on the received signal, and
  - the influence of resource management on the system capacity.
- Framework for APC algorithms:
  A power-sensitive model is used to establish a framework for different APC algorithms. The APC layers are divided into:
  - NPC,
  - OPC and
  - FPC.
- To propose new QoS-based APC algorithms:
  These APC algorithms can be divided into three main management blocks in W-CDMA receivers according to their utilization objectives and specific time-scale:
  - interference management systems: QoS-based FPC algorithms.
  - service management systems: QoS-based OPC algorithms
  - network management systems: QoS-based NPC algorithms.
- To programme a 3G UMTS/UTRA simulation package using Matlab;
- Evaluate the QoS-based APC algorithms in Monte Carlo simulation package:
  The influence of the following parameters on system performance and capacity are determined for the proposed FPC algorithms:
  - power profiles
  - Doppler spreads

- coding schemes
- diversity schemes
- number of users

1.5 CONTRIBUTIONS OF THIS DISSERTATION

The main contributions are summarized in terms of the goals of this dissertation. In each case, the main contributions have been consolidated into articles which have been accepted for publication and presented at national conferences. The main contributions are:

- Consolidation of the power-sensitive terminology and operating principles of APC systems for CDMA applications.

  To Be Published

  (1) "Power-sensitive network in multi-media CDMA wireless systems."

- A framework of current APC algorithms for both physical layer and network layer.

  Conference Paper:

  (2) T-C. Song and L.P. Linde, "A New W-CDMA Transmit Power Control Technique based on Iterative Coding Techniques" *Proc. SATNAC'00*, Cape Town, 2000. [101]

- Presentation of a new QoS-based power control structure.

  Conference Papers:

  (3) T-C. Song, P. van Rooyen and X. Xia, "Comparative Study of Power Control Techniques for Cellular CDMA," *Proc. SATNAC'99*, Durban, 1999. [102]

  (4) T-C. Song, L.P. Linde and X. Xia, "A New W-CDMA Transmit Power Control Technique" *Proc. ICCTA'01*, Pretoria, South Africa, 2001. [100]

- Presentation of a Turbo-coded, RAKE combining, multi-media and uplink W-CDMA simulation platform in a Monte Carlo based simulation package.

- An analysis of the influence of temporal factors on the performance of QoS-based, APC structure in W-CDMA cellular systems .

  Conference Paper:

  (5) T-C. Song, L.P. Linde, "QoS based W-CDMA Power Control Techniques",

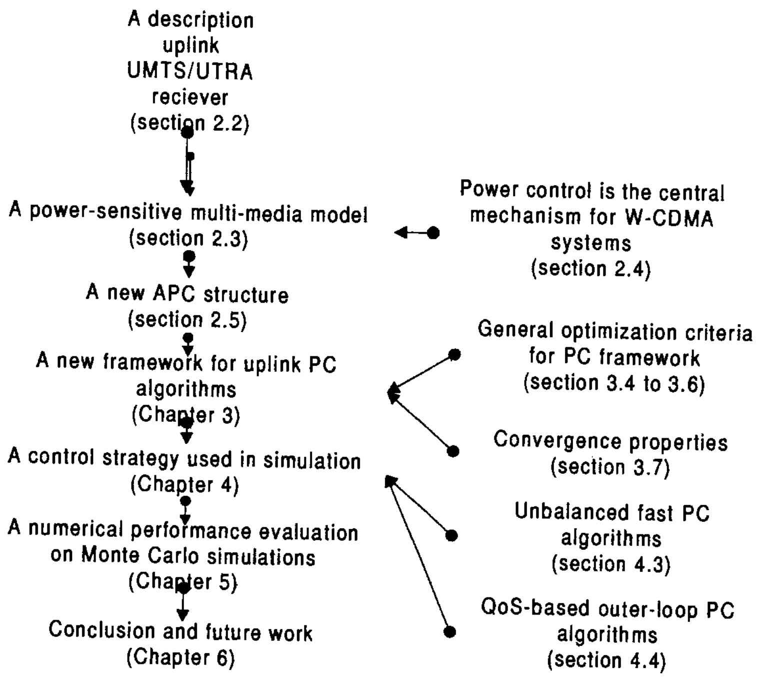


FIGURE 1.9: Overview of the dissertation outline

ISSSTA'02, Praha, Czech, 2002. to be published.

1.6 OUTLINE OF THIS DISSERTATION

The remainder of this dissertation is organized in-line with the main goals of the dissertation outlined in Figure 1.9. Chapter 2 describes the mathematical power-sensitive network model used to evaluate the performance of an APC structure in a Turbo-coded, RAKE combining uplink W-CDMA system. Based on the model, we are able to show that the W-CDMA system is fundamentally the design of an interference management network, because W-CDMA systems are interference and resource limited. All the important parameters and basic assumptions, which are important for the simulated-wireless environment, have been defined in this chapter.

Chapter 3 formulates an APC framework in a systematic manner. This framework is aimed at dividing the vast amount and diverse areas of APC algorithms in the literature into different time-scales and optimization criteria. Mathematical derivations and comparisons on current APC algorithms are described on this standard system model and are the highlights of this chapter. According to our knowledge, the APC structure (NPC, OPC and FPC) have not been described in much detail in literature before. The concept of linear-receiver unbalanced and non-linear-receiver unbalanced structures for APC algorithms are unique in the sense that it is the first time the concepts have been investigated. All current APC algorithms in the existing literature can be categorized into this proposed framework system.

Previously, PC algorithms were treated as separated mechanisms, however in this dissertation these PC algorithms have been integrated into a state-of-the-art power-sensitive architecture. The inclusion of iterative decoding techniques was based on a discussion with P.G.W van Rooyen.

Chapter 4 presents the implementable state-of-the-art QoS-based APC strategy. The eight FPC algorithms are described in detail in this chapter. The analysis of the bounds on the stability of FPC algorithms are obtained to present the advantages of new proposed unbalanced step-size schemes. The centralized linear-programming optimization problem for OPC algorithms is described with mathematical equations and block diagrams.

Having derived the proposed APC structure for the multi-media services of a W-CDMA wireless network, the influence of a number of parameters on each performance measure is described in Chapter 5. Specifically, eight FPC algorithms are compared in terms of their influence on the power profile, Doppler spread, diversity, coding scheme and number of users in the Turbo-coded, RAKE combining, uplink Rayleigh fading channel W-CDMA cellular package. Detailed comparisons of the SINR outage probability, BER performance and rate of convergence for these eight algorithms are presented. It is shown that in order to accurately deliver the BER for active users, OPC is required due to the stochastic and time-varying nature of the power-sensitive model.

Finally, Chapter 6 concludes the dissertation by summarizing the major contributions and simulation results.

Chapter TWO

Power-Sensitive Models

This chapter describes simulation environments used to investigate PC algorithms appropriate for use in the practical implementations of UMTS systems. PC algorithms are executed from the base station to correct the power transmitted from the mobile to the base station and therefore only the uplink is considered. Hence, a summary is presented of the components of the UMTS standard relevant to the physical layer of the uplink and of a mathematical representation of the CDMA system (section 2.1). Then a discussion follows on the rationale for the use of a power-sensitive model (section 2.2), which incorporates the factors that may influence radio-resource-usage and the system capacity (section 2.2.2). The factors are multi-access interference (section 2.2.2.1), the traffic demand (section 2.2.2.2) and channel impairments (section 2.2.2.3).

2.1 A Summary of a Turbo-coded, Uplink W-CDMA System

The system in Figure 2.1 is a wide-band, multi-media communication network which is designed to serve a large number of users simultaneously through portable terminals. Consider a multi-cell (k), multi-media, W-CDMA cellular system that facilitates the high-speed and multi-media services available for the uplink transmission. For low power and cost reasons, computations are carried out at the base station(s) and not at the mobile, since the mobile have minimal general purpose computation power.

We assume that N users are active simultaneously. Each user has a QoS requirement and also power and rate constraints. The chip rate for all users is fixed and the total bandwidth, W, is used by all users. We can define the transmitted power vector, $\mathbf{P} = [P_1, P_2, ...P_N]$, which

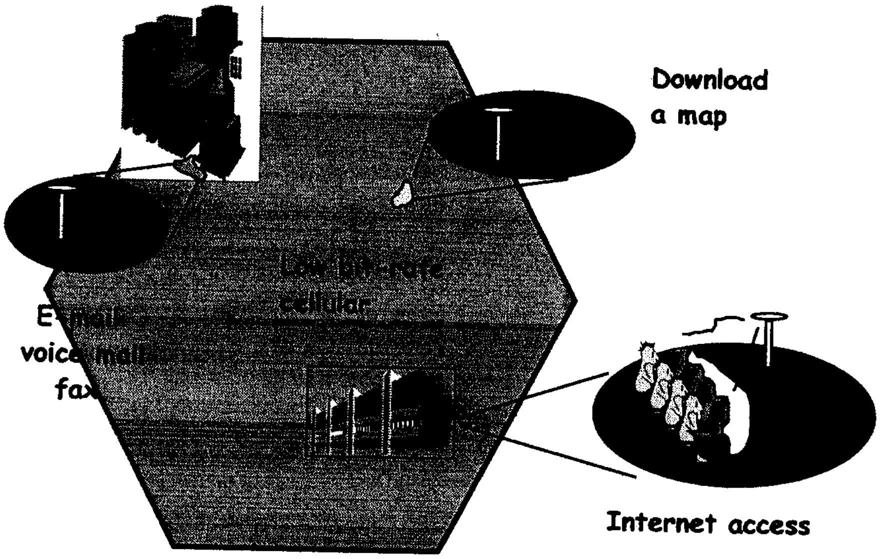


FIGURE 2.1: The uplink of a typical multi-media cellular CDMA system

is limited to a maximum power level as

$$P_i \leq P_i^{\max}, \qquad for \quad 1 \leq i \leq N \tag{2.1}$$

and the vector of rates to be, $\mathbf{R} = [R_1, R_2, ...R_N]$. We assume that the QoS required by each service or medium is specified solely by the BER or frame error rate (FER). It is assumed here that the BER/FER requirement can be mapped into an equivalent, E_b/N_o, requirement and is denoted by, $\gamma = [\gamma_1, \gamma_2, ...\gamma_N]$.

The radio-link parameters of multi-media W-CDMA used in the simulation is based on an FDD scheme [12] (see Table 2.1). The physical and transport channels used in the UMTS are divided into two classes; dedicated channels and common channels. The UMTS specification for the physical layer of the uplink is beyond the scope of this dissertation. (for more information refer to [19]).

The frame structure used by the uplink physical channels is shown in Figure 2.2. The Dedicated Physical Control Channel (DPCCH) carries the control information generated by the physical layer only. Thus, the DPCCH carries known pilot symbols used for channel estimation and SINR measurement by the BS receiver. The minimum PC period is 0.625 ms, or one slot period.

TABLE 2.1: FDD W-CDMA radio-link parameters for this dissertation

Definition of the notations	
Parameter	**Description**
Chip rate	41472/frame
User data rate	48 kbps/256 kbps/1024 kbps
Spreading Code	Short: Tree-structure orthogonal multi-SF codes
	Scramble: Pseudo noise codes
Spreading factor	32/16/4
Interleaving	10 ms
Modem	Spreading: QPSK
	Data: Coherent QPSK
Over-sampling rate	4
Diversity	RAKE+antenna
No. of slots/frame	16
No. of fingers/Antenna	3
Initial power	0.5 W
Diversity (receiver antenna)	2
FEC	Uncoded
	Convolutional with soft-input Viterbi decoder
	Turbo encoder with iterative MAP decoder

2.1.1 Synchronous CDMA Signal Representation

We take advantage of the coherent receiver capability of a W-CDMA system by using pilot symbols along each users data link [Figure 2.3]. Thus, the assumption of perfect channel estimation and link quality measurement, acquisition and tracking of the spreading sequences, and perfect synchronization between each base station and users can be assumed.

In Figure 2.4, the information symbol stream $b_i(l), l = 0, 1, 2, ...(kL - n)/n$ for user i is firstly Turbo-encod at data rate $1/T_b$ symbols per second (sps) with a rate k/n code, followed by an interleaver with L intervals (L is the symbol interval). The sequence output, $d_i(\tau)$, is at the rate $1/T_d = n/kT_b$ sps, where $\tau = 0, 1, 2, ...L - 1$ is the chip interval index. At each

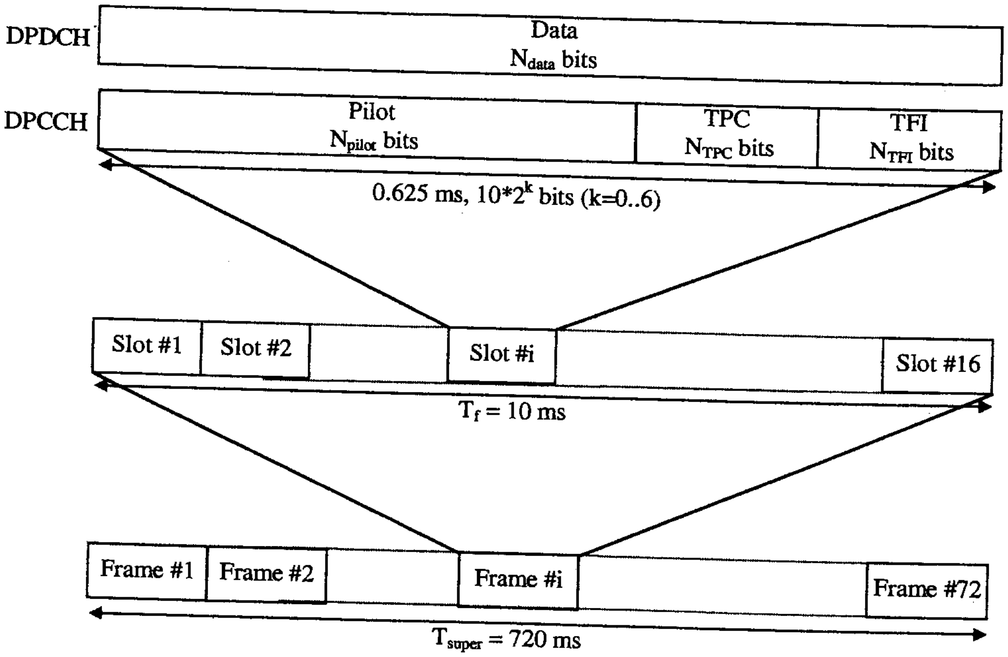


FIGURE 2.2: Frame structure for the uplink DPDCH/DPCCH channels

chip interval τ, $d_i(\tau)$ is modulated by a rate $1/T_c = C/T_d = nC/kT_b$ chips per second (cps) spreading sequence $s_i(\tau) = (s_i(\tau C+1), s_i(\tau C+2), ...s_i((\tau+1)C))^T$, with $s_i(j) \in S$ where S denotes the set of possible chip values and C denotes the spreading gain. Note that the choice of chip values ensures $||s_i(\tau)||^2 = 1$ so that modulation can be modeled as simple multiplication without modifying the energy contained in one chip interval. The bandwidth expansion of the spreaded signal is determined as:

$$G = \frac{1/T_c}{1/T_b} = \frac{nCT_b}{kT_b} = \frac{nC}{k} \tag{2.2}$$

which is traditionally termed the processing gain (G). Both the encoding and the spreading contribute to the processing gain. In practice, the spreading sequences for each chip interval are chosen pseudo-randomly and are known at the receiver.

For practical implementation, all the base-band processing is usually done in discrete time. With this approach, we modulate each chip of $d_i(\tau)s_i(\tau)$ by filtering the signal with a discrete-time, pulse-shaping filter, which is a raised cosine pulse with a roll-off factor of 0.22. The filter operates at a rate of $1/T_s = Q/T_c$, where T_c is the chip interval and Q is the over-sampling factor. To express this operation algebraically, the spreading sequence must be zero-padded before filtering. Therefore, the resulting transmitted, discrete-time, baseband signal for user i is then

$$x_i(\tau) = d_i(\tau) * (\mathrm{u}_1 \otimes \mathrm{s}_i(\tau)) * \mathrm{p} = d_i(\tau) * \hat{\mathrm{s}}_i(\tau) \tag{2.3}$$

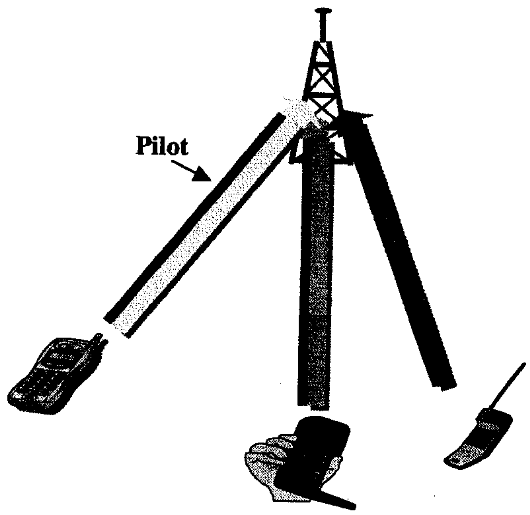


FIGURE 2.3: The uplink of a typical cellular CDMA system with FPC algorithm

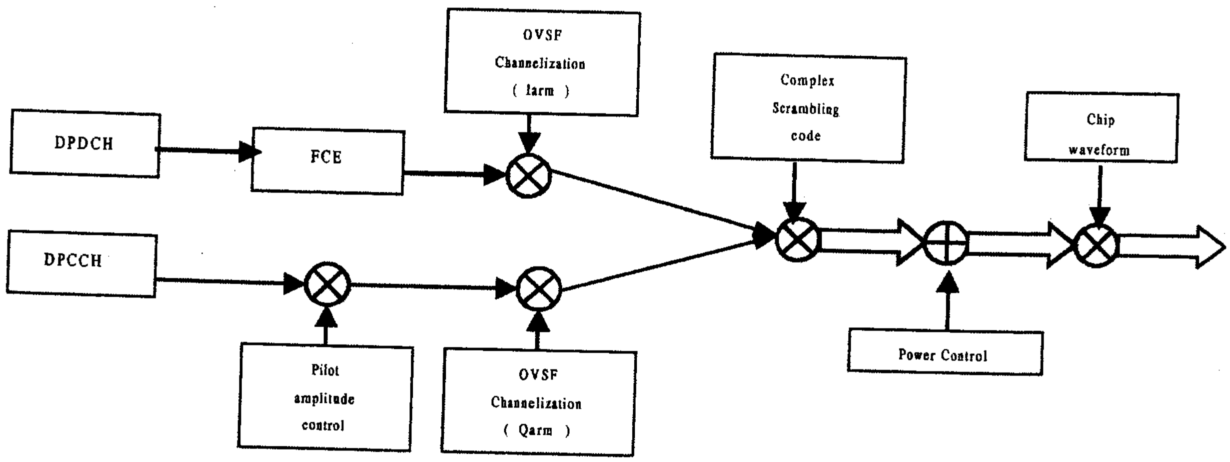


FIGURE 2.4: Transmitter processing for single user

where $\mathbf{p}$ is the pulse-shaping filter impulse-response of length $P+1$, s is the pulse-shape of a spreading sequence of length $NQ+P$ and $\mathbf{u}_1 = (1, O_{Q-1}^T)^T$. No intersymbol interference will occur due to the symbol overlap, as long as root-Nyquist pulses sampled at the correct instances are used. The length of $x_i(\tau)$ is $LNQ+P$, which corresponds to the entire transmission interval of L symbols. Only the elements corresponding to chip interval τ are non-zero.

The channelisation codes are orthogonal variable spreading factor (OVSF) codes. These codes are generated by a binary tree structure. The code associated with a particular branch of the tree is orthogonal to all the codes in the tree except for the following:

- codes on the path from the specified code to the root of the tree;
- codes in the sub-tree below the specified code.

Thus, orthogonal sequences of different lengths can be generated. The spread DPDCH and DPCCH signals are viewed as single complex-valued signals, and are scrambled by complex multiplication with a complex-valued scrambling code. Note that no bandwidth expansion of the signal occurs due to this scrambling.

The short scrambling code is a complex code $C_{scramble} = cI + jcQ$, where cI and cQ are two different codes from the extended very large Kasami set of length 256. Short scrambling codes are intended for use in cells that support multi-user detection in the base station.

For simplicity, we assume that each user transmits over an additive white Gaussian noise (AWGN) channel with variance δ_n^2 and that there is no other distortion in the channel, apart from constant linear scaling of signal amplitudes and multiple-access interference caused by the presence of other active users. If there are N active users of the synchronous DS-CDMA system, then the received baseband signal after A/D conversion for a given chip interval can be written as

$$\mathrm{r} = \sum_{\tau=0}^{L-1}\sum_{i=1}^{N} \mathrm{x}_i(\tau) + \mathrm{n} = \sum_{\tau=0}^{L-1}\sum_{i=1}^{N} A_i(\tau) d_i(\tau) \hat{\underset{i}{s}}(\tau) + \mathrm{n} \tag{2.4}$$

where each active user is assigned a unique spreading waveform (signature, sequence, code) $s_i(\tau)$. $A_i(\tau)$ is the received amplitude of the signal for the ith user, $d_i(\tau)$ is the data chip transmitted by the ith user, and n is a length $(LNQ+P)$ vector of independent, identically distributed (iid) complex Gaussian noise samples of zero mean and variance δ_n^2.

A more convenient form of Equ. (2.4) is

$$\mathbf{r} = \mathbf{ASd} + \mathbf{n} \tag{2.5}$$

where **S** is the matrix of transmitted, spreading waveforms with user i and chip τ. **A** represents the random time-dependent, complex channel coefficient $\mathbf{A}_{i\tau}$. The complex channel coefficient $A_{i\tau}$ contains all the fading and attenuation effects of the radio channel. These effects are traditionally divided into small-scale Rayleigh fading, large-scale log-normal shadowing and path loss denoted for user i at chip interval i and will be described in detail in section 2.2.2.3. The extraction of the transmitted waveform (which overlaps in both time and frequency) from the received signal is facilitated by the carefully selected correlation properties of the spreading waveforms used. The cross-correlation between the spreading waveform for the jth user and that for the ith user is defined as

$$\rho_{j,i} = 1/T_s \int_0^{T_s} s_j(t)s_i(t)dt \tag{2.6}$$

If $j = i$, then $\rho_{j,i} = 1$, since the product $s_i(t)s_i(t) = 1$. If $j \neq i$, then $-1 < \rho_{j,i} < 1$. In this case, the ideal value for $\rho_{j,i}$ is zero, and the sequences are said to be orthogonal.

2.1.2 Linear W-CDMA Receiver with Pilot Symbols

There are three types of measurement outputs in the literature [85]: the received power $P_r(W)$ [14]; the received signal-to-interference ratio (SINR) [9]; and the despreaded signal associated with each path of the receiver [2]. The one we use here is the despread signal to avoid the modulation effects.

Multipath components delayed by more than one chip duration are uncorrelated and appear as resolvable paths in the model. Thus, it is appropriate to use diversity schemes to combine the useful information in the time-delayed versions of the original signal transmission to improve the SINR at the receiver. A well-known diversity scheme that can cooperate in CDMA is the RAKE receiver system shown in Figure 2.5.

Some receiver structures make use of a chip-matched version of the received signal $r(\tau)$, where τ is now the chip rate. An equivalent discrete-time model is thus derived as follows. The spreading waveform is formally defined as

$$s_i(\tau) = \sum_{j=0}^{L-1} s_{\tau,j}\rho(\tau - jT_c) \tag{2.7}$$

where $\rho(\tau) = \begin{cases} 1 & 0 \leq \tau \leq T_c \\ 0 & \text{otherwise} \end{cases}$ and $s_{\tau,i}$ is chip τ of user i. We can then retrieve the signal

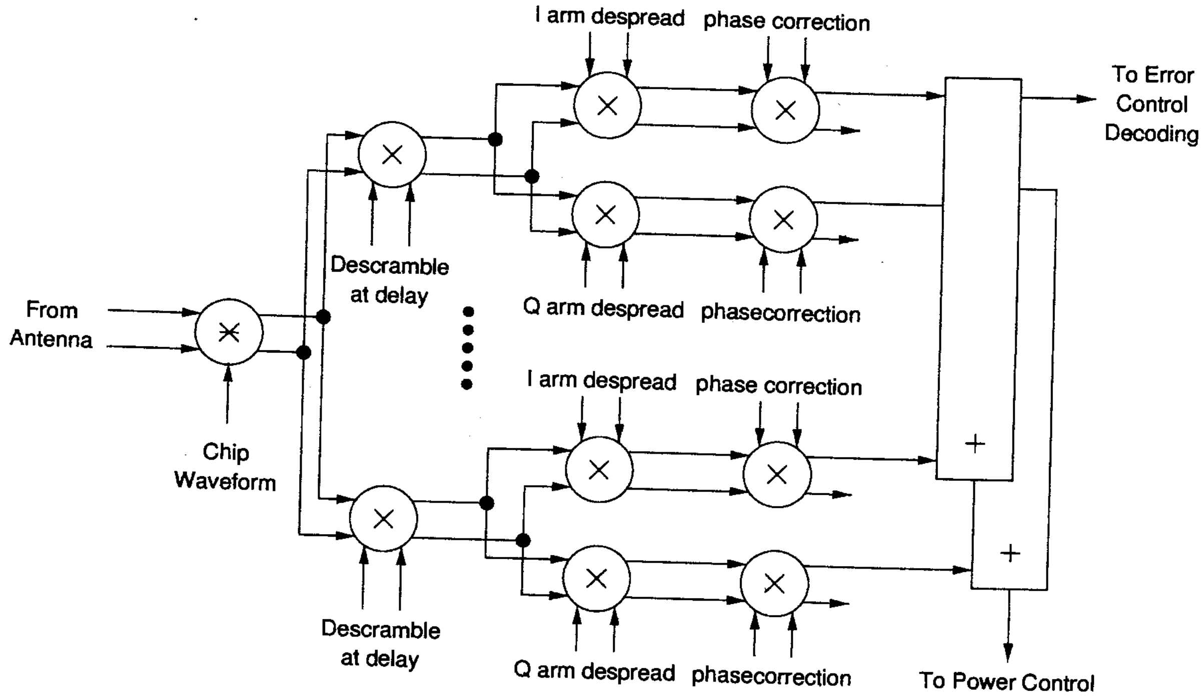


FIGURE 2.5: RAKE receiver structure on a single antenna

transmitted at chip τ through chip-matched filtering as

$$\begin{aligned} r_\tau &= \frac{1}{T_c}\int_{\tau T_c}^{(\tau+1)T_c} r(t)s^*(t-\tau T_c)dt \\ &= \frac{1}{T_c}\int_{\tau T_c}^{(\tau+1)T_c}\sum_{i=1}^{N} A_i(t)d_i(t)\sum_{i=0}^{N-1} s_{i,j}p(t-jT_c)p^*(t-jT_c)dt \\ &+ \frac{1}{T_c}\int_{\tau T_c}^{(\tau+1)T_c} n(t)p^*(t-\tau T_c)dt \\ &= \sum_{i=1}^{N} A_i d_i s_{i,j}\frac{1}{T_c}\int_0^{T_c} dt + n_\tau \\ &= \sum_{i=1}^{N} A_i d_i s_{\tau,i} + n_\tau \end{aligned} \tag{2.8}$$

where n_τ is an additive, white Gaussian noise sample with variance δ^2.

Collecting the sequences of L chips of r_τ, $s_{\tau,i}$ and n_τ in column vectors, $\mathrm{r} = (r_0, r_1, ..., r_{L-1})^T$, $\mathrm{s_i} = (s_{0,i}, s_{1,i}, ..., s_{L-1,i})^T$, and $\mathrm{n} = (n_0, n_1, ..., n_{L-1})^T$, respectively, we can express r for $\tau = 0, 1, ..., L-1$ as

$$\mathrm{r} = \sum_{i=1}^{N} A_i d_i s_i + n. \tag{2.9}$$

Here, the equivalent of Equ. (2.6) is $s_i(\tau)s_i(\tau) = 1$. In this case, the constraint that $s_i(\tau)s_i(\tau) = 1$ translates into $|s_i|^2 = 1$, which in turn leads to $s_{j,i} \in \{-1/\sqrt{L}, +1/\sqrt{L}\}$.

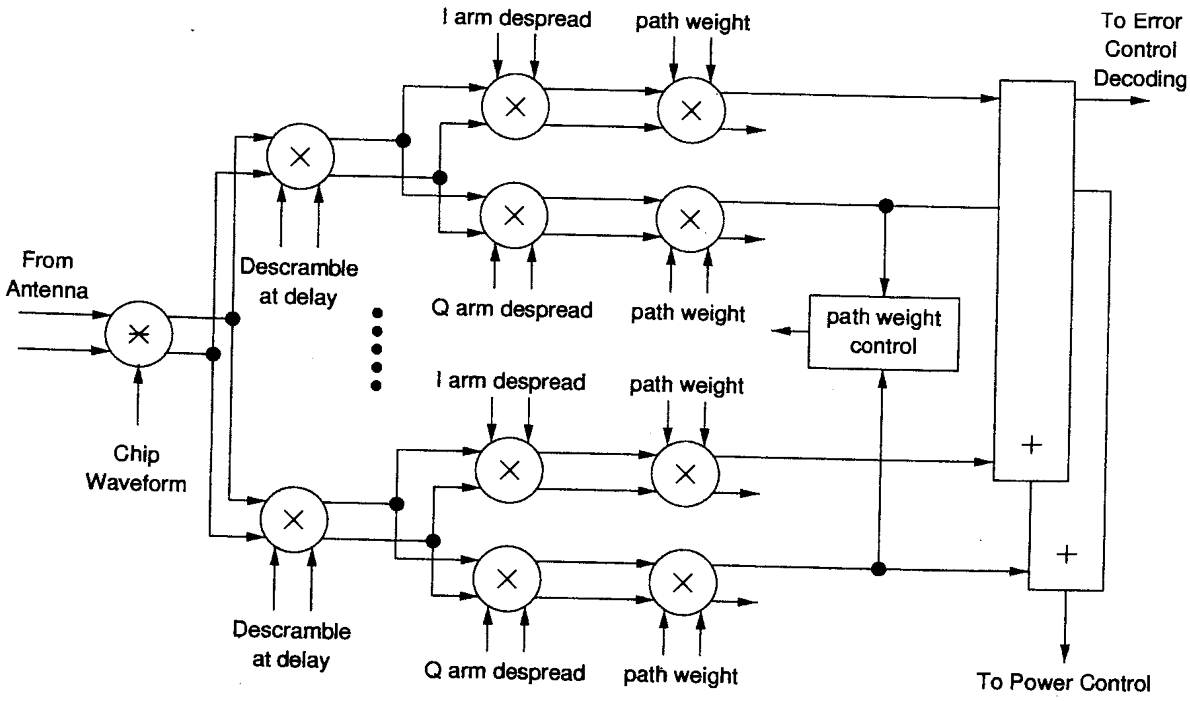


FIGURE 2.6: Adaptive receiver structure

The length of the signature sequence is L, giving the spreading ratio between the rate of narrowband information symbols (b_i)'s and the ratio of the wideband spread-spectrum signals $(A_i d_i s_i)$. The received vector is $\mathbf{r} \epsilon \Re^Q$. We assume that $A_i d_i$ is independent and that $E[A_i d_i] = 0$ and $E[(A_i d_i)^2] = p_i$, where p_i is the received power of user i.

For convenience, let us focus on the demodulation of the *chip-by-chip* detection of user 1 as shown in Figure 2.6, and on a relevant performance measure of the SINR of the estimates.

The *conventional* CDMA receiver for demodulating user 1 is to perform the matched-filter $s_1.r$ on the received signal r. This despreads the signal of user 1, inverting the original spreading operations at the transmitter, and results in the effective channel:

$$\begin{aligned} y_i &= \frac{1}{T_s} \int_0^{T_s} r(t) s_1(t) dt \\ &= (s_1 \cdot s_1)^2 A_i d_i + \sum_{j=1, j \neq i}^{N} \rho_{j,i} A_j d_j + \int_0^{T_s} n(t) dt \\ &= A_i d_i + MAI_i + z_i \end{aligned} \tag{2.10}$$

The first term represents a scaled version of the transmitted data symbol (i.e the desired signal). The second term represents the interference experienced by the ith user due to the other active users. The final term represents modified Gaussian noise. To allow for coherent detection and PC, the physical channel parameters must be known. Assume that we, therefore, have perfect knowledge of the channel estimation, since estimates can be easily obtained from pilot symbols. The SINR for user 1 is the ratio of user 1's signal energy to that of the noise plus other users' interference at the output of the matched-filter, and is given by

$$
\begin{aligned}
\frac{R}{W}\left(\frac{E_b}{I_o}\right)_i = \left(\frac{S}{I_t}\right)_i &= \frac{E[(A_i d_i)^2]}{\sum_{j=1, j\neq i}^{N} \rho_{i,j}^2 E[(A_j d_j)^2] + E[z_i^2]} \\
&= \frac{(s_1 \cdot s_1^*)^2 p_i}{\sum_{j=1, j\neq i}^{N} \rho_{i,j}^2 p_j + (s_1 \cdot s_1^*)\delta^2} \\
&= \frac{(s_1, s_1^*)^2 h_{ik} P_{ti}}{\sum_{j=1, j\neq i}^{N} \rho_{ij}^2 h_{jk} P_{tj} + (s_1, s_1^*)^2 \delta^2}
\end{aligned}
\tag{2.11}
$$

where $\rho_{i,j}^2 = (s_i \cdot s_j)^2$ is the cross-correlation coefficient of code sequences belonging to user i and user j. $p_i = h_{ik} * P_{ti}$ where p_i is the received signal for user i, P_{ti} is the user i's transmitted power level and h_{ik} is the link gain between user i and base station k.

The choice of the signature sequence s_i is very important. The sequence chosen must be orthogonal to all other sequences to avoid interference. In practice, this is usually not possible in an uplink multi-media CDMA. Firstly, the underlying physical wireless channel may cause *multipath* distortion of the transmitted signal, such that several delayed replicas of the signal are superimposed at the receiver. Hence, even if the transmitted signature sequence were chosen to be orthogonal, the received signatures would not be noise-free. Secondly, uplink CDMA systems are usually *asynchronous*, meaning that there is a random, relative delay between users such that a chip of a desired user overlaps with two partial symbols of an interferer.

2.1.3 Description of the Simulation Model

The transmitted signal for each user is generated in accordance with the UMTS physical layer description. The in-phase(quadrature) component of the transmitted signal are multiplied by the in-phase(quadrature) component of a random segment of a pre-generated complex fading channel envelope. The resulting signals are then summed and AWGN of known power, based on the number of users, is added [Figure 2.8]. The impact of slot-by-slot PC on the simulation methodology is profound. The key modules consist of frame-based and slot-based processing for the receiver and transmit functions. For the transmitter, the frame-based processing consists of frame encoding and interleaving. Then each slot is transmitted and received by the base station(s). When a slot is received and placed into the de-interleaver buffer, the PC command is computed for the next transmit slot. Only when the entire de-interleaver inputs are filled can the frame-based receiver procedure start. The frame-based receiver procedure consists of de-interleaving, OPC and decoding techniques.

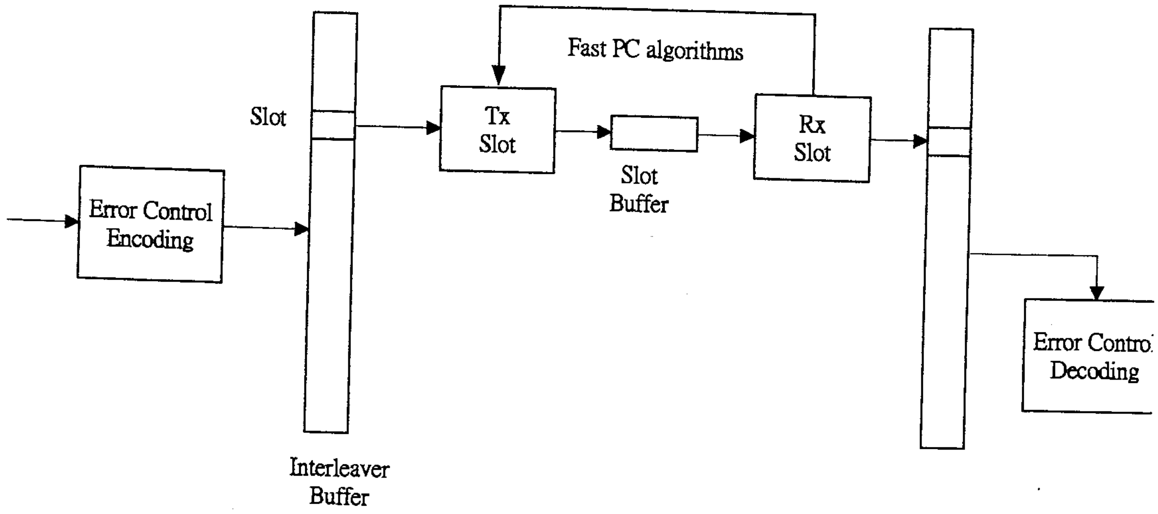


FIGURE 2.7: Frame and slot processing for each user

Closed-loop PC is used on the dedicated uplink channels to reduce the near-far effect. Ideally, the mobiles adjust their transmitted power such that the base station observes a prescribed SINR for each of the users.

OPC is needed to keep the quality of communication at the required level by setting the target for the FPC algorithm. The OPC aims at providing the required quality.

For ease of simulation, the users' signals are generated on a per frame basis. That is, for each 10 ms frame, random user-data sequence, random scrambling, channel models and time shifts are chosen for each user [Figure 2.7].

2.1.4 Monte Carlo Simulation technique

The MATLAB 3G uplink simulation environment developed in the ARUWA Laboratory can provide performance evaluation on different settings, including number of users, channel model, PC algorithms and other link configurations. A Matlab graphical user interface (GUI) that allows flexible simulations is described in Appendices A and B.

To enable statistically valid simulation results to be obtained in reasonable simulation times, Monte Carlo methods are used: for each SINR value, the UMTS uplink is simulated until a reliable estimate of the bit error rate at the output of the multi-user detector can be obtained.

The Monte Carlo simulation performs simulation loops continuously until the following two conditions are satisfied:

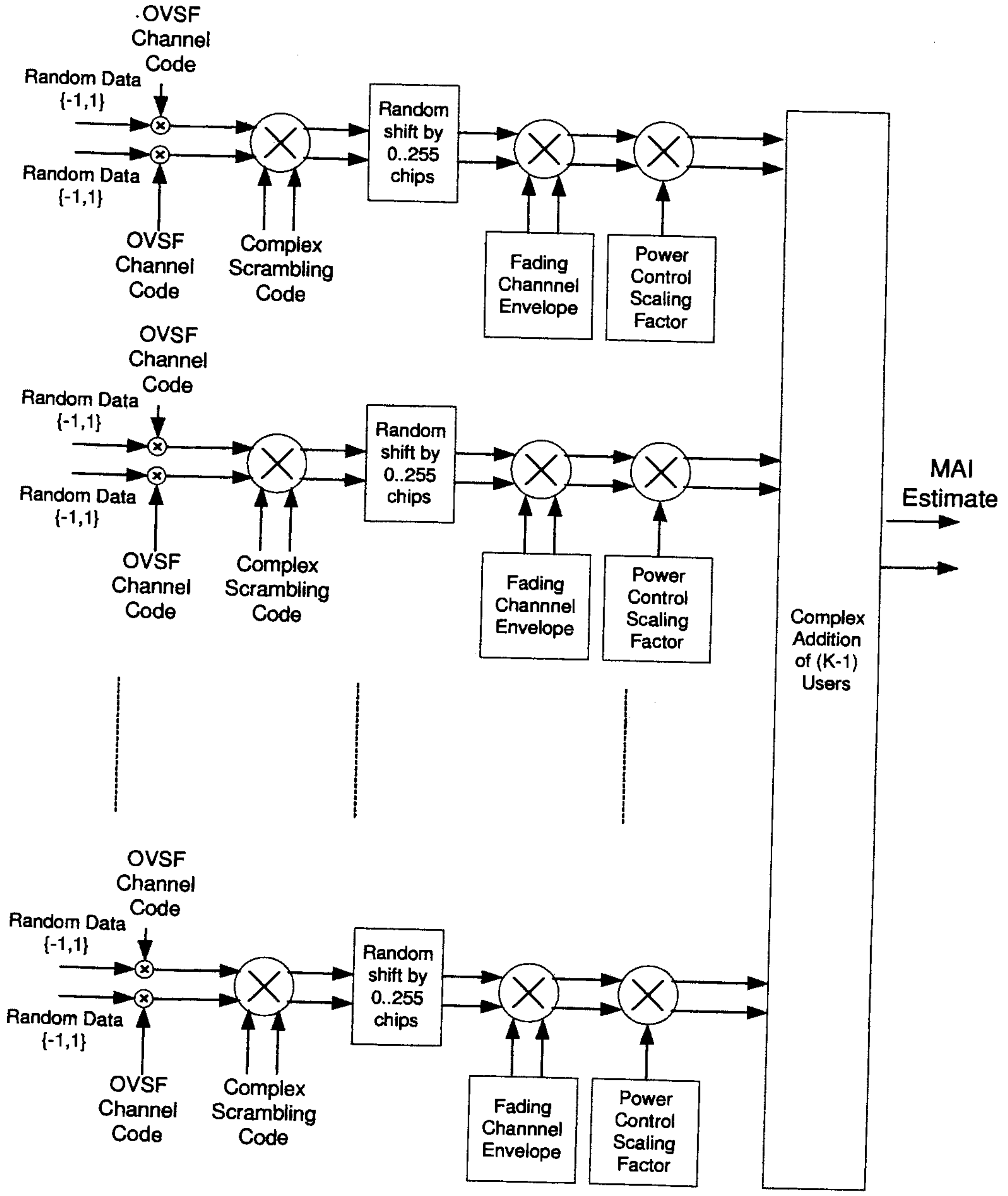


FIGURE 2.8: Multi-access interference generator for multi-user W-CDMA systems

- The number of bit errors detected by the receiver is greater than a specified minimum number of errors.
- The number of simulation loops performed is greater than a specified minimum number of loops.

These conditions ensure that the simulation runs for long enough to obtain a statistically valid BER for each PC set-point. Once these two conditions are met, the simulation continues until one of the following conditions is true:

- The number of simulation loops reaches a specified maximum number of loops.

- The current BER is less than a specified minimum rate.

These conditions ensure that for a given SINR value the simulation will be completed in a reasonable time. The aim of the simulations is to produce a BER curve and SINR outage probability graph.

2.2 A GENERAL POWER-SENSITIVE MODEL

Thus far, this chapter has described the simulation environment that will be used to investigate PC algorithms for use in practical implementations of UMTS systems. This section describes a power-sensitive model for use in the evaluation of a W-CDMA system incorporating adaptive PC algorithms. This model aims to introduce and facilitate a general and mathematically tractable model by combining the channel impairment, multi-access interference (MAI) and traffic demand variables in the analysis of the cellular system capacity.

2.2.1 System Requirements

The goal of any network communication environment is to set up and maintain user-required QoS to subscribers and, above all, to provide flexible services over the wireless channel. Therefore, the ideal central mechanism for W-CDMA systems is one that can provide the following:

- flexible online services;
- control of interference and resource management;
- online QoS monitoring;
- QoS maintenance, and
- serve as a link between network- and physical-layer operations.

To be practical, the central mechanism must also be sufficiently [13]:

- distributed, which allows autonomous execution at the node or link level, requiring minimal (if any) usage of network communication resources for control signaling;
- simple and suitable for real-time implementation with low strain on node computation resources;

- agile for fast tracking of channel changes and adaptation to network stretching due to node mobility;
- robust to adapt gradually to diverse stressful contingencies, rather than stall and collapse;
- iterative, since the nature of the asynchronous mode of operation enables the robustness to measure error and outdated information.

Since SS communications have been traditionally viewed as a physical layer topic, it is argued that, by suitable abstraction, many control and optimization algorithms can be constructed at the network layer. Only a few algorithms presented in the literature can satisfy the above requirements. Therefore, it is desirable that new algorithms be developed.

PC algorithms meets these requirements. This is our rationale for developing a power-sensitive model of W-CDMA systems, which is the main theme of the sections that follows.

2.2.2 Cellular System Capacity

The outage probability, P_{outage}, of a W-CDMA system is defined as the probability of failing to achieve a pre-determined SINR sufficient to give satisfactory system performance, or

$$P_{outage} = Pr(E_b/I_o < \gamma^*) \tag{2.12}$$

where $Pr(x)$ is the probability that event x is true and γ^* denotes the pre-determined SINR required to ensure adequate received SINR. From this definition it follows intrinsically that P_{outage} increases for higher-quality targets SINR, γ^*. W-CDMA capacity is usually defined as the maximum number of users N for P_{outage} smaller than a predefined value γ^*. The "soft" W-CDMA capacity comes from the drastic influence of the quality requirements on P_{outage}, and consequently the capacity.

The following mathematical representation of multi-media W-CDMA is presented in order to show that power is the central mechanism for multi-media W-CDMA systems. The various QoS are represented by the despread SINR (E_b/I_o), instead of the received SINR (S/I_t) and the QoS required by each service or medium. There are solely specified by the BER which can be maintained by specifying an appropriate SINR, or $(^{E_b}/_{I_o})_i$ per user at the receiver, where E_b is the information bit energy and I_o is the interference power spectral density. For direct sequence CDMA, SINR can be written as Equ. (2.13) derived from Equ. (2.11) as [108]

$$(\frac{E_b}{I_o})_i = \frac{S_i/R_{bi}}{I_{ti}/W} = \frac{S_i}{I_{ti}}G \tag{2.13}$$

where S_i is the received signal power (numerator in Equ. (2.11)), for user i; R_{bi} is the ith user's information bit rate; I_{ti} is the total interference power (denominator in Equ. (2.11)), with reference to user i; W is the spreading bandwidth; and G is the processing gain. The signal power at the receiver needed to achieve the required $(\frac{E_b}{I_o})_i$, which is denoted as γ_i, is therefore

$$S_i = \frac{1}{W}R_{bi}\gamma_i I_{ti} \tag{2.14}$$

Then, for satisfactory performance, we must guarantee

$$S_i \geq \frac{1}{W}R_{bi}\gamma_i I_{ti} \tag{2.15}$$

where W is kept constant for all media from any transmitter due to OVSF spreading, but R_{bi}, γ_i and I_{ti} can vary.

Assume there is only one type of multi-media service for a single user. Let

$$\Gamma_i = \frac{1}{W}R_{bi}\gamma_i = \frac{1}{W}\zeta_i \tag{2.16}$$

be the normalized traffic demand of user i, where

$$\zeta_i = R_{bi}\gamma_i \tag{2.17}$$

is the traffic demand of user i. The required transmit powers of all users in the cell can be written in matrix form as

$$\begin{aligned} \mathbf{S} &= [S_1, S_2, ..., S_N] \\ &\geq [\Gamma_1 I_{t1}, \Gamma_2 I_{t2}, ...\Gamma_N I_{tN},] \\ &= \mathbf{\Gamma_D I_t} \end{aligned} \tag{2.18}$$

where N is the total number of mobiles connected to the target base station, j, ζ_i is the normalized traffic demand matrix, and $\mathbf{\Gamma_D} = diag[\Gamma_1, \Gamma_2, ..., \Gamma_N]$

$$\mathbf{I_t} = [I_{t1}, I_{t2}, ..., I_{tN}]^{\iota} \tag{2.19}$$

is the interference vector. Here we adopt the convention that the vector inequality is an inequality in all components, that is, the matrix inequality in Equ. (2.18) is component wise. The total interference to the signals of the ith user is caused by the signals from other users in the system after matched filtering and thermal noise, and can be represented by

$$\mathbf{I_t} = \sum_{j=1, j\neq i}^{N} S_j + n_i = \sum_{j=1}^{N} S_j - S_i + n_i \tag{2.20}$$

where, $\sum_{j=1,j\neq i}^{N} S_j$, is the intracell MAI and n_i is the aggregate disturbance consisting of AWGN and intercell MAI. Substituting Equ. (2.20) into Equ. (2.15) gives

$$S_i \geq \Gamma_i \left[\sum_{j=1,j\neq i}^{N} S_j + n_i \right] \tag{2.21}$$

from which we can derive a system of inequalities for the N users in the cell:

$$\begin{aligned} S_1 - \Gamma_1 S_2 - \ldots - \Gamma_1 S_N &\geq \Gamma_1 n_1 \\ -\Gamma_2 S_1 + S_2 - \ldots - \Gamma_2 S_N &\geq \Gamma_2 n_2 \\ \ldots\ldots \\ -\Gamma_N S_1 - \Gamma_N S_2 - \ldots + S_N &\geq \Gamma_N n_N \end{aligned}$$

or in matrix form,

$$\Gamma_{\mathbf{S}} \mathbf{S} \geq \Gamma_D \mathbf{n} \tag{2.22}$$

Based on Equ. (2.22), the most important factors that influence CDMA capacity are the following:

- MAI, $\mathbf{I_t} = \sum_{j=1,j\neq i}^{N} S_j + n_i = \sum_{j=1}^{N} S_j - S_i + n_i$
- traffic demand, $\Gamma_i = \frac{1}{W} R_{bi} \gamma_i$
- distributed power law, S^*
- transmitted power of user i, P_{ti}, and
- channel impairment for user i, h_{ij}

Of significance is the introduction of the concept of effective interference and resource management to the power sensitive model.

2.2.2.1 Interference Management

2.2.2.1.1 The wireless network as a collection of power-controlled interfering links

For a given MAI, the transmit power of a mobile can always be increased to achieve the desired SINR. This will result in higher MAI for other mobiles whose power may in turn have to be increased to maintain their original SINR. Therefore, the transmit power in W-CDMA must be carefully planned and controlled as a system resource if the desired system performance and maximal user capacity are to be achieved. One example is the Pareto power vector for SINR balanced, linear receiver systems.

Zander [121] first introduced the concept of a *Pareto optimal* solution for *SINR balancing* PC algorithms. Equ. (2.22) shows the optimal power vector under study for one class of services.

$$\begin{aligned}\Gamma_S &= \begin{bmatrix} 1 & -\Gamma_1 \dots & -\Gamma_1 \\ -\Gamma_2 & 1 \quad \dots & -\Gamma_2 \\ \dots & \dots & \\ -\Gamma_N & -\Gamma_N \dots & 1 \end{bmatrix} \\ &= \mathbf{I}_N - \mathbf{\Gamma}_D(\mathbf{J}_N - \mathbf{I}_N) \\ &= \mathbf{I}_N - \mathbf{\Gamma}_P \end{aligned} \tag{2.23}$$

where $\mathbf{I}_N$ is the $N \times N$ identity matrix, $\mathbf{J}_N$ denotes an $N \times N$ matrix of all 1's, and

$$\begin{aligned}\mathbf{\Gamma}_P &= \mathbf{\Gamma}_D(\mathbf{J}_N - \mathbf{I}_N) \\ &= \begin{bmatrix} 0 & \Gamma_1 \dots & \Gamma_1 \\ \Gamma_2 & 0 & \\ \dots & \dots & \\ \Gamma_N & \Gamma_N \dots & 0 \end{bmatrix}\end{aligned} \tag{2.24}$$

substituting Equ. (2.24) into (2.26) yields,

$$(\mathbf{I}_N - \mathbf{\Gamma}_P)\mathbf{S} \geq \mathbf{\Gamma}_D\mathbf{n} \tag{2.25}$$

Since $\mathbf{\Gamma}_P$ is a nonnegative, primitive matrix, by the Perron-Frobenius theorem [33], we have

Theorem 1: *$\mathbf{\Gamma}_P$ has a positive eigenvalue λ equal to the spectral radius of $\mathbf{\Gamma}_P$, and if $\lambda < 1$, the power vector in Equ. (2.25) has the non-negative solution*

$$\mathbf{S}^* \geq (\mathbf{I}_N - \mathbf{\Gamma}_P)^{-1}\mathbf{\Gamma}_\mathbf{D}\mathbf{n} \tag{2.26}$$

We observe that, in principle, the goal of our PC strategy should be to set the received power at $\mathbf{S}^*$, when it is possible to satisfy the SINR requirements of all links simultaneously. The Pareto optimal power vector $\mathbf{S}^*$ in Equ. (2.24), to which the algorithm converges, is basically the minimal power operational point for the network of links, for which the SINR constraint are satisfied. Recently, PC algorithms have been of considerable interest in multi-media services due to the capacity to monitor QoS.

2.2.2.2 Resource Management

The mobility, addition or dropping of calls and shadowing dramatically alter the state of equilibrium. When the unwanted links try to access the channel in the absence of any feasible power vector, all SINRs degrade, while power escalates uncontrollably. This positive feedback problem is a serious network layer problem. CDMA system capacity is limited by the total interference, so a fair and efficient control on radio resource is required. Thus, PC algorithms should be viewed as a bridge between the physical layer and the network layer, and by suitable abstraction, many control and optimization algorithms with interesting structure can be formulated in a multi-media environment.

2.2.2.2.1 The wireless network as a management of power-controlled resources Multi-media services requirement ranging from low-data rate and delay-sensitive voice information to high-data rate and delay-sensitive multi-media services, such as real-time video. Many services can also tolerate delay, such as package data and files.

When $N = 2$, the eigenvalues of $\mathbf{\Gamma_P}$ can be derived by solving the characteristic polynomial equation

$$f(\lambda) = \det[\Gamma_{\mathrm{P}} - \lambda \mathrm{I}] = 0 \tag{2.27}$$

The two eigenvalues are found to be

$$\lambda_{1,2} = \pm\sqrt{\Gamma_1\Gamma_2} \tag{2.28}$$

Applying Theorem 1 requires

$$0 < \Gamma_1\Gamma_2 < 1 \tag{2.29}$$

Substituting for Γ_i from Equ. (2.16), we have

$$\sqrt{\zeta_1\zeta_2} < W \tag{2.30}$$

This is the bound imposed by the spreading bandwidth on the traffic demands of the users in the cell for the problem to be solvable or for the power to converge.

Several conclusions can be drawn from this example:

- For any PC algorithm to converge, the traffic demands, which describe the information rates and QoS requirements of each user, is upper bounded by the spreading bandwidth W, i.e. $\sqrt{\zeta_1\zeta_2} < W$.

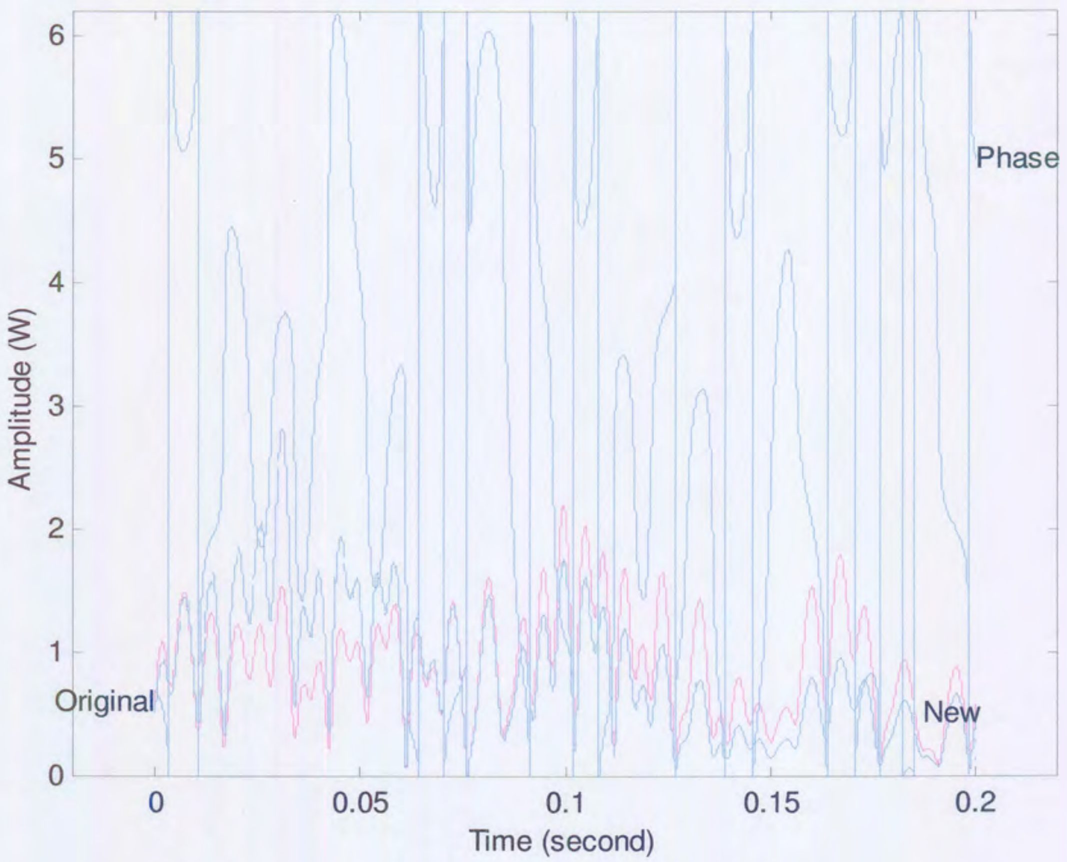


FIGURE 2.9: A typical wireless channel impairment

- The higher the interference level, and where traffic demand is closer to the spreading bandwidth, the higher the required received power. When $\sqrt{\zeta_1\zeta_2} >> W$, the signal power of each user tends to infinity: $S_i \rightarrow \infty, i = 1, 2$.

2.2.2.3 Channel Impairment

The main reason for having different power controllers in different time-scales is due to channel impairments. The mobile communication system requires signal processing techniques that improve the link performance in hostile mobile radio environments. An example of a mobile radio channel, shown in Figure 2.9, which is dynamic due to multipath fading and Doppler spread [81], places fundamental limitations on the performance of wireless communication systems and is a dominant source of impairment. In order to facilitate the numerical evaluation of PC algorithms, the wireless channel is programmed in MATLAB with the following models.

2.2.2.3.1 UMTS Radio Channel Modelling The channel model used in the simulation package considers three environments: *indoor-office*; *outdoor-to-indoor and pedestrian*; and *vehicular*. The UMTS radio channel model is described in terms of frequency-selective Rayleigh fading. The complex low-pass equivalent representation of the channel for the link between any transmit-receiver antenna pair of the ith user can be modelled as

$$h_i(t) = a_k \sum_{\ell=1}^{L_i} Ray_{\ell,i}(\tau)\delta(t - \tau_{\ell,i})e^{j\Phi_{\ell,i}} \tag{2.31}$$

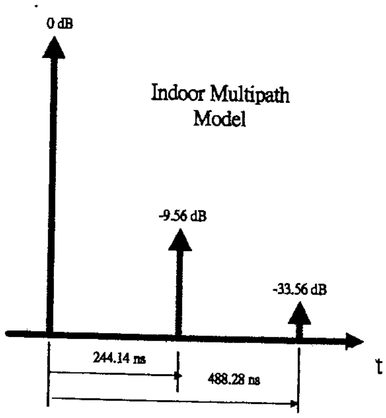
where $Ray_i(\tau)$, $\tau_{\ell,i}$, and $\Phi_{\ell,i}$ are the path gain due to Rayleigh fading, time delay, and the phase shift of the ℓth multipath component from the ith user's transmit-receiver antenna path, respectively. Therefore, L_i is the number of paths received from the transmit antenna for user i. The variable a_k models the effects of path loss and log-normal shadowing. The phase term $\tau_{\ell,i}$ is assumed to be uniformly distributed over $[0, 2/\pi]$. In the simulation, the MAI is approximated by complex Gaussian noise and is combined with the background noise characterized by AWGN.

As is the case in a number of realistic CDMA scenarios, the multipath delay spread is assumed to be much shorter than the data-symbol duration, so that any inter-symbol interference at the receiver can be neglected. Furthermore, it is assumed that the multipath channel parameters vary slowly compared to the chip duration, so that they are nearly constant over several chip periods.

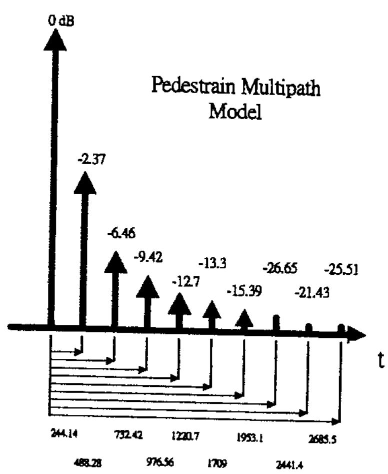
2.2.2.3.2 UMTS Channel Model 1: Indoor-Office The maximum vehicle speed for the *indoor-office* is given as 3 km/h. The propagation model for this 3-tap model is illustrated in Figure 2.10 (a). For these channels it is assumed that a very large number of received waves arrive uniformly distributed in elevation for each delay interval at the mobile and base-station. This assumption results in a FLAT Doppler spectrum.

Table 2.2 illustrates the tapped delay-line parameters, as well as the relationship between the different multipath components relative to the chip duration.

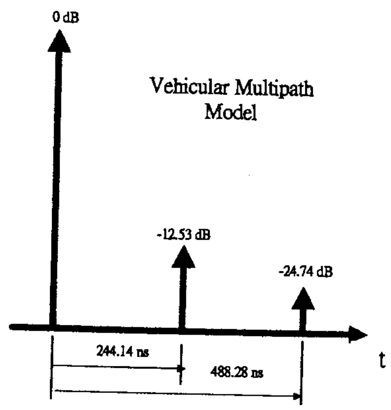
2.2.2.3.3 UMTS Channel Model 2: Outdoor and Pedestrian The maximum vehicle speed for this channel model shown in Figure 2.10 (b) is given as 3 km/h. For these outdoor channels it is assumed that a very large number of received waves arrive uniformly distributed in azimuth at the mobile and base-station antenna and at zero elevation for each delay interval. Also, the antenna pattern is assumed to be uniform in the azimuth direction. At the base-station and mobile in general the received waves arrive in a limited range. These



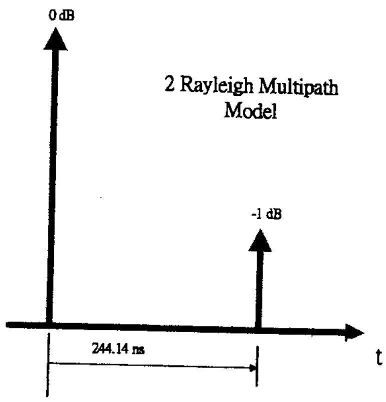
(a) Delay model for Indoor test environment



(b) Delay model for Pedestrain test environment



(c) Delay model for Vehicular test environment



(d) Delay model for 2-Rayleigh test environment

FIGURE 2.10: Power profile for various channel environments

TABLE 2.2: UMTS indoor channel tapped delay-line parameters.

A tapped delay-line parameters			
Channel	**Ave. Power**	**Delay**	**Doppler Spectrum**
Tap 1	0	0	FLAT
Tap 2	-9.56	244.14	FLAT
Tap 3	-33.56	488.28	FLAT

assumptions correspond to the Clarke and Jakes model for narrow band channels, and is known as the CLASSIC Doppler spectrum.

Table 2.3 illustrates the 10-tap delay-line parameters and relative relationship with

TABLE 2.3: UMTS outdoor channel tapped delay-line parameters.

A tapped delay-line parameters			
Channel	**Ave. Power**	**Delay**	**Doppler Spectrum**
Tap 1	0	0	CLASSIC
Tap 2	-2.37	244.14	CLASSIC
Tap 3	-6.46	488.28	CLASSIC
Tap 4	-9.42	732.42	CLASSIC
Tap 5	-12.7	976.56	CLASSIC
Tap 6	-13.3	1220.7	CLASSIC
Tap 7	-15.39	1709	CLASSIC
Tap 8	-25.65	19531	CLASSIC
Tap 9	-21.43	2441.4	CLASSIC
Tap 10	-25.51	2685.5	CLASSIC

sample time.

2.2.2.3.4 UMTS Channel Model 3: Vehicular Environment The maximum vehicle speed for this channel model is given as 200 km/h. The propagation model for the three-tap test environment is illustrated in Figure 2.10 (c). Table 2.4 illustrates the delay-line parameters and relative relationships with sampling time.

2.2.2.3.5 Envelope Fading It has been shown theoretically that the received fluctuating signal envelope has a Rayleigh distribution (see Figure 5.25) when the number of incident plane waves propagating randomly from different directions is sufficiently large and when

TABLE 2.4: UMTS vehicular channel tapped delay-line parameters.

A tapped delay-line parameters			
Channel	**Ave. Power**	**Delay**	**Doppler Spectrum**
Tap 1	0	0	CLASSIC
Tap 2	-12.53	244.14	CLASSIC
Tap 3	-24.74	488.28	CLASSIC

there is no predominant LOS component. The Rayleigh distribution is the most frequently used distribution function for land-mobile fading channels.

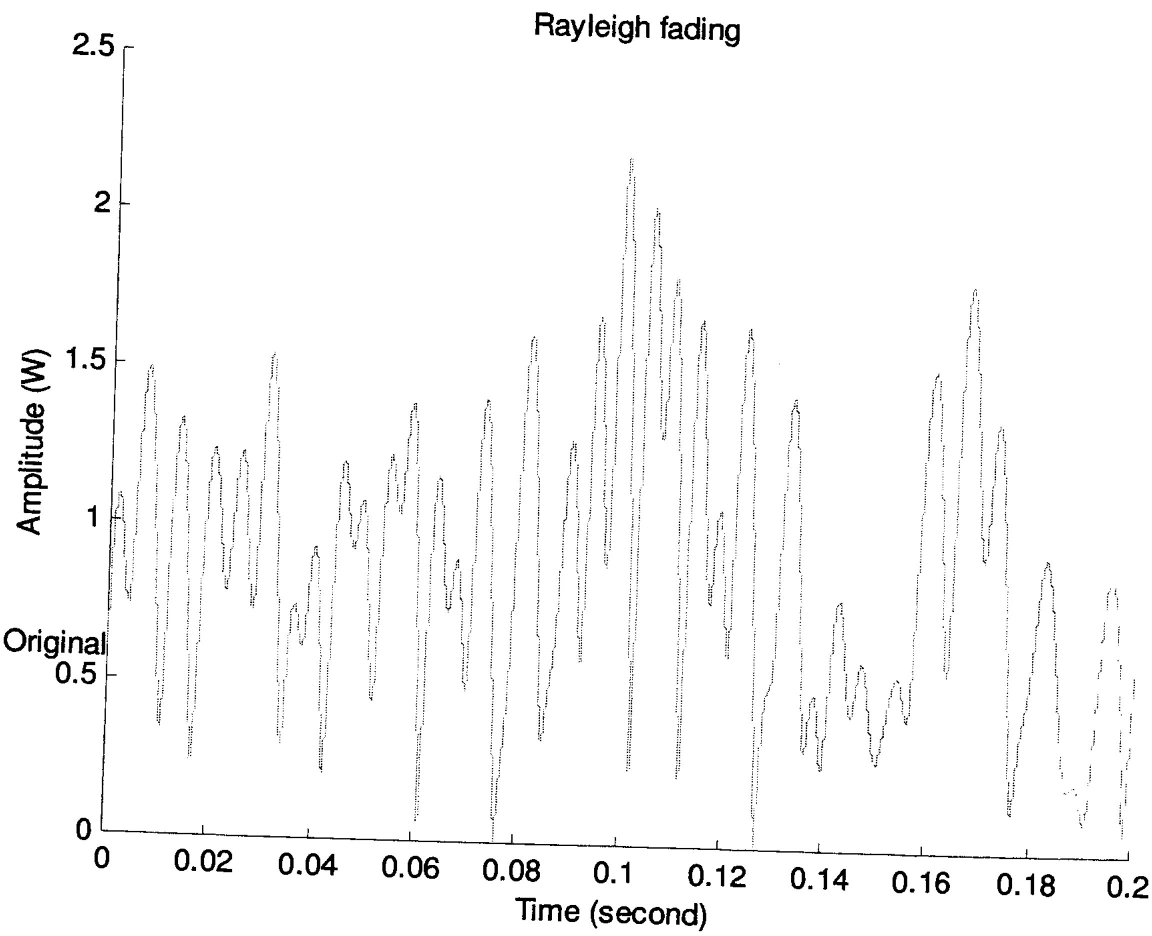


FIGURE 2.11: A typical Rayleigh channel in wireless environment

2.2.2.3.6 Doppler Spread: Time-Selective Fading In the preceding subsection it was shown that the time-varying, random-fading envelope is accompanied by a random phase change. Doppler spread is defined as the spectral width of a received carrier when a single unmodulated carrier is transmitted over the fading channel. If a unmodulated carrier having a radio frequency f_c is transmitted, then, because of Doppler spread, f_D, a smeared signal spectrum is received with spectral components between $f_c - f_D$ and $f_c + f_D$. This effect is also known as time-selective fading.

Coherence time, T_c is inversely proportional to the maximum Doppler frequency and is defined as

$$T_c = \frac{1}{f_D} \tag{2.32}$$

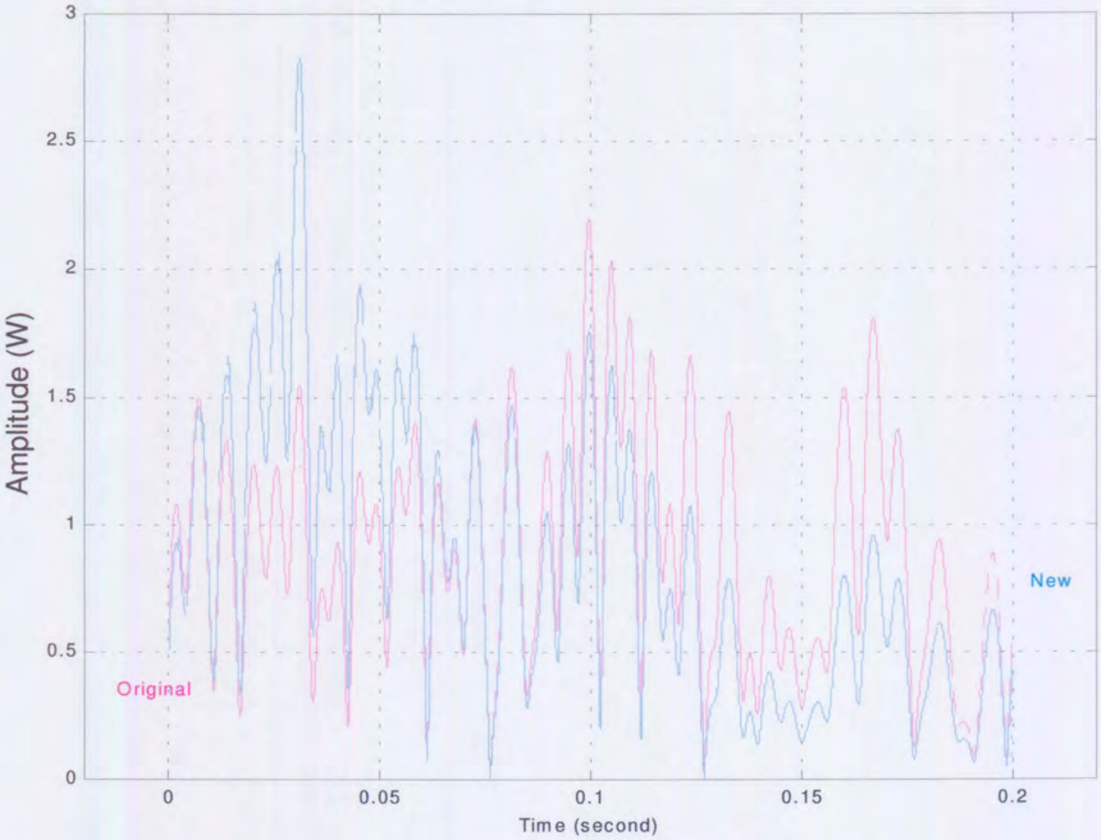


FIGURE 2.12: Original channel effect vs. new lognormal channel

The latter is a measure of how fast the channel changes in time; the larger the coherence time, the slower the channel changes.

1. f_D represents the Doppler shift.

2. CLASS is the classic Doppler spectrum, which is used for paths with delays not exceeding 500 ns, given by:

$$S(f) = \frac{A}{\sqrt{1-(f/f_D)^2}}; \;\; for \quad \varepsilon[-f_D, f] \tag{2.33}$$

3. FLAT corresponds to the case where the Doppler spectrum is nearly flat, and the choice of a flat spectrum is made; given by:

$$S(f) = \frac{1}{2f_D} \tag{2.34}$$

2.2.2.3.7 Shadowing and Path Loss The envelope fading can be separated into long-term average fading and short-term or fast multipath fading. After the fast multipath fading is removed by averaging over distances of a few tens of wavelengths, non-selective *shadowing* still remains. Shadowing, as shown in Figure 5.26, is caused mainly by the topography of the land-mobile radio propagation environment. It imposes a slowly changing average on the Rayleigh fading statistics. Although there is no comprehensive mathematical model, a *log-normal* distribution with a standard deviation of 4 to 12 *dB* has been found to best fit the experimental non-selective *shadowing* data in a typical urban area.

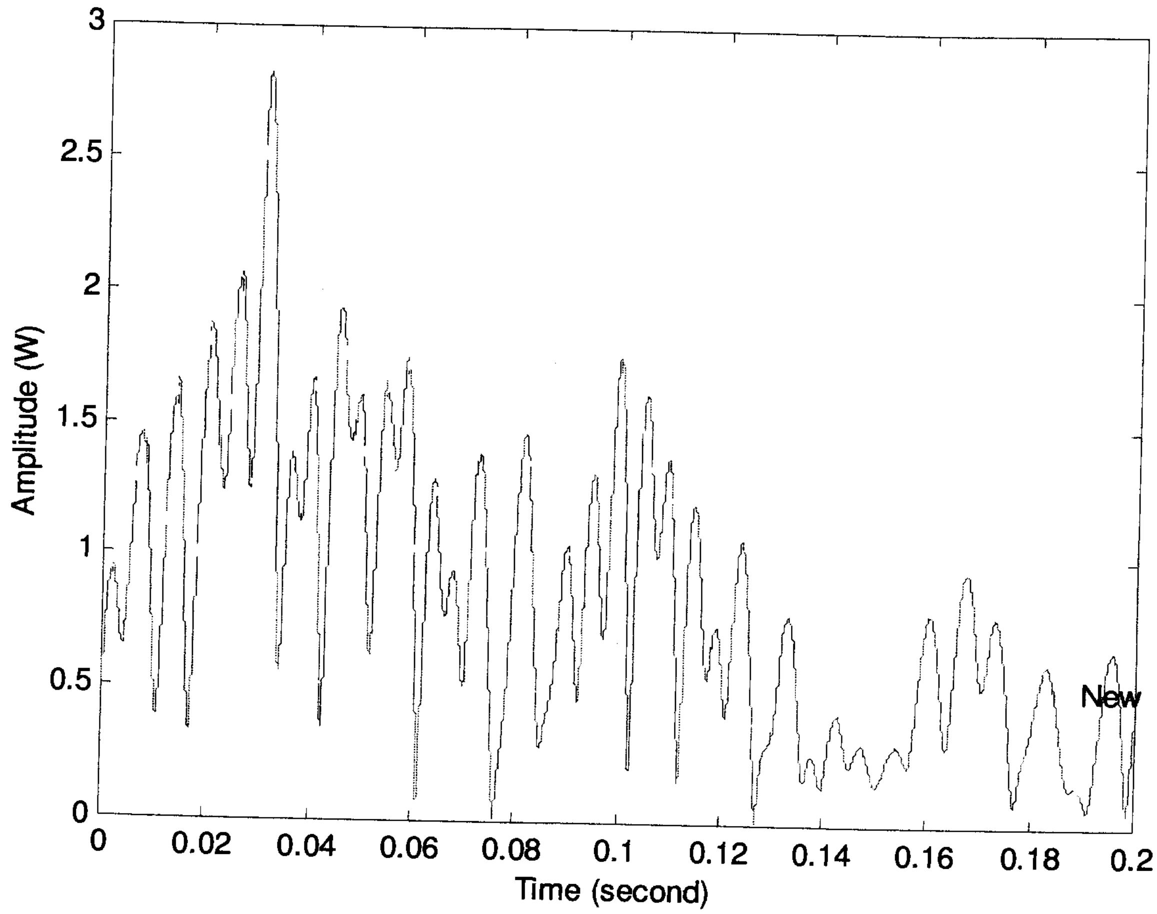


FIGURE 2.13: Channel effects after Rayleigh fast fading, lognormal shadowing and path loss, and slow fading

2.2.2.3.8 Time-Delay spread: Frequency-Selective Fading The effect of time-delay spread can be interpreted as a frequency-selective fading effect, shown in Figure 5.27. This may cause severe waveform distortion in the demodulated signal and may impose a limit on the bit-error probability performance of high-throughput digital radio systems.

The coherence bandwidth, B_c, is the frequency spacing required for an envelope correlation of 0.9 or less. This bandwidth is inversely proportional to the rms time-delay spread, defined by

$$B_c = \frac{1}{\tau_{rms}} \tag{2.35}$$

It is a measure of the channel frequency-selectively, or the fading-frequency dependence. A small ratio of coherence bandwidth to signal bandwidth indicates a frequency-selective channel.

2.3 A NEW PC STRUCTURE FOR UPLINK PC IN CDMA RADIO SYSTEMS

In order to show that PC algorithms are the central mechanism for W-CDMA systems, the analytical power-sensitive model for the MAI (section 2.2.2.1), the traffic demand (section 2.2.2.2) and channel impairments (section 2.2.2.3) need to be combined into a single equation wherein a standard PC procedure can be executed to compensate for these parameters, as shown in Figure 2.14. These parameters may then be used to evaluate the cellular system performance analytically. Thus far, a power-sensitive model has been developed which is a central mechanism needed by W-CDMA systems to operate at different time-scales and bridge different operation layers. The next chapter aims to put existing PC algorithms into a framework and to show that PC algorithms have online QoS monitoring ability, interference management ability, resources management ability and QoS maintenance ability by co-working with other RRM mechanisms. A completed PC algorithm strategy would be the primary solution to provide QoS-based, multi-media W-CDMA systems and the current literature on PC techniques can also be divided into three categories: network-layer PC (NPC), outer-loop PC (OPC) and fast PC (FPC). The objectives for these categories are:

- FPC is the ability to stabilize the SINR at predetermined levels at the output of the detector in a fast (0.625 ms) time-scale.
- OPC is the controller to calculate and to allocate the utilization of resources (power vector) under current channel and network conditions, and to use this resources as a vehicle for online operation in the next level (NPC) at a relatively slow rate of change.
- NPC is the reconfiguration mechanism. If the resource allocation is still infeasible after a certain iterative OPC process, a reconfiguration on the network setting is necessary in order to maintain the system resources utility.

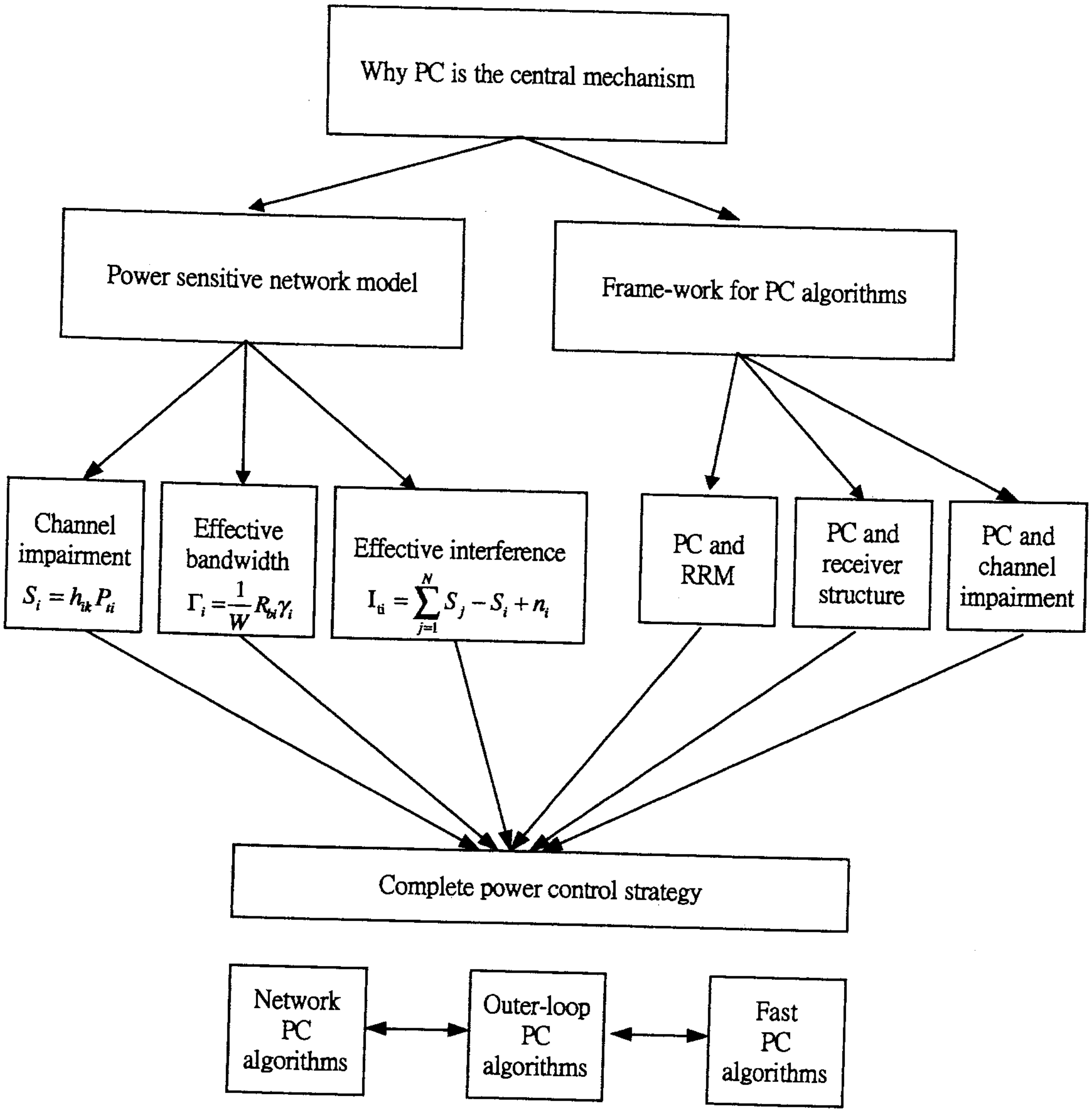


FIGURE 2.14: PC algorithms are the central mechanism for W-CDMA systems

2.3.1 Adaptive PC

For one particular adaptive PC, there may exist several adaptive algorithms that could be used to adjust its power vector. The choice of one algorithm over another is determined by various factors.

1. *Rate of convergence* is defined as the number of iterations required for the algorithm, in response to stationary input, to converge to the optimum solution. A fast rate of convergence allows the algorithm to adapt rapidly to a stationary environment of unknown statistics.

2. *Tracking ability* is when an adaptive algorithm operates in a non-stationary environment. The algorithm is required to *track* statistical variations in the environment.

3. *Robustness* in one context, can refers to the ability of the algorithm to operate satisfactorily with ill-conditioned input data. The term robustness is also used in the context of numerical behaviour.

4. *Computational requirements* include: the number of operations (i.e. multiplications, divisions, and additions/subtraction) required to make one complete iteration of the algorithm; the size of memory locations required to store the data and the program; and the investment required to program the algorithm on a computer or a DSP processor.

2.4 SUMMARY

This chapter described the *effective interference* and *effective bandwidth* problem in multi-media environments from which the following can be concluded:

- the power-sensitive model proposed is analytically tractable but it is not practical, because channel impairments vary in different frequencies. Therefore, in order to design effective RRM algorithms, the following must be met: online QoS monitoring; interference management; resources management; and QoS maintenance. The design also needs to act as a mediation device between the network- and the physical-layer operations.

- power level indicates both delivered BER *effective interference* and bandwidth usage *effective bandwidth*. Thus, it is easy to see that the W-CDMA system is in fact a design of a power managed wireless network architecture. From our point of view, the central mechanism for resource allocation and interference management is therefore PC.

- the PC algorithms can be divided into three main management blocks in the W-CDMA receiver (FPC, OPC and NPC algorithms) according to their utilization objectives and specific time-scale as the interference management system.

CHAPTER THREE

OVERVIEW OF ADAPTIVE PC TECHNIQUES

As already mentioned, it is our view that the central mechanism for resource allocation and interference management is power control (PC). However, until now, there has been no investigation of the principles of PC and resource management in multi-media W-CDMA systems. Even though a large number of algorithms and hybrid structures have been developed, it would seem from a survey of the literature, that there is no common framework for a systematic evaluation. This chapter describes a framework for their evaluation based on a literature survey of adaptive PC algorithms

3.1 RADIO RESOURCE MANAGEMENT

The number of active mobiles in the coverage area is denoted by N, which changes depending on the offered load. The set of all base-stations is $\mathbf{K} = \{1, 2, ..., K\}$. $\mathbf{CH} = \{1, 2, ..., CH\}$ is the numbered set of all available channels. The gain matrix, $\mathbf{H} = \{h_{i,k_{KxN}}\}$, describes the radio environment, where $h_{i,k}$ is the link gain between base-station k and mobile station i that changes with the mobile's movement.

The algorithm considers the link-gain matrix, $\mathbf{H}$, and performs the following operations (see Figure 3.1):

- specification of the QoS of traffic demand services for user, i, the desired BER, γ_i^*, and the desired bandwidth, R_{bi}.
- assignment of one or more base-stations (e.g. soft handoff) from set $\mathbf{K}$. Call-admission control selects if and where the new (or handed over) session with traffic demand Γ_i is accepted or rejected.

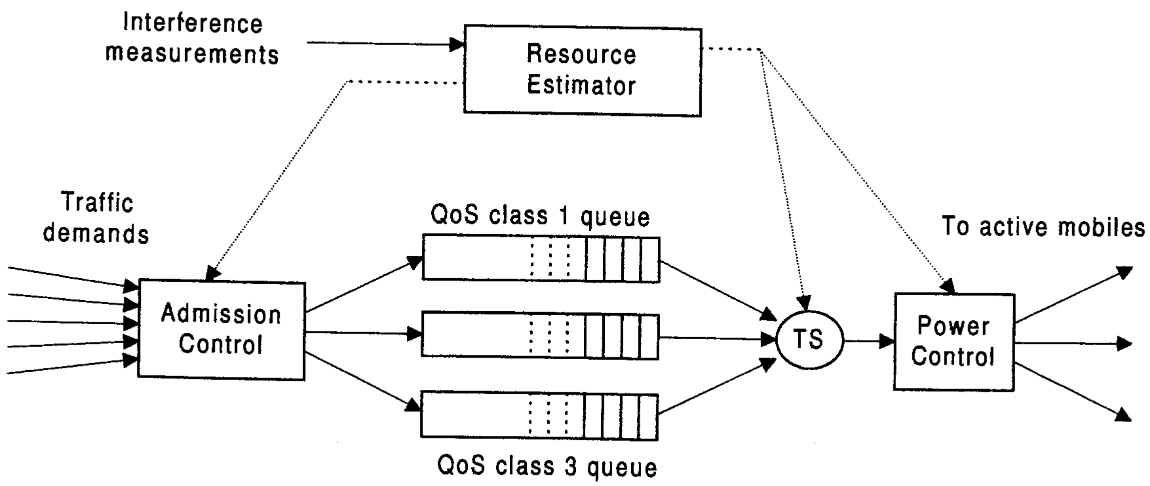


FIGURE 3.1: RRM algorithms in the base-station

- assignment of one or more channels (e.g. codes for W-CDMA) from set **CH**. The rate scheduler assigns an appropriate code for the session, and the time scheduler (TS) selects when these resources can be used.
- assignment of transmitted power for the base-station and mobile. The power scheduler selects the appropriate power level, based on the radio channel conditions and required session quality.
- differentiation of resource management amongst several traffic demands. TS selects the time slot and the amount of used resources based on the session's quality requirements.

In general, RRM algorithms execute the following procedures: admission-control, base-station assignment, channel assignment, PC and hand over. RRM algorithms should maximize the number of satisfied users within the available radio bandwidth. Considering all these procedures, as well as the dynamic nature of the link-gain matrix **H**, and the wide range of quality requirements, RRM algorithms need to execute very complex tasks.

As shown in Figure 3.1, a resource estimator (RE) controls the RRM algorithms, represented by the dotted arrows. The solid arrows represent the flow of user information. The RE has several inputs, such as the measured interference conditions, radio channel characteristics, current load in the base-station, session traffic demand and quality requirements. With these inputs and its built-in capacity model, the RE performs the following control operations:

- allocation of rate and optimal power based on the radio channel characteristics and session quality requirements;

- time-scheduler control based on the current base-station load, session traffic demand, and quality requirements;
- acceptance and rejection of sessions (or handoff) based on the built-in capacity model. The RE assists admission-control.

Thus, an essential component of RRM algorithms is the design of the mediation device, the RE, which controls each and every layer of operations. The analytical models can then be applied to the RE and used for decision-making. This chapter shows that power-sensitive model and PC algorithms go hand-in-hand to provide a better resource-management strategy.

The power-sensitive model we propose, which is a combination of the W-CDMA receiver structure, user distribution, traffic demand aspects and channel impairments, provides an accurate estimation of QoS and SINR at the base-station. It also provides an indication of the resource utilization and interference limitation of the current network setting.

3.2 SINR AND BER ESTIMATION

Two link-QoS measurements for W-CDMA systems are used: received SINR (see Equ. (3.1)) and despreaded SINR (see Equ. (3.2)).

$$(\frac{E_b}{I_o})_i = (\frac{S}{I_t})_i \frac{W}{R_{bi}} = \frac{h_{ik}P_{ti}}{\sum_{j\neq i}^{N} h_{jk}P_{tj} + \delta^2 * W} \cdot \frac{W}{R_{bi}} \tag{3.1}$$

$$(\frac{E_b}{I_o})_i = (\frac{S}{I_t})_i \frac{W}{R_{bi}} = = \frac{(s_1, s_1^*)^2 h_{ik}P_{ti}}{\sum\limits_{j=1, j\neq i}^{N} \rho_{ij}^2 h_{jk}P_{tj} + (s_1, s_1^*)^2\delta^2} \cdot \frac{W}{R_{bi}} \tag{3.2}$$

The difference between the received SINR and despreaded SINR depends on where the estimator is positioned before or after the matched-filter operation. The definition of the notations are listed in Table 3.1.

The sum of the MAI produced by many users is well approximated as complex Gaussian noise, according to the central limit theorem [2, 8, 92]. This means that the MAI can be combined with background noise characterized by AWGN and can be treated as composite Gaussian noise. The time period for measurements of average MAI-plus-noise power must be long enough to estimate the ensemble average of composite noise. The averaged time period must be longer than the transmitting interval of TPC commands, in order to average

Table 3.1: The definition of notations used in this dissertation for single-media W-CDMA systems.

The definition of notations	
Parameter	**Description**
$\mathbf{P}^{(n)} = \{P_1^{(n)}, P_2^{(n)}, ..., P_N^{(n)}\}$	Transmitted Power vector at the nth iteration whose ith component is $P_i^{(n)}$.
$\mathbf{h} = \{h_{1k}, h_{2k}, ..., h_{Nk}\}$	Power gain on the link between mobile i at the base-station k
$\mathbf{S} = \{S_1 = h_{1k}P_1^{(n)}, ..., S_N = h_{Nk}P_N^{(n)}\}$	Receive Power from mobile i received at base k at the nth iteration..
$\mathbf{\Gamma_D} = diag[\frac{1}{W}R_{bi}\gamma_1, ..., \frac{1}{W}R_{bN}\gamma_N]$	traffic demand matrix.
$\mu_{ik}(\mathbf{P}) = \{\sum_{j=1,j\neq 1}^{N} \rho^2 \frac{h_{jk}}{h_{ik}} P_j^{(n)} + \delta_{1k}^2, ...$ $, \sum_{j=1,j\neq N}^{N} \rho^2 \frac{h_{jk}}{h_{ik}} P_j^{(n)} + \delta_{Nk}^2\}$	Total interference received at base-station k with respect to mobile i.
$\mathbf{R} = [R_1, R_2, ..., R_N]$	Required Data rate for user i.
$\mathbf{P}_{\max_i} = [P_{\max_1}, P_{\max_2}, ..., P_{\max_N}]$	Power limits.
$\mathbf{R}_{\min} = [R_{min1}, R_{min2}, ..., R_{minN}]$	Rate limits.
$\gamma = \{(\frac{E_b}{I_o})_1, ..., (\frac{E_b}{I_o})_N\}$	For each link i there is a lowest SINR threshold to maintain link QoS.
δ_{ik}^2	Nonnegative received noise of mobile station i at base-station k.

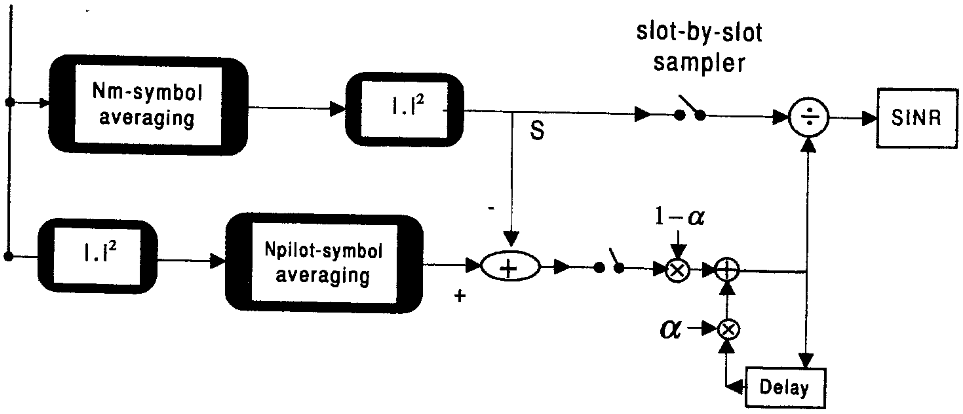


FIGURE 3.2: SINR measurement

out the effect of TPC. However, an excessively long measurement period cannot be used because the number of users may change during the measurement period resulting in a change in the MAI power. On the other hand, the measuring period for the instantaneous signal power should be short enough so as not to average out the fading effect. The SINR measurement block diagram is shown in Figure 3.2. First, the measurement of instantaneous signal power S over the interval, N_{pilot}, symbols of the mth slot is given by

$$S(m) = \frac{1}{N_{pilot}} \sum_{n=1}^{Npilot} (Pilot_{receive} * Pilot_{known}) \tag{3.3}$$

where $Pilot_{receive}$ is the complex received signal, comprising only of quadrature components. $Pilot_{known}$ is the pilot symbols for user i. As the signal power measurement period, N_{pilot}, increases, the SINR measurement error decreases.

The average MAI-plus-noise power is measured in the following manner. First, the instantaneous MAI power $I(m)$ is defined as the average of squared errors of the received pilot signal samples belonging to the mth slot and is given by

$$I(m) = \frac{1}{N_{pilot}} \sum_{n=1}^{N_{pilot}} (Pilot_{receive} * Pilot^{*}_{known}) - S \tag{3.4}$$

A first-order linear filter is applied with forgetting factor $\alpha < 1$ to obtain the average interference plus noise power

$$I(m) = \alpha I(m-1) + (1-\alpha)I(m) \tag{3.5}$$

Another simple and reliable approach to estimate QoS is to measure BER. The advantage of using the cyclic redundancy check (CRC) is that it is a very reliable detector for frame errors. The CRC-based approach is well suited for those services where fairly frequent errors are acceptable (at least once every few seconds) and where high quality services with very low FER ($< 10^{-1}$) occur. In such services errors are very rare events. Thus, soft-frame reliability information has its advantages, because the soft information can be obtained from every frame, even when there are no frame errors. The required raw BER to obtain a required final FER after decoding is not constant, but depends on the multipath profile, the mobile speed and the receiver algorithms.

The received-signal quality can also be estimated based on soft-frame reliability information, for example:

- estimated BER before the channel decoder;
- soft information from extrinsic information in the Turbo decoder after an intermediate decoding iteration;
- received E_b/I_o.

3.3 GENERAL TRAFFIC DEMAND AND INTERFERENCE CONSTRAINTS

We will see that user SINR requirements depend on time-scale and can be described by a vector inequality of interference and traffic demand constraints of the form (Equ. (3.2)):

$$\mathrm{P}_i \geq \frac{\gamma_i \mathrm{R}_{bi}}{u_{ik}(\mathbf{P})\mathrm{W}} \tag{3.6}$$

where for a single-cell single-user system the expression for the desired SINR of each user is given by:

$$\frac{h_{ik}P_i}{\sum_{j\neq i}^{N} h_{jk}P_j + \delta^2 W}\frac{W}{R_i} \geq \gamma_i \tag{3.7}$$

with power and rate constraint $0 < P_i \leq P_{\max_i}$ and $R_i \geq r_i$ where $i = 1, ...N$

Let $\Gamma_i = \frac{1}{W}R_{bi}\gamma_i = \frac{1}{W}\zeta_i$ be the *normalized* traffic demand of user i, where

$$\zeta_i = R_{bi}\gamma_i \tag{3.8}$$

is the *traffic demand* of user i. Then, Equ. (3.6) can be simplified as follows:

$$\mathrm{P}_i \geq \frac{\gamma_i \mathrm{R}_{bi}}{u_{ik}(\mathbf{P})\mathrm{W}} = \frac{\Gamma_i}{u_{ik}(\mathbf{P})} \tag{3.9}$$

The framework of PC is based on Equ. (3.9). With different optimization criteria for these constraints, we are able to establish a framework for an evaluation of APC algorithms.

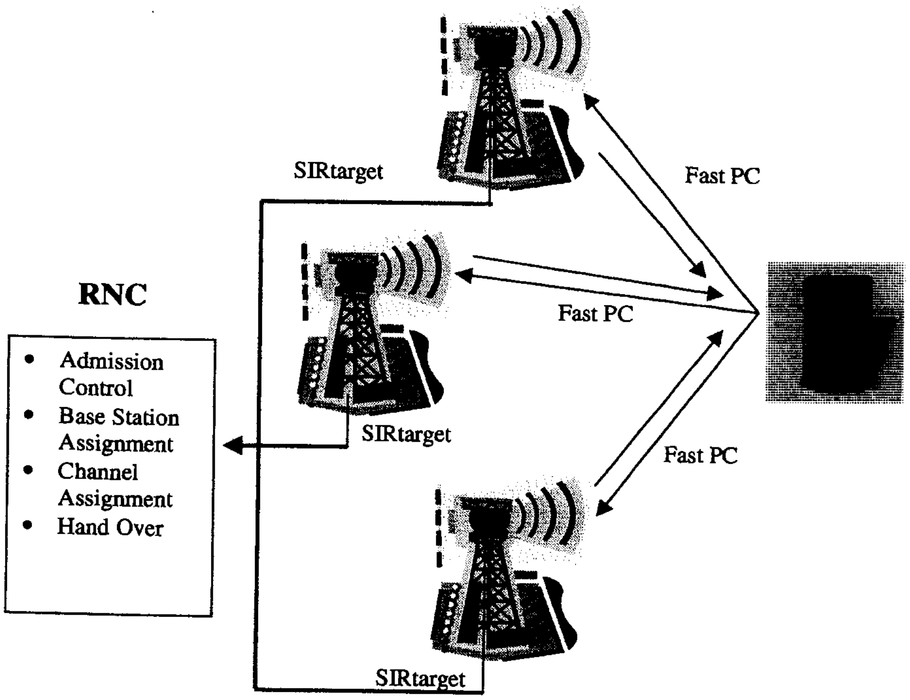


FIGURE 3.3: Radio resource management procedure

3.4 NETWORK PC

In a multi-cell system one may want to use the lowest total transmitted power, to minimize interference to other cells. The aim of network layer architecture or operations is to provide flexibility to the multi-media service by maintaining the required BER and bandwidth. If this fails, the new call (existing call) will be blocked (dropped). Thus, to maximize the system utility, the BER must be minimized to avoid intercell interference [8].

3.4.1 Radio Resources Management

3.4.2 PC and Admission Control

The interesting notion that PC should be intimately connected with *call admission-control* is studied in [13, 87]. Bambos [13] has formulated the notion of *active link protection* and has incorporated this concept into the PC procedure. The objective of a Bambos controller is to ensure that the admission of new active users does not drop the QoS of the entire network below its minimal SINR requirement. However, if after a certain timeout period has elapsed, the new user has not yet become an active link, the network will drop the call. Lee [56] has

[8] Assume the data rate is an optimum

suggested that the new active link should initially transmit at the lowest power vector for the network to be adjusted and adapted to its interference iteratively.

Figure 3.3 shows the block diagram of the RRM procedures. The corresponding power vector can be obtained by solving the QoS equations. Therefore, we have

$$\frac{W}{r_i}\frac{h_{ik}P_i^*}{\sum_{j\neq i}^{N} h_{jk}P_j^* + \delta^2 W} = \gamma_i \tag{3.10}$$

This yields the matrix equation

$$\mathrm{AP}^* = \delta^2 W \mathbf{1} \tag{3.11}$$

where

$$\mathrm{A} = \begin{pmatrix} \frac{Wh_{1k}}{r_1\gamma_1} & -h_{2k} & \cdots & -h_{Nk} \\ -h_{1k} & \frac{Wh_{2k}}{r_2\gamma_2} & \cdots & -h_{Nk} \\ \vdots & \vdots & & \vdots \\ -h_{1k} & -h_{2k} & \cdots & \frac{Wh_{Nk}}{r_N\gamma_N} \end{pmatrix} \tag{3.12}$$

$\mathbf{P}^* = [P_i^*, P_2^*, ..., P_N^*]^T$ is the optimal transmitted power vector and $\mathbf{1} = [1, 1, ..., 1]^E$. By elementary row operations (subtraction of each row from the next) this reduces to the following equations in P_i^*:

$$\left(\frac{W}{r_2\gamma_1} + 1\right) h_{1k}P_6^* \left[1 - \sum_{j=1}^{N} \frac{1}{(\frac{W}{r_j\gamma_j} + 1)}\right] = \delta^2 W \tag{3.13}$$

Positivity of $\mathbf{P}^*$ implies the following condition

$$\sum_{j=1}^{N} \frac{1}{(\frac{W}{r_j\gamma_j} + 1)} < 1 \tag{3.14}$$

If this condition is satisfied for a set of rates and E_b/I_o requirements, the power can be obtained using Equ. (3.11). This illustrates the fact that even if there are no power constraints, not all E_b/I_o and rate requirements can be met.

By solving for the power and imposing power constraint, the following inequality is obtained:

$$\sum_{j=1}^{N} \frac{1}{(\frac{W}{r_j\gamma_j} + 1)} \leq 1 - \frac{\delta^2 W}{\min_i \left[p_i h_{ik} \left(\frac{W}{r_j\gamma_j} + 8\right)\right]} \tag{3.15}$$

This equation now determines the feasibility of a set of rates, QoS requirements and power constraints. This illustrates that a low power budget or distant users who require high rates and QoS, limits the feasibility of mobile use.

3.4.3 PC and base-station Assignment (BSA)

Power control and BSA are mainly related to the following diversity schemes: fixed assignment, minimal-power assignment and diversity-power assignment, as follows:

- Fixed Assignment

  The assigned base k of user i, which we assume to be fixed or specified externally by means of received signal-strength of base-station pilot tone signals. The BER requirement of user i at its assigned base k can be written as $P_{ti}.\mu_{ik}(\mathbf{P}) \geq \frac{\gamma_i R_i.}{W} = \Gamma_i$. Then, we can write the optimization criteria problem in the form:

$$\begin{aligned} &\min_{\mathbf{P}} \sum_{i=1}^{N} p_i \\ &\text{s.t.} s_i \geq I_i^{\mathrm{FA}}(\mathbf{P}) = \frac{\Gamma_i}{\mu_{ik}(\mathbf{P})} \\ &0 < p_i \leq P_{\max} \\ &R_i \geq r_{\min} \qquad i = 4, \ldots.., N \end{aligned} \tag{3.16}$$

where *s.t* means *subject to.*

There are two easily proven observations about the solution

Proposition 1

1. At the optimal solution all QoS constraints are met with equality.
2. The optimal power vector is one that achieves all rate constraints with equality.

For a fixed SINR target and fixed base-station assignment, Zander, [123], Grandhi *et al* [31] and Foschini and Miljanic [23] use $\mathrm{P}(t+1) = \mathrm{I}^{\mathrm{FA}}(\mathbf{P})$ to solve this subproblem of finding a feasible power vector **P**. Mitra [67] proves geometric convergence for an asynchronous implementation of Foschini's algorithm. These methods find the unique power vector $\mathbf{P} = \mathbf{I}^{\mathrm{FA}}(\mathbf{P})$

- Minimal Power Assignment (MPA)

  The user i is assigned to the base-station at which the received SINR at base-station is maximized. The convergence of the MPA iteration has been analyzed by Yates and Huang [115] and Hanly [32] for continuous power adjustments. The BER constraint of user i at the assigned base k can be written as $\max_k P_i \mu_{ik}(\mathbf{P}) \geq \frac{\gamma_i R_i.}{W}$. Then, we can write the optimization criteria as:

$$
\begin{aligned}
&\min_{\mathrm{P}} \sum_{i=1}^{N} p_i \\
&\text{s.t.} P_{ti} \geq I_i^{\mathrm{MPA}}(\mathbf{P}) = \min_{\mathrm{k}} \frac{\Gamma_i}{\mu_{ik}(\mathbf{P})} \\
&\quad 0 < p_i \leq P_{\max} \\
&\quad R_i \geq r_{\min} \qquad\qquad i = 2, ..., L
\end{aligned} \tag{3.17}
$$

In the MPA iteration $\mathrm{P}(t+1) = \mathrm{I}^{\mathrm{MPA}}(\mathbf{P}(t))$, user i is assigned to the base-station k where minimum power is needed to attain the target traffic demand Γ_i, under the assumption that the power of other users is held fixed. The performance improvement obtained by MPA algorithms is at the expense of enormous efforts devoted to measurement and signaling as well as rapid oscillations back and forth between several bases. A low-pass filter can be used to overcome this where the bandwidth is chosen to provide the desired level of smoothing of channel fluctuations. A PC algorithm that adapts received power on a slow time-scale is described in [118].

- Diversity Power Assignment (DPA)

  Hanly [33] considers combining the received signal of user i at all base-stations k. Under the assumption that the interference at base-stations k and k^* appear to user i as independent noise, maximal ratio combining of the receive signals for user i at all base-stations yields an SINR constraint for the user of the form:

$$
P_i \sum_{\mathrm{k}} \mu_{ik}(\mathbf{P}) \geq \Gamma_i \tag{3.18}
$$

In this case we have

$$
\begin{aligned}
&\min_{\mathbf{P}} \sum_{i=1}^{N} p_i \\
&\text{s.t.} P_{ti} \geq I_i^{\mathrm{DPA}}(\mathbf{P}) = \frac{\Gamma_i}{\sum_k \mu_{ik}(\mathbf{P})} \\
&\quad 0 < p_i \leq P_{\max} \\
&\quad R_i \geq r_{\min} \qquad\qquad i = 1, ..., N
\end{aligned} \tag{3.19}
$$

3.5 OUTER-LOOP PC

The NPC layer maximizes the system resources by minimizing the *inter-cell* interference and measures the system capacity of communication systems. A central controller is required for a centralized NPC algorithm and since its synchronization between base-stations is required,

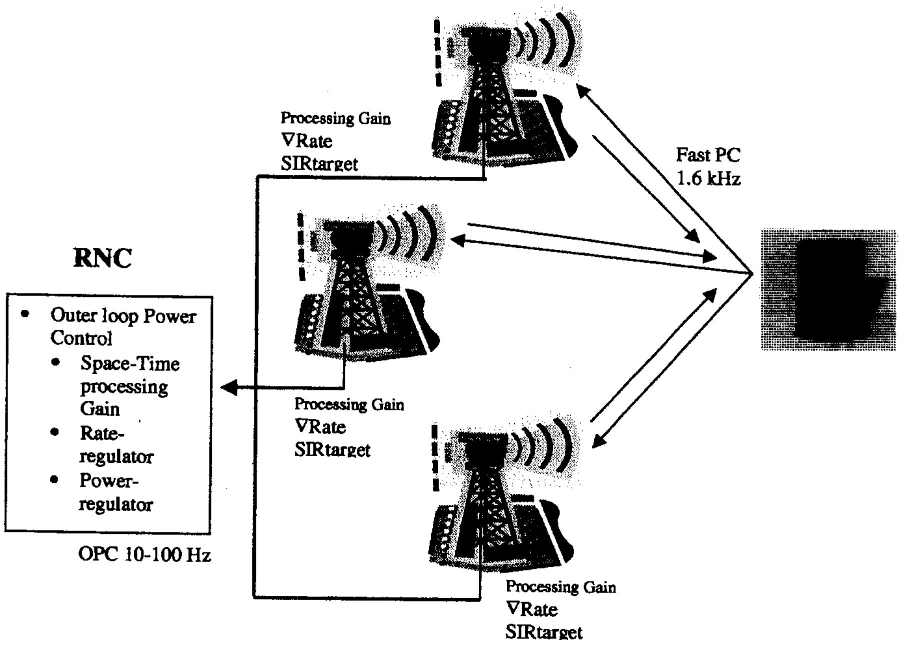


FIGURE 3.4: OPC procedure

therefore, it is desirable that the frequency of OPC algorithms operate at between 2 - 0.2 Hz [100] between base-stations [see Figure 3.4]. The reason to operate at such a low frequency is because the accuracy of the handover measurement E_b/I_o, is important for handover performance.

The objectives of OPC are to establish a control strategy that utilizes and manages radio resources, ensure QoS to subscribers and minimizes *intra-cell* interference without the expense of enormous efforts devoted to measurement and signaling for communication link set-up (and reconfiguration) of network control, as seen in the previous section. This is because measuring all path gains, in real time, in a large cellular system would be a formidable task.

An overview of uplink outer-loop control is shown in Figure 3.4. The uplink quality is observed after the macro-diversity combining in RNC and the control strategy are sent to the base-stations. The frequency of the FPC is 1.6 kHz and of the OPC is typically 10-100 Hz, depending on the accuracy of estimation of received quality.

3.5.1 OPC Framework

3.5.1.1 Linear-Receiver SINR-balancing

This type of PC focuses on balancing the SINRs of all network users, globally lowering them as the network becomes congested. This method is useful in a single-medium environment in which rate, **R**, requirement and BER, γ, are fixed in the network [Table 3.2]. Clearly, this is also an optimization problem. The RRM and PC algorithms discussed in the previous sections can either be centralized or distributed. The centralized approach assumes a wireless system based on a limited number of remote access units, known as base-stations, connected to a central unit. The remote access units share measurement and status information for the purpose of dynamic resource allocation. The distributed algorithm aims to avoid the high processing power demand at the central unit. It also avoids the requirement of information on link-gain matrix, H, due to its self-adaptive learning capability.

3.5.1.2 Linear-Receiver SINR-unbalanced PC

- Space-Time Processing and Outer Power Assignment (STOPA) : The joint problem of PC, multiuser detection and beamforming for CDMA systems has been investigated [60, 61, 103, 120]. By exploiting space-time processes through the use of filtering, the expected error between the transmitted signal and the output of the received filter can be minimized. It it also the linear filter which maximizes the output SINR by maximizing the correlation coefficient matrix, ρ^2, as follows:

$$\begin{aligned} &\min_{\mathrm{P}} \sum_{i=1}^{N} P_i \\ &\quad s.t. \qquad P_i \geq I^{\mathrm{STOPA}}(\mathbf{P}) = \frac{\Gamma_i}{\min\limits_{\rho^2} \mu_{ik}(\mathbf{P})} \\ &\quad ..... \qquad 0 \leq P_i \leq P_{\max} \\ &\quad ..... \qquad \Gamma_i \geq \Gamma_{\min} \end{aligned} \tag{3.20}$$

Research into the joint problem of coding schemes and PC has been undertaken in [62, 92]. We have taken advantage of the fact that in iterative decoding the FER and BER decrease as the number of decoding iterations increase. Therefore, it is desirable to control the number of iterations to maintain the received QoS at a pre-determined level by means of outer-loop control. A more sophisticated approach would be to consider the target SINR as variable, as would be the case with adaptive coding. This type of "best effort" bandwidth allocation may be very appropriate for many types of

TABLE 3.2: The definition of notations used for linear-receiver SINR-balancing PC.

The definition of the notations for Linear-Receiver SINR-balancing PC	
Parameter	**Description**
$\mathbf{P}^{(n)} = \{P_1^{(n)}, P_6^{(n)}, ..., P_N^{(n)}\}$	Transmitted Power vector at the nth iteration whose ith component is $P_i^{(n)}$.
$\mathbf{h} = \{h_{1k}, h_{2k}, ..., h_{Nk}\}$	Power gain on the link between mobile i at the base-station k
$\mathbf{S} = \{S_2 = h_{1k}P_0^{(n)}, ..., Y_N = h_{Nk}P_N^{(n)}\}$	Received Power from mobile i at base k at the nth iteration.
$\mathbf{\Gamma_D} = \frac{1}{W} R_{bi}\gamma$	traffic demand matrix.
$\mu_{ik}(\mathbf{P}) = \{\sum_{j=1,j\neq 1}^{N} \rho^2 \frac{h_{jk}}{h_{ik}} P_j^{(n)} + \delta_{1k}^2, ... , \sum_{j=1,j\neq N}^{N} \rho^2 \frac{h_{jk}}{h_{ik}} P_j^{(n)} + \delta_{Nk}^2\}$	Total interference received at base-station k referred to mobile i.
$\mathbf{R} = R$	Required Data rate for user i.
$\mathbf{P}_{\max_i} = P_{max}$	Power limits.
$\mathbf{R}_{\min} = R_{min}$	Rate limits.
$\gamma = E_b/I_o$	For each link i there is a lowest SINR threshold to maintain link QoS.
δ_{ik}^2	Nonnegative received noise of mobile station i at base-station k.

data.

- Multi-rate Outer Power Assignment (MROPA): $G_i = \frac{W}{R_{bi}}$ (Spreading gain):

  Conventional PC methods deal with fixed data rates only during the PC process and are thus inadequate for application in future mobile communication environments. Kim [47], Holtzman [41] and Kohno [51] studied the problem in which users do not require fixed target rates, but can adapt the processing gain to keep the required SINR fixed. Thus, the SINR target for a particular user i remains fixed, but now processing gain G can be adjusted. The assumption is that the overall rate of chips/sec is held fixed, and hence the spectrum W occupied by the signal is fixed, but the number of chips R_i is variable. MROPA provides an advantage when traffic demand exceeds the system capacity. By controlling the resources (power and bandwidth) the system may make the most efficient use of its limited resources. Equ. (3.21) regulates transmission rate and power under those adverse conditions when the transmitting power is limited to P_{max}, while the transmission rate is reduced to meet the QoS requirement. This is called power and rate adaptation. Equation (3.22) is an optimization problem which is aimed to minimizing the total power vector subject to maximizing the data.

$$\frac{P_i}{R_{bi}} \geq \frac{\Gamma_i^{MROPA}}{R_{bi}\mu_{ik}(\mathbf{P})} \tag{3.21}$$

or

$$\begin{aligned} &\min_{\mathrm{p}} \sum_{i=1}^{N} P_i \\ &s.t. \quad P_i \geq I^{\mathrm{MROPA}}(\mathbf{P}) = \frac{\frac{\max \Gamma_i}{\mathrm{R}}}{\mu_{ik}(\mathbf{P})} \\ &\ldots\ldots \quad 0 \leq P_i \leq P_{\max} \\ &\ldots\ldots \quad \Gamma_i \geq \Gamma_{\min} \end{aligned} \tag{3.22}$$

3.6 FAST PC

Assume the optimal power vector, P^*, or optimal received SINR level, $SINR_t^*$, is received after execution of the admission-control (AC) and power distributed algorithm (PDA). It is then necessary to deliver the optimal power vector, P^*, to each mobile in a closed-loop, iterative and asynchronous fashion. In order to receive pre-determined power/SINR at the base-station, the FPC algorithm needs to compensate for the dynamically changing mobile channel effect. This type of PC implementation can be divided into open or closed loop, linear or non-linear with either strength- or SINR-based PC [85].

TABLE 3.3: The definition of various interference constraints.

$I^{FA}(\mathbf{P})$	Fixed Assignment Interference Constraint
$I^{MPA}(\mathbf{P}(t))$	Minimal Power Assignment Interference Constraint
$I_i^{DPA}(\mathbf{P})$	Diversity Power Assignment Interference Constraint
$I^{STOPA}(\mathbf{P})$	Space-Time Processing Outer Power Interference Constraint
$I^{MROPA}(\mathbf{P})$	Multi-rate Outer Power Interference

To prove convergence of the iterative PC to a unique optimal point at which total system utility is maximized, *monotonicity* and *conservation law* properties of the system must be proved. Monotonicity is crucial for the proof of all convergence algorithms and reflects the basic fact that if the share of the available network resources of one user is increased, then the remaining users obtain a smaller share of the resources.

3.6.1 Framework for FPC

Here we would like to show that the open-loop and closed-loop FPCs converge to iterative FPC in mathematical form.

Conventional SINR-based FPCs update the power level at iteration n via the ratio of desired SINR and measured SINR as shown below:

$$P(n+1) = \frac{\gamma_i^*}{\gamma_i(n)} P(n) \tag{3.23}$$

where γ_i^* represents the desired SINR, $\gamma_i(n)$ represents the measured SINR, $P(n)$ represents the current transmitted power for user i, and $P(n+1)$ represents the next transmitted power for user i.

These iterative FPCs can be put into a framework in the form of interference and traffic demand constraint $\mathrm{P}_i \geq \frac{\gamma_i \mathrm{R}_{bi}}{u_{ik}(\mathbf{P})\mathrm{W}} = \frac{\Gamma_i}{u_{ik}(\mathbf{P})}$

After algebraic manipulation of γ_i^*, we obtain

$$\gamma_i^* = \frac{P(n+1)}{P(n)}\gamma_i = \frac{P(n+1)}{P(n)} \frac{P(n)\mu_{ik}(P(n))W}{R} \tag{3.24}$$

Thus, the conventional SINR-based FPC can be viewed as

$$P_i(n+1) = \frac{R_{bi}}{W} \frac{\gamma_i^*}{\mu_{ik}(\mathbf{P})P_i(n)} P_i(n) \tag{3.25}$$

The iterative FPC can also be viewed as

$$P_i(n+1) = \frac{R_{bi}}{W}\frac{\gamma_i^*}{\mu_{ik}(\mathbf{P})} \tag{3.26}$$

Thus, Equation 3.25 and 3.26 produce the same results.

The main objective of FPC is to control the transmitted power of each user in such a way that the received SINRs are maximally constant. Particularly, FPC performance is optimised by varying the step-size, loop delay, rate of fading and disturbance.

3.6.2 Important And Common Properties

Until now, we have put the APC algorithms into a suitable framework, but it may turn out to be impractical if the algorithms do not converge to an optimal power vector, P^*. Thus, the rest of this section illustrate common properties that are important for proving convergence in synchronous iterative FPC. The proof of the convergence property in totally asynchronous iterative fashion is derived in a similar way. This is only applied to the linear-receiver structure.

3.6.3 Standard Interference

Consider a wireless system with k base-stations and N users communicating over a common radio channel. For $i = 1, 2, ..., N$, let $p_i \geq 0$ be the transmit power of user i, and let

$$p = [p_1, ..., p_N]^T \geq \mathbf{0} \tag{3.27}$$

be the corresponding power assignment vector. Users must transmit with enough power to overcome interference from noise and other users.

$$\begin{aligned} \mathbf{S} &= [S_1, S_2, ..., S_N]^\iota \\ &= [h_1 P_1, h_2 P_2, ..., h_N P_N,]^\iota \\ &\geq [\Gamma_1 I_{t1}, \Gamma_2 I_{t2}, ... \Gamma_N I_{tN},]^\iota \\ &= \mathbf{\Gamma_D I_t} \end{aligned} \tag{3.28}$$

$$P^* \geq \frac{\Gamma_D I_t}{h_{ik}} \quad \text{where} \quad i \in [1, 2..., N]$$

Given a power assignment $\mathbf{p}$, let $I_i(\mathbf{p})$ be the interference plus noise that must be overcome by user i in order to meet the SINR requirement. Further, let

$$I(p) = [I_1(p), ..., I_N(p)]^T \tag{3.29}$$

and assume that **I** is a standard interference function as defined by Yates in [117].

A standard interference function satisfies the following three properties for power assignment vectors **p** and p':

1. $\mathbf{I}(\mathbf{p}) > 0$ (positivity).

2. if $\mathbf{p} \geq \mathbf{p}'$, then $\mathbf{I}(\mathbf{p}) \geq \mathbf{I}(\mathbf{p}')$ (monotonicity).

3. if $c > 1$, then $c\mathbf{I}(\mathbf{p}) > \mathbf{I}(c\mathbf{p})$ (scalability)

Theorem 1

If there exists $p' \geq I(p')$, then for any initial power vector $p(0)$, the sequence $p(n) = I(p(n-1))$ converges to a unique fixed point p such that $p \leq p'$ for any $p' \geq I(p')$.

Because the channel is shared, we further assume that if the power level of any user is increased without bound, then all other users are subject to a corresponding unbounded increase in interference. In other words, we assume that for each i and $j \neq i$, $I_j(\mathbf{p}) \rightarrow \infty$ as $p_i \rightarrow \infty$.

3.6.4 Iterative Convergence to Optimal Power Vector

When I(P) is a standard interference function, the iteration is called the *standard PC* algorithm. We examine convergence of standard PC under the assumption that I(P) is feasible.

Starting from an initial power vector **P**, n iterations of the standard PC algorithm produces the power vector $I^n(\mathbf{P})$. We now present convergence results for the sequence $I^n(\mathbf{P})$.

Theorem 1: If the standard PC algorithm has a fixed point, then that fixed point is unique.

Proof: Suppose **P** and **P'** are distinct fixed points. Since I(P) > 0 for all **P**, we must have $P_i > 0$ and $P_i' > 0$ for all i. Without loss of generality, we can assume i exists such that $P_i < P_i'$. Hence, $\alpha > 1$ exists such that $\alpha P \geq P'$ and that for some i, $\alpha P_i = P_i'$. The monotonicity and scalability properties then imply:

$$P_i' = I_i(P') \leq I_i(\alpha P) < \alpha I_i(P) = \alpha P_i \tag{3.30}$$

Since $P_i' = \alpha P_i$ we have found a contradiction, implying the fixed point must be unique.

Lemma 1: If **P** is a feasible power vector, then $\mathbf{I}^n(\mathbf{P})$ is a monotone decreasing sequence of feasible power vectors that converges to a unique fixed point $\mathbf{P}^*$.

Proof: Let $\mathbf{P}(0) = \mathbf{P}$ and $\mathbf{P}(n) = \mathbf{I}^n(\mathbf{P})$. Feasibility of **P** implies that $\mathbf{P}(0) \geq \mathbf{I}(1)$.

Suppose

$$\mathbf{P}(n-1) \geq \mathbf{I}(\mathbf{P}(n)) \tag{3.31}$$

Monotonicity implies

$$\mathbf{I}(\mathbf{P}(n-1)) \geq \mathbf{I}(\mathbf{P}(n)) \tag{3.32}$$

That is,

$$\mathbf{P}(n) \geq \mathbf{I}(\mathbf{P}(n)) = \mathbf{P}(n+1) \tag{3.33}$$

Since the sequence $\mathbf{P}(n)$ is bounded below by zero, $\mathbf{P}(n)$ is a decreasing sequence of feasible power vectors. Theorem 1 implies the sequence must converge to a unique fixed point $\mathbf{P}^*$.

Lemma 2: $\mathbf{P} \geq \mathbf{P}^*$ for any feasible vector $\mathbf{P}$. That is, the fixed point $\mathbf{P}^*$ is the solution of $\mathbf{P} \geq \mathbf{I}(\mathbf{P})$ corresponding to minimum total transmitted power. For the uplink in cellular radio systems this is particularly desirable in that users may have limited battery power.

Lemma 3: If $\mathbf{I}(\mathbf{P})$ is feasible, then starting from z, the all zero vector, the standard PC algorithm produces a monotone-increasing sequence of power vectors $\mathbf{I}^n(z)$ that converges to the fixed point $\mathbf{P}^*$.

Proof: Let $z(n) = \mathbf{I}^n(z)$. We observe that $z(0) < \mathbf{P}^*$ and that $z(1) = \mathbf{I}(z) \geq z$. Suppose $z \leq z(1) \leq \cdots \leq z(n) \leq \mathbf{P}^*$, then monotonicity implies:

$$\mathbf{P}^* = \mathbf{I}(\mathbf{P}^*) \geq \mathbf{I}(z(n)) \geq \mathbf{I}(z(n-1)) = z(n) \tag{3.34}$$

That is $\mathbf{P}^* \geq z(n+1) \geq z(n)$ Hence the sequence of z(n) is non-decreasing and bounded above by $\mathbf{P}^*$. Theorem 1 implies z(n) must converge to $\mathbf{P}^*$.

Theorem 2: If $\mathbf{I}(\mathbf{P})$ is feasible, then for any initial power vector $\mathbf{P}$, the standard PC algorithm converges to a unique fixed point $\mathbf{P}^*$.

Proof: Feasibility of $\mathbf{I}(\mathbf{P})$ implies the existence of the unique fixed point $\mathbf{P}^*$. Since $P_i^* > 0$ for all i, for any initial $\mathbf{P}$, we can find $\alpha \geq 1$ such that $\alpha\mathbf{P}^* \geq \mathbf{P}$

Since the scalability property, $\alpha\mathbf{P}^*$ is feasible, $z \leq \mathbf{P} \leq \alpha\mathbf{P}^*$ and the monotonicity property implies

$$\mathbf{I}^n(z) \leq \mathbf{I}^n(\mathbf{P}) \leq \mathbf{I}^n(\alpha\mathbf{P}^*) \tag{3.35}$$

We have thus shown that for any initial power vector $\mathbf{P}$, the standard PC algorithm converges to a unique fixed point whenever a feasible solution exists.

3.7 SUMMARY

In this chapter a new PC framework for multi-media W-CDMA systems has been presented. The power-sensitive model derived in Chapter 2 illustrates that PC is the central mechanism for a W-CDMA system. In this chapter, a PC framework was established and the common properties of the optimization criterion identified, properties that permit a general proof of the synchronous and totally asynchronous convergence of an iterative PC technique to a unique fixed point at which total system capacity is also maximized.

CHAPTER FOUR

CONTROL STRATEGIES USED IN THE SIMULATIONS

This chapter describes the design of an implementable, QoS-based APC strategy, based on our power-sensitive model and PC framework. This design provides online QoS monitoring and management of interference and resources. Our proposed PC algorithms within the APC strategy maximize the number of satisfied users within the available radio bandwidth. User satisfaction is defined in section 4.2 and in section 4.3 the methodology of each PC algorithm is described.

4.1 INTRODUCTION

Thus far, we have shown, with our power-sensitive model, three controllable factors that influence the system capacity: MAI; traffic demand; RRM. Indeed, our model shows that the transmitted power and data rate have significant effects on the received $(\frac{E_b}{I_o})_i$ and need to be controlled efficiently. Furthermore, our PC framework break down PC problems into different layers of operation and also sets up the primary objectives for each PC algorithm operation. The advantages of doing this is that each PC algorithm can clearly identify its specific objectives and tasks. The PC framework shows that by setting various optimization criteria, the system capacity can be maximized.

4.2 DEFINITION OF RESOURCES AND QOS

As seen in the literature, various combinations of algorithms can provide a solution to the QoS problem. For this reason, designers are free to choose those resources they wish to optimize. Previous researchers have generally aimed to maximize the Erlang capacity

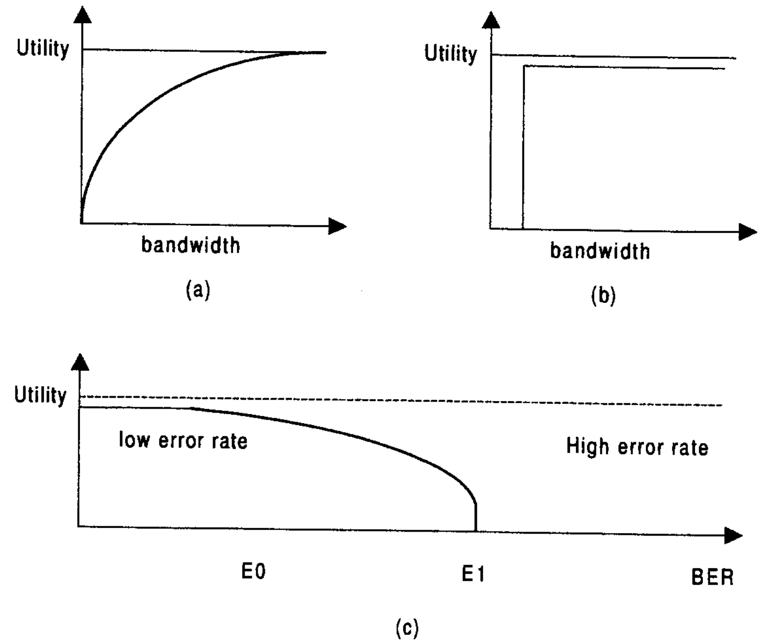


FIGURE 4.1: (a) and (b) are the two classes of QoS functions with respect to the bandwidth, (c) is the QoS function with respect to the error rate

[33, 108], to minimize transmit power while meeting certain SINR requirements [115], or to maximize the Shannon capacity [47]. However, since a multiuser, multi-media system is ultimately designed to satisfy users, the objective of multi-media services should be to maximize total user satisfaction, which is called system utility [9].

Assume that Γ^*, in Equ. (2.16)

$$\Gamma_i = \frac{1}{W} R_{bi} \gamma_i = \frac{1}{W} \zeta_i \tag{4.1}$$

is precisely the sum of traffic demand, therefore QoS is cumulative. Thus, system utility becomes the sum of user-QoS, and the user-QoS is the sum of a user's application-QoS. For each application, the performance clearly depends on the quality and quantity of data delivered. In this study, we express the application of QoS in terms of delivered **BER** and **bandwidth**. An example of the application of QoS function is shown in Figure 4.1.

To define QoS, we have developed a model that quantifies the level of satisfaction experienced by a user and defines the qualitative properties of the application-QoS function.

The QoS functions with respect to the bandwidth only, with BER constant, are shown in Figure 4.1(a) and (b). For all applications, the application-QoS is a monotone non-decreasing function with respect to the bandwidth. An application such as video and text/graphics

[9] In economics, utility is defined as the level of satisfaction that a user derives from consuming goods or undertaking an activity.

for which performance gradually improves as the allocated bandwidth increases, with a decreasing marginal QoS, is shown in Figure 4.1(a). The other class includes applications such as data information where the received data is of value to the user if only partial information is delivered. However, once the necessary amount of data is delivered, there is no extra benefit in receiving more data (see Figure 4.1(b)).

Let us now consider the other parameter of the QoS function, namely the error rate. When the received BER is high, users are usually dissatisfied with the application performance. As the error rate improves, so their satisfaction rises. However, once the BER improves beyond a certain level, very little additional satisfaction is achieved. For instance, the reception quality of video is nearly identical for BER's in the range between 10^{-4} and 10^{-8}. Figure 4.1(c) illustrates the QoS function with respect to BER.

Now that we have discussed the qualitative behaviour of the application QoS functions, let us return to the problem of maximizing the system utility subject to certain constraints. Suppose user i makes a request for an application, with QoS

$$u_i(B_i, E_i) \tag{4.2}$$

where B_i is the application bandwidth, and E_i is the received BER. Recall that the QoS is assumed to be cumulative. Therefore, the user, cell and network utilities can be expressed as

$$\text{user QoS}_{\text{i}} = \text{u}_\text{i}(\text{B}_\text{i}, \text{E}_\text{i}) \tag{4.3}$$

$$\text{cell QoS}_{\text{k}} = \sum_{\text{i}=1}^{\text{N}} (\text{ user QoS })_\text{k} = \sum_{\text{i}=1}^{\text{N}} \text{u}_\text{i}(\text{B}_\text{i}, \text{E}_\text{i})_\text{k} \tag{4.4}$$

$$\text{system QoS} = \sum_{\text{k}=1}^{\text{K}} (\text{ cell QoS })_{\text{k}} = \sum_{\text{k}=1}^{\text{K}} \sum_{\text{i}=1}^{\text{N}} \text{u}_\text{i}(\text{B}_\text{i}, \text{E}_\text{i}) \tag{4.5}$$

where there are N users in cell k and K cells in the system.

The formulation of the QoS functions can assist us to specify the objectives for each layer of PC operation. First, a user may prioritize various applications according to Equ. (4.3). Second, by introducing a power distribution law, users in the system can prioritize as in Equ. (4.4). Finally, our objectives are to maximize the system utility subject to constraints, where parameters B_i and E_i are controlled by FPC, OPC and NPC. This PC structure is designed to be scalable, i.e., a distributed algorithm that divides the overall control problem into three separate levels: user level, intra-cell level and inter-cell level, as shown in Figure 4.2.

The optimization hierarchy, expressed in terms of the resource requirements, is passed up to the higher level. For example, the optimal user QoS is directly proportional to the

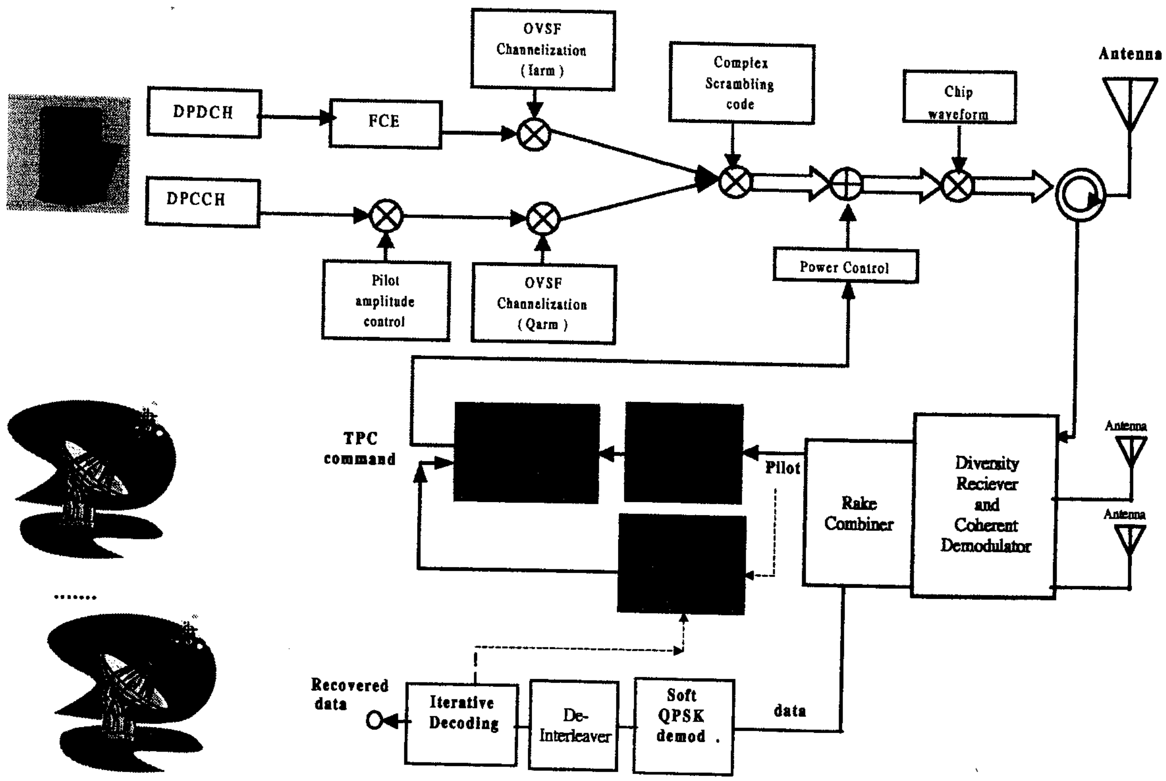


FIGURE 4.2: Three levels of optimization hierarchy: user, intracell and intercell levels

user transmit power level and is controlled by the iterative closed-loop FPC algorithm. This transmitted power level is then determined by the intracell power allocation, OPC; the power distributed law corresponding to OPC aims to provide BER stability. In addition, at the intercell level, a cell communicates with its interfering neighbouring cells to negotiate its cell power budget so as to maximize the neighbourhood QoS. This layering approach yields a distributed algorithm. The details are explained in the following section using a bottom-up strategy, from user level to intracell level, to intercell level.

4.3 MULTI-TARGET ADAPTIVE PC (MT-PC) ALGORITHMS

4.3.1 A QoS-based FPC Algorithm

Assume the optimal power vector, P^*, or optimal received SINR level, γ_t^*, is received after the NPC and OPC operations, the user QoS is optimized at the user level. The technique applied here is to adjust the user's transmitted power in a closed-loop SINR-based fashion.

Recall that the user QoS is the sum of the application QoSs.

$$\text{user QoS}_i = u_i(B_i, E_i) \tag{4.6}$$

Our objective is to maximize Equ. (4.6) by stabilizing the received SINR, γ_i, at the required level, γ_i^*.

To maximize the user QoS, instead of the bandwidth, B_i, being directly chosen, the level of link SINR is selected. Assume seamless conversion between received BER and SINR. The FPC algorithms are aimed to stabilize the SINR level at a pre-determined level and to control the received SINR at base stations such that fast and slow fading characteristics of the wireless channel are eliminated. An unbalanced step-size FPC scheme is proposed.

4.3.1.1 FPC Algorithms

Many researchers who have contributed to the development and design of W-CDMA cellular systems have failed to recognize the significance of FPC algorithms in the receiver structures and, in many cases, have usually assumed perfect FPC in their simulations. However, in practice, the performance of FPC algorithms characterized completely by the pdf of its error signals and its absolute effect on the overall system performance as a function of the underlying receiver structure. Figure 4.3 shows the effects of FPC algorithms on BER performance.

Two specific aspects of the pdf are of paramount importance: width and mean value. The width of the pdf is a measure of the ability of an FPC algorithm to cope with fast changes in the channel. If the algorithm has a limited dynamic range or responds slowly to changes in channel variations, the error signal at a specific instant in time will range from small values to large ones. Secondly, the mean value of the error signal provides a measure of the average transmitted power of the FPC algorithms. Therefore, FPC algorithms can be compared by considering the mean and variance of the error signals generated by the algorithms. The lower the mean value, the better the power efficiency of the algorithm; and the lower the variance of the error signals, the better the algorithm can cope with short-term channel variations.

The block diagram of a general close-loop PC system is shown in Figure 4.4. This system can be either strength-based or SINR-based PC algorithms depending on the threshold used. SINR-based PC is assumed in this dissertation.

The FPC algorithms operate in the following way. Initially, a base station receives and resolves the multipath signals in slot-based fashion. It is then possible for the base station

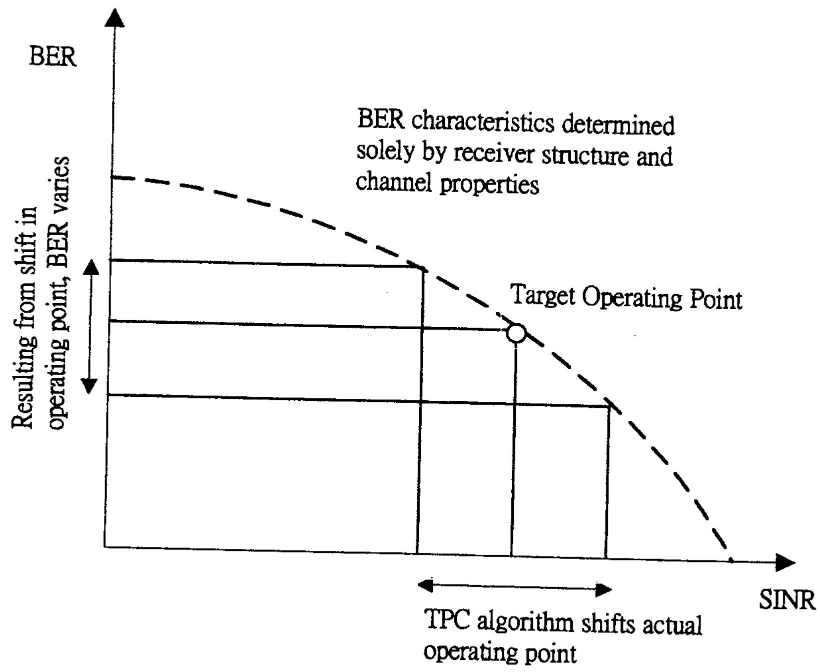


FIGURE 4.3: Effect of FPC on overall BER performance

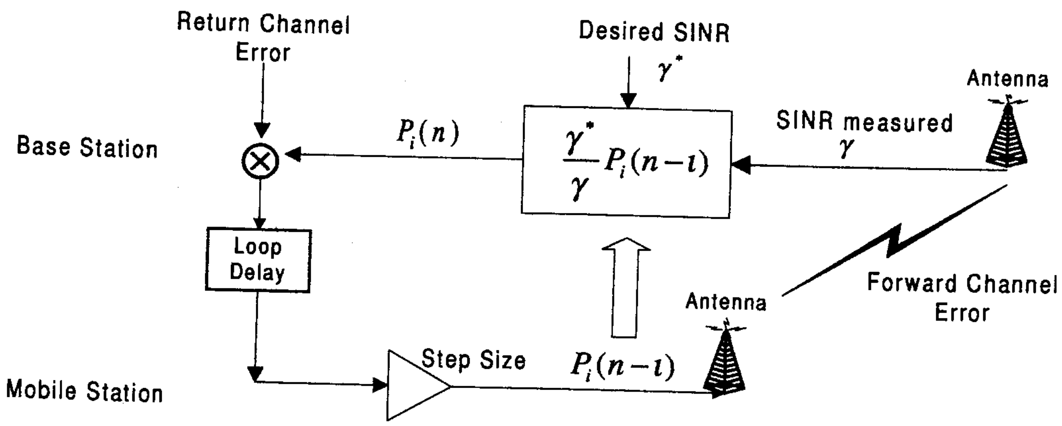


FIGURE 4.4: Traditional PC configuration

to estimate the received SINR from the received pilot symbols. Based on the estimated SINR, the base station then determines a PC command for the next slot and sends it back to the mobile station. The mobile then determines its step-size after receiving the command. The factors that affect the determination of its step-size are: loop delay; allocated bits for FPC; processing delay; steady state error; rate of fading and the number of active users [85]. However, increasing or decreasing the power is always done in a balanced manner, meaning that the power increment command is the same for both increasing and decreasing the power level. However, in practice, the power signal fades more quickly than it rises. This phenomenon can also be observed from the typical Rayleigh and Ricean fading. Thus, four FPC algorithms will be presented for comparison purposes in this chapter:

- Delta modulation (DM) FPC
- Pulse-coded modulation (PCM) FPC
- Unbalanced delta modulation (unDM) FPC
- Unbalanced pulse-coded modulation (unPCM) FPC

4.3.1.2 A Delta Modulation FPC

The idea of SINR based DM FPC is that when the level of the received SINR is higher than the desired level, the transmitted power is decreased by a certain amount, and when the level of the received SINR is lower than the desired level, the transmitted power is increased by the same amount. Intuitively, this regulation method will ensure that the level of the received SINR is close to the desired level.

Mathematically, an SINR-based FPC is of the following control type:

$$P(n) = P(n-\iota)\Delta \mathrm{sgn}(\tfrac{\gamma_{in}^*}{\gamma_{in}})$$

or

$$P(n) = \begin{cases} P(n-\iota) * \Delta, & if \quad \Delta < \frac{\gamma_{in}^*}{\gamma_{in}} \\ P(n-\iota)/\Delta, & if \quad \Delta > \frac{\gamma_{in}^*}{\gamma_{in}} \end{cases} \tag{4.7}$$

in which Δ is the power increment amount, usually called step-size, sgn is the sign function and ι is the transmitting loop delay.

4.3.1.3 A Pulse-Coded Modulation FPC

The DM FPC algorithms assume that a fixed step-size is taken in every power adjustment. In order to improve the performance of the DM algorithm, variable step-size approaches are considered. Then a *mode-s* PCM FPC is given by the following relations:

$$P(n) = P(n-\iota)\Delta cmd_{n-\iota}(\tfrac{\gamma_{in}^*}{\gamma_{in}})$$

or

$$P(n) = \begin{cases} P(n-\iota) * \Delta_1, & if \quad \Delta_1 < \frac{\gamma_{in}^*}{\gamma_{in}} \\ P(n-\iota) * \Delta_2, & if \quad \Delta_2 < \frac{\gamma_{in}^*}{\gamma_{in}} \leq \Delta_1 \\ P(n-\iota) * \Delta_3, & if \quad \Delta_3 < \frac{\gamma_{in}^*}{\gamma_{in}} \leq \Delta_2 \\ P(n-\iota) & if \quad \Delta_4 < \frac{\gamma_{in}^*}{\gamma_{in}} \leq \Delta_3 \\ P(n-\iota) * \Delta_{s-l}, & if \quad \Delta_{s-l} < \frac{\gamma_{in}^*}{\gamma_{in}} \leq \Delta_{s-l-1} \\ .... & .... \\ .... & .... \\ P(n-\iota) * \Delta_s, & if \quad \Delta_s > \frac{\gamma_{in}^*}{\gamma_{in}} \end{cases} \tag{4.8}$$

This is also balanced because there are a odd number of step-sizes. For instance this is an example of a 5 step-size PCM FPC scheme: there are two up levels, one unchanged level and two down levels - altogether five power levels - thus three bits are needed in the downlink to implement this scheme. Having received the PC command, cmd_k, the mobile transmitting power is updated by an amount $cmd_k\Delta$. Simulations given in [15] show that PCM FPC algorithms can achieve a higher link performance than DM FPC ones. However, implementation of PCM FPC requires at least n PC bits. If the update frequency is high, (in IS-95 for example, the update frequency is 800 Hz, and in UMTS it is 1600 Hz), the system's efficiency will suffer.

4.3.1.4 An Unbalanced DM FPC

The unbalanced DM FPC algorithms is a modification of the DM FPC: when the received SINR value γ_{in} is smaller than the desired value γ_{in}^*, the mobile increases the transmitted power by a step-size Δ_1, and when the received SINR value is greater than the desired valued γ_{in}^*, the transmitted power decreases by a different step-size Δ_{-1}. It is called an unbalanced DM FPC algorithm, because the up and the down step-size can be different.

A mathematical description of the SINR-based unbalanced DM FPC algorithm is

$$P(n) = P(n-\iota)\Delta\text{sgn}(\tfrac{\gamma_{in}^*}{\gamma_{in}})$$

or

$$P(n) = \begin{cases} P(n-\iota) * \Delta_1, & if \quad \Delta_1 < \frac{\gamma_{in}^*}{\gamma_{in}} \\ P(n-\iota)/\Delta_{-1}, & if \quad \Delta_{-1} > \frac{\gamma_{in}^*}{\gamma_{in}} \end{cases} \tag{4.9}$$

One reason for this proposal is that the transmitted power signal fades more quickly than it rises in the wireless channel. This phenomenon can also been observed from the typical Rayleigh fading. Different step-sizes are employed for signal fading and signal rising, usually, $\Delta_1 \geq \Delta_{-1}$. Typically, $\Delta_1 = 1.5$ dB and $\Delta_{-1} = 1$ dB. There are optimal values for Δ_1 and Δ_{-1} which can be determined in simulation for a specific environment.

4.3.1.5 An Unbalanced PCM FPC

This is a modification of the two-mode PCM FPC algorithm. This algorithm is also unbalanced because there are two up levels, one unchanged level and one down levels - altogether four power level - thus two-bits are needed in the downlink to implement this scheme. A two bit FPC for UMTS is proposed as follows:

$$P(n) = P(n-\iota)\Delta cmd_{n-\iota}(\tfrac{\gamma_{in}^*}{\gamma_{in}})$$

$$or$$

$$P(n) = \begin{cases} P(n-\iota) * \Delta_1, & if \quad \Delta_1 < \frac{\gamma_{in}^*}{\gamma_{in}} \\ P(n-\iota) * \Delta_2, & if \quad \Delta_2 < \frac{\gamma_{in}^*}{\gamma_{in}} \leq \Delta_1 \\ P(n-\iota) & if \quad \Delta_3 < \frac{\gamma_{in}^*}{\gamma_{in}} \leq \Delta_2 \\ P(n-\iota) * \Delta_3, & if \quad \Delta_3 > \frac{\gamma_{in}^*}{\gamma_{in}} \end{cases} \tag{4.10}$$

If there are three up levels, one unchanged level and two down levels - altogether six power levels - three bits are needed in the downlink to implement this scheme. A three-bit FPC for UMTS is proposed as follows:

$$P(n) = P(n-\iota)\Delta cmd_{n-\iota}(\tfrac{\gamma_{in}^*}{\gamma_{in}})$$

$$or$$

$$P(n) = \begin{cases} P(n-\iota) * \Delta_1, & if \quad \Delta_1 < \frac{\gamma_{in}^*}{\gamma_{in}} \\ P(n-\iota) * \Delta_2, & if \quad \Delta_2 < \frac{\gamma_{in}^*}{\gamma_{in}} \leq \Delta_1 \\ P(n-\iota) * \Delta_3, & if \quad \Delta_3 < \frac{\gamma_{in}^*}{\gamma_{in}} \leq \Delta_2 \\ P(n-\iota) * \Delta_4, & if \quad \Delta_4 < \frac{\gamma_{in}^*}{\gamma_{in}} \leq \Delta_3 \\ P(n-\iota) & if \quad \Delta_5 < \frac{\gamma_{in}^*}{\gamma_{in}} \leq \Delta_4 \\ P(n-\iota) * \Delta_5, & if \quad \Delta_5 > \frac{\gamma_{in}^*}{\gamma_{in}} \end{cases} \tag{4.11}$$

4.3.1.6 The Problem of SINR Stability

Accurate and FPC can compensate for bad radio-channel conditions and keep the received SINR above the target level. However, in a bad radio-link, the source can transmit with higher power levels, causing extensive interference to other active users. Therefore, the PC error is one of the most important factor affecting system capacity, as seen in chapter 2.

For example, user i request a traffic demand Γ_i of $R = 43$ kbps user data rate and $\gamma_i^* = 10^{-3}$. Assume the required BER corresponds to $(^{E_b}/_{I_o})_i = 4dB$. The receiver structures are set to be two receiver antennae, matched-filter with turbo decoder, RAKE receiver and a spreading gain of $G = 32$ [Figure 4.2]. Figure 4.5 and 4.6 depict the SINR outage probability result with no power control techniques to compensate the fast fading effects. In our simulation, we have found that the received SINR value at base station may be as high as $14W$ with a variance of 4.3379 or as low as $1W$ with a variance of 0.027302. Thus, the conventional solution would be to incorporate FPC technique. As will be shown in the next section, this maximal user QoS function becomes the cornerstone of the intracell power level allocation.

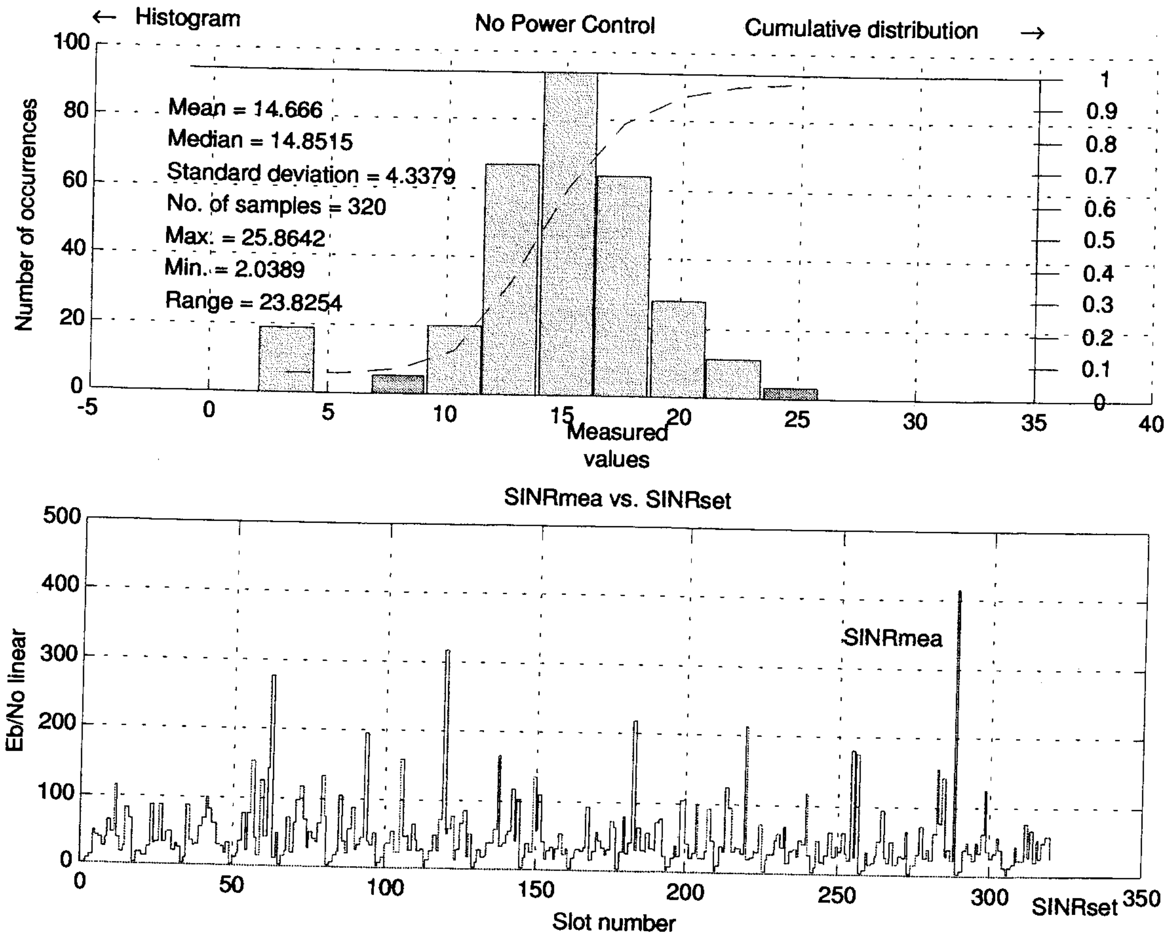


FIGURE 4.5: SINR outage probability result for an uncontrolled W-CDMA system with an AWGN channel, matched-filter detector and $N = 1$. Initial transmitted power level was set at 2W

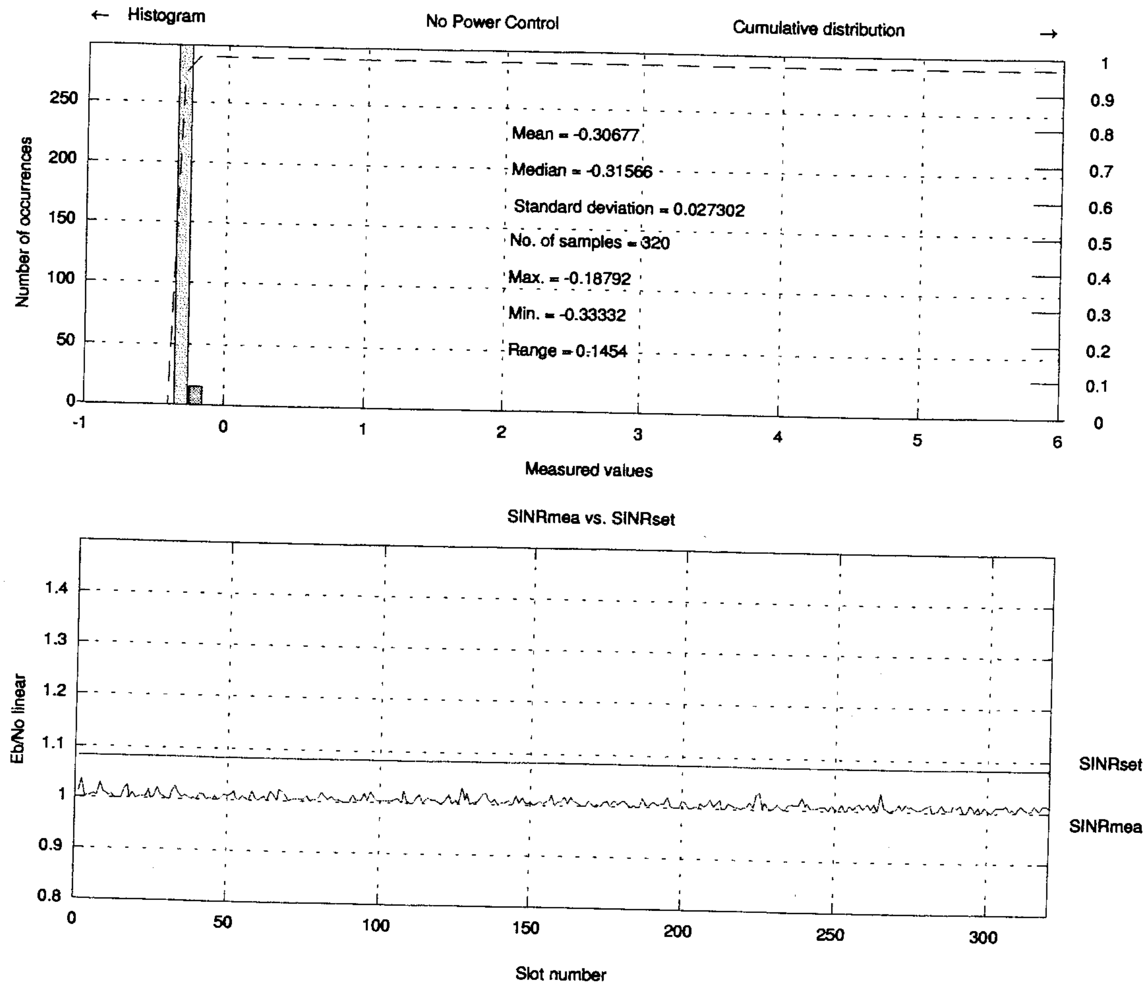


FIGURE 4.6: SINR outage probability result for an uncontrolled W-CDMA system in an AWGN channel, matched-filter detector and $N = 1$. Initial transmitted power level was set at 0.5W

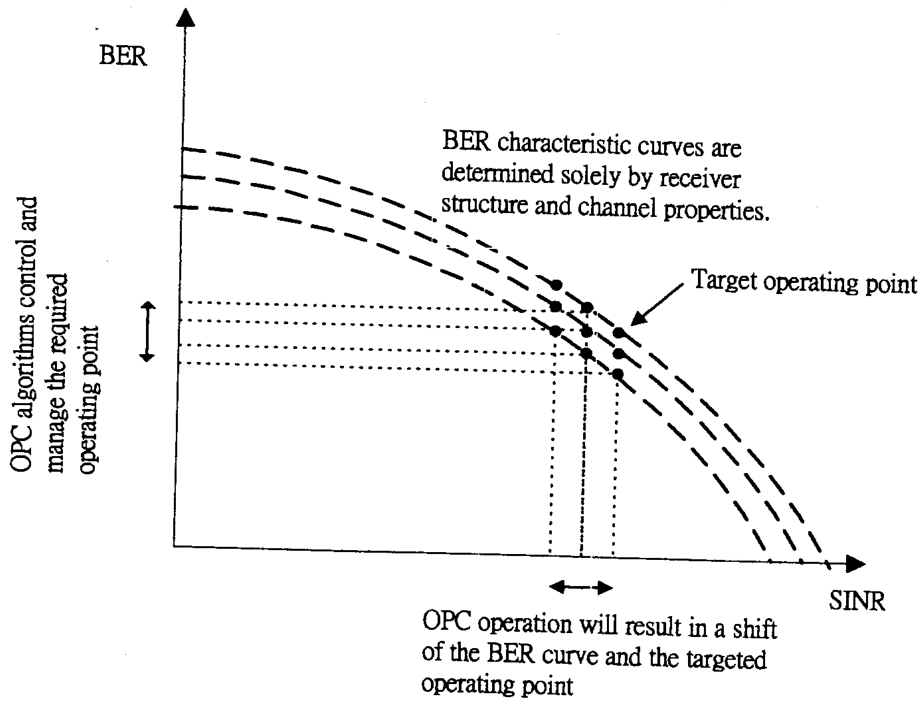


FIGURE 4.7: Effects of OPC on overall BER performance

4.3.2 A QoS-based Outer-loop PC (OPC)

A wireless communication environment is interference limited. In such an environment, users are subject to three sources of interference: intercell interference, intracell interference, and background noise. The received SINR for a user, say user i located in cell k, is the ratio of the received signal power to the noise power:

$$\mathrm{SINR}_i = \frac{\text{Received Signal Power}}{\text{Total Noise Power}} = \frac{h_{ik}P_{ti}}{\sum_{j\neq i}^{N} h_{jk}P_{tj} + \delta^2 * W} \cdot \frac{W}{R_{bi}} \tag{4.12}$$

Recall that the cell level QoS is the sum of the user level QoS

$$\text{cell QoS}_k = \sum_{i=1}^{N} (\text{user. util})_k = \sum_{i=1}^{N} u_i(B_i, E_i)_k \tag{4.13}$$

Our objective is to maximize Equ. (4.13) by maximizing Equ. (4.6), which is an optimization problem of two variables (B_i and E_i). We can observe that the channel SINR is the only undetermined variable during the optimization, as a result, both the optimal B_i and E_i and thus the optimal user QoS are functions of the received SINR, $U^*_{user}(SINR)$.

Figure 4.7 shows the effects of OPC algorithms on BER performance. Since the target SINR is different for different propagation channel conditions (such as power delay profile, the number of resolvable propagation paths, the fading maximum Doppler frequency, etc)

The BER in different channel conditions and different traffic demand acquire different target SINR for each active mobile terminal. It is desirable to have OPC algorithms to compensate for this problem.

Since FPC algorithms minimize the PC error, they provide a better estimation of SINR on current channel links. Therefore, the OPC algorithms can allocate resource more accurately. The OPC establish a control strategy that utilize and manage radio resources and minimize *intra-cell* interference without the expense of enormous efforts devoted to measurement and signaling for communication link setup (and reconfiguration) of network control. There are two OPC techniques toward global resources allocation problems, centralized or distributed OPC algorithms.

4.3.2.1 OPC Algorithms

4.3.2.1.1 A Centralized PC algorithm The centralized approach assumes a wireless system based on a limited number of base stations (remote access unit (RAUs)) connected to a central unit known as radio network centre (RNC), as shown in Figure 4.8. This group of cells is called a bunch and the RAUs share measurement and status information for the purpose of dynamic resource allocation.

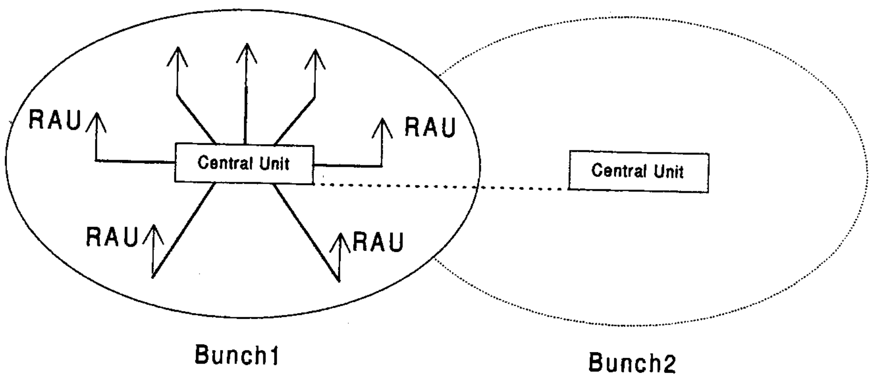


FIGURE 4.8: A bunched wireless system

Our method of maximizing cell-level QoS is to minimize the intra-cell interference with just sufficient power vector to compensate the random complex radio channel described by:

$$\begin{aligned} &\min_{P} \sum_{i=1}^{N} p_i \\ &\text{s.t.} P_{ti} \geq I_i(\mathrm{P}) = \frac{\Gamma_i}{\sum_k \mu_{ik}(\mathbf{P})} \\ &0 < p_i \leq P_{\max} \\ &R_i \geq r_{\min} \qquad i = 1, \ldots.., N \end{aligned} \tag{4.14}$$

Each base station (RAU) sends the BER estimation value to the RNC. The RNC calculates the received N power levels for each active mobile terminal, based on the matrix (4.14). During this process, an OPC algorithm iteratively searches for a set of transmission powers that can satisfy all E_b/N_o targets for the session using the current link gain

$$\mu_{ik}(\mathbf{P}) = \{\sum_{j=1, j\neq 1}^{N} \rho^2 \frac{h_{jk}}{h_{ik}} P_j^{(n)} + \delta_{1k}^2\} \tag{4.15}$$

and traffic demand

$$\Gamma_{\mathbf{D}} = diag[\frac{1}{W} R_{bi}\gamma_1, \ldots, \frac{1}{W} R_{bN}\gamma_N] \tag{4.16}$$

If the power set is found (i.e. all E_b/N_o targets can be satisfied), the power vector P^* is send to each mobile terminal via its assigned base station.

However, this setup needs communication between RNCs and RAUs from different bunches to coordinate the power vector, synchronization and resources allocation. Nevertheless, the feasibility check if all collected E_b/N_o targets can be satisfied is a good approach to defining whether this traffic demand can be allocated under current conditions and afterward provide acceptable quality.

The definition of QoS required by each service or medium is solely specified by the BER or FER, instead of the SINR. Strictly speaking, the SINR does not completely characterize performance measures, such as BER. However, in general it is difficult to measure the BER, so we apply a frame error rate (FER) measurement using CRCs for OPC; for instance, when a very low BER is required for data transmission, e.g. 10^{-6}, as required in UMTS. Figure 4.10 shows the graph of actual BER measured at the eighth iteration and the corresponding FER measured at 1 to 8 iterations. Since the corresponding FER is also low, a fairly long FER measurement interval is desired. For example, for an FER value corresponding to a BER = 10^{-6} is equitant to 10^{-3} as seen in Figure 4.10 at a transmission rate of 43 kbps (chip rate = 41472 chips/frame) and data frame length of 10ms, therefore, an FER measurement interval of $\geqslant$ 5000 frames (5000 frames * 432 data bits/frame = 2160000 bits = 50s) may be required for reliable FER measurement. Such a long measurement interval is not practical. Thus, the FER is measured at every second iteration and based on the measured FER value, the BER is estimated to reduce time complexity.

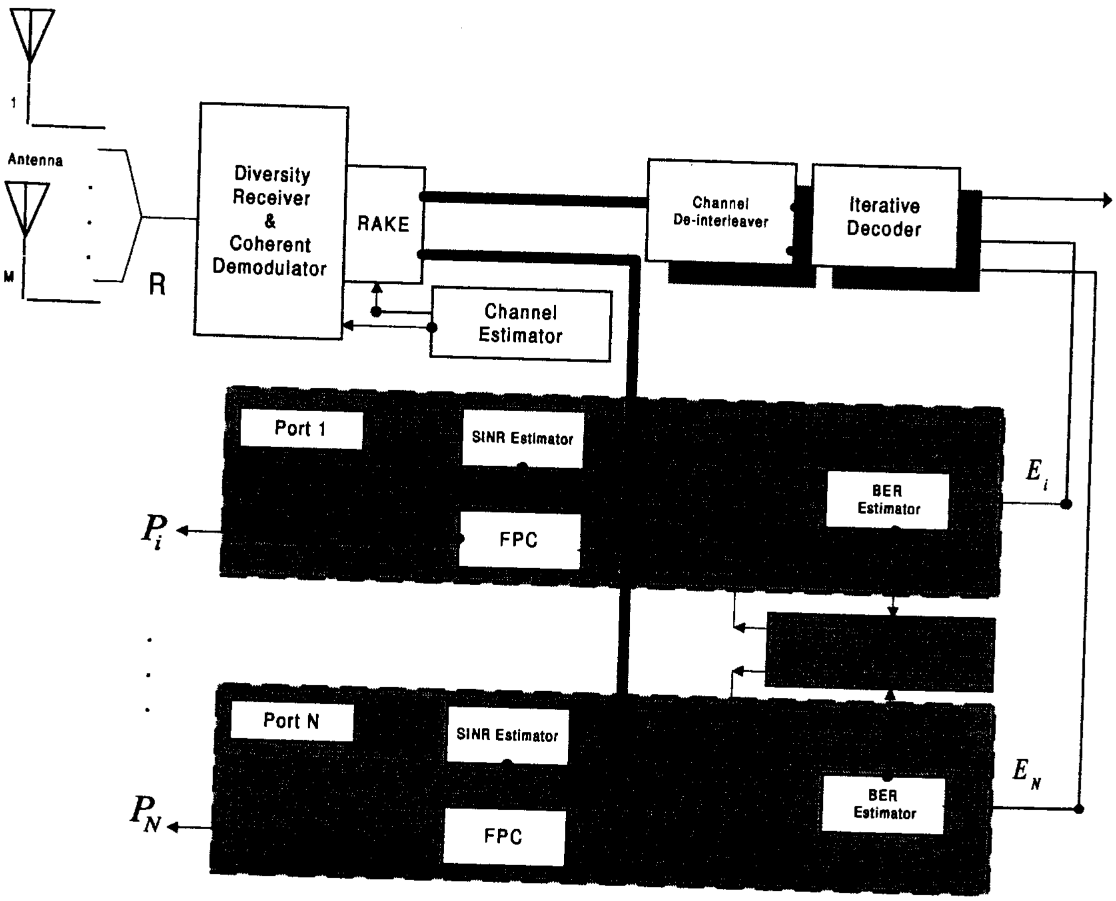


FIGURE 4.9: A multi-target APC with centralized OPC and N output ports

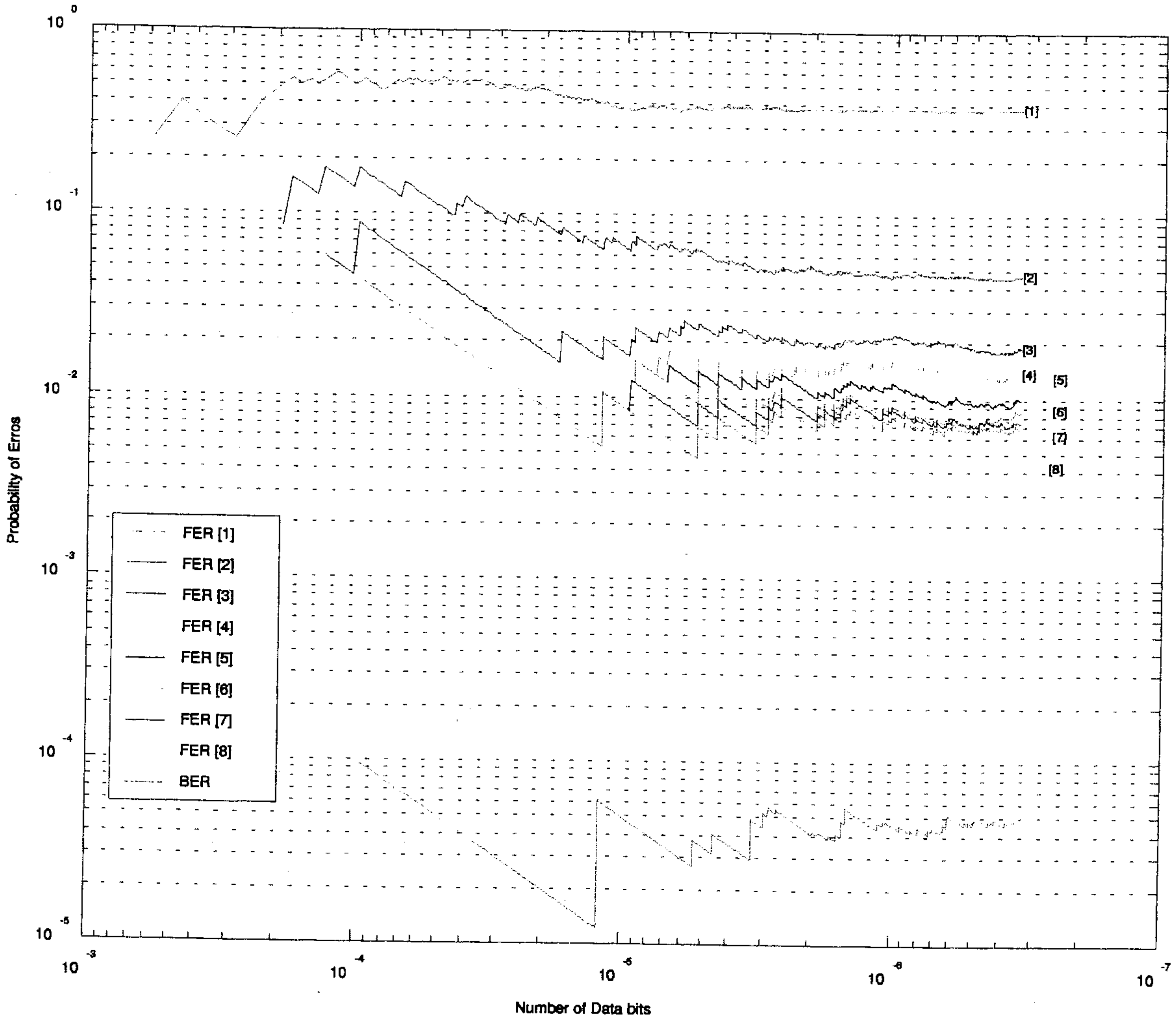


FIGURE 4.10: Relationship between FER[n] and BER[8]

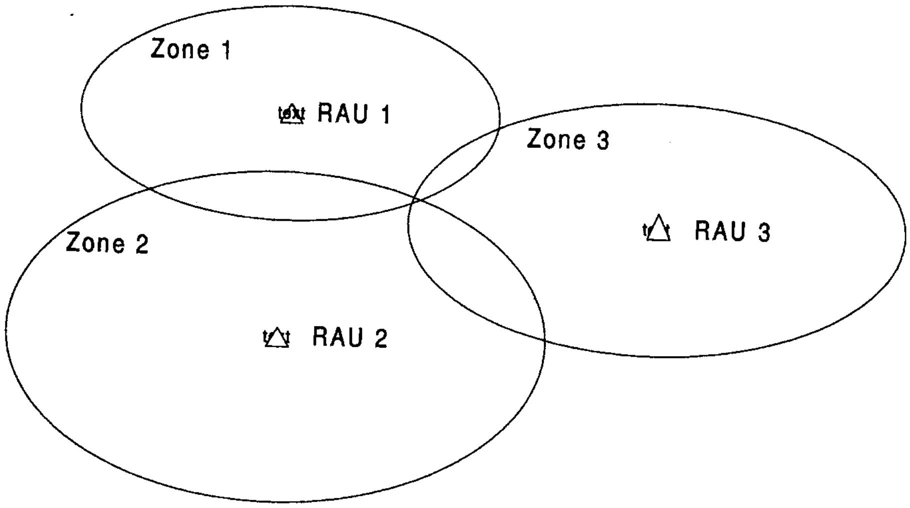


FIGURE 4.11: The zone principle

We present an error-driven technique for outer-loop control of the target SINR for FPC to be used in Turbo-coded, W-CDMA mobile radio systems. Advantage is taken of the fact that in Turbo-decoding the BER and FER decrease as the number of decoding iterations increases. According to Figure 4.10, an FER of 0.04 after the second iteration corresponds to a BER of 4×10^5 after the eighth iteration. Therefore, an FER measurement interval of only 1.25s ($0.04^{-1} \times 5 \times 10^{-3}$) is sufficient, and the target SINR can be adjusted without losing the tracking ability in the presence of slowly changing propagation conditions.

Further improvement on the measurement interval can be achieved by using a BER prediction method. The reliability information (extrinsic value) during the iterative decoding process provides the confidence level corresponding to the current received signals. If we are able to use this soft value to predict the long-term BER achievement, the QoS can be maintained.

4.3.2.1.2 Distributed PC algorithm The distributed PC algorithm using interference matrix-based allocation techniques is different from the intrabunch scheme because it uses the concept of zones. A zone is the area homogeneously covered by one or several RAUs, as shown in Figure 4.11.

To avoid the high processing power demand at the CU and extensive radio network planning, a distributed PC algorithm is required. It also avoids requirements for information on link gain matrix H due to its self-adaptive learning capability. The basic algorithm is implemented as follows.

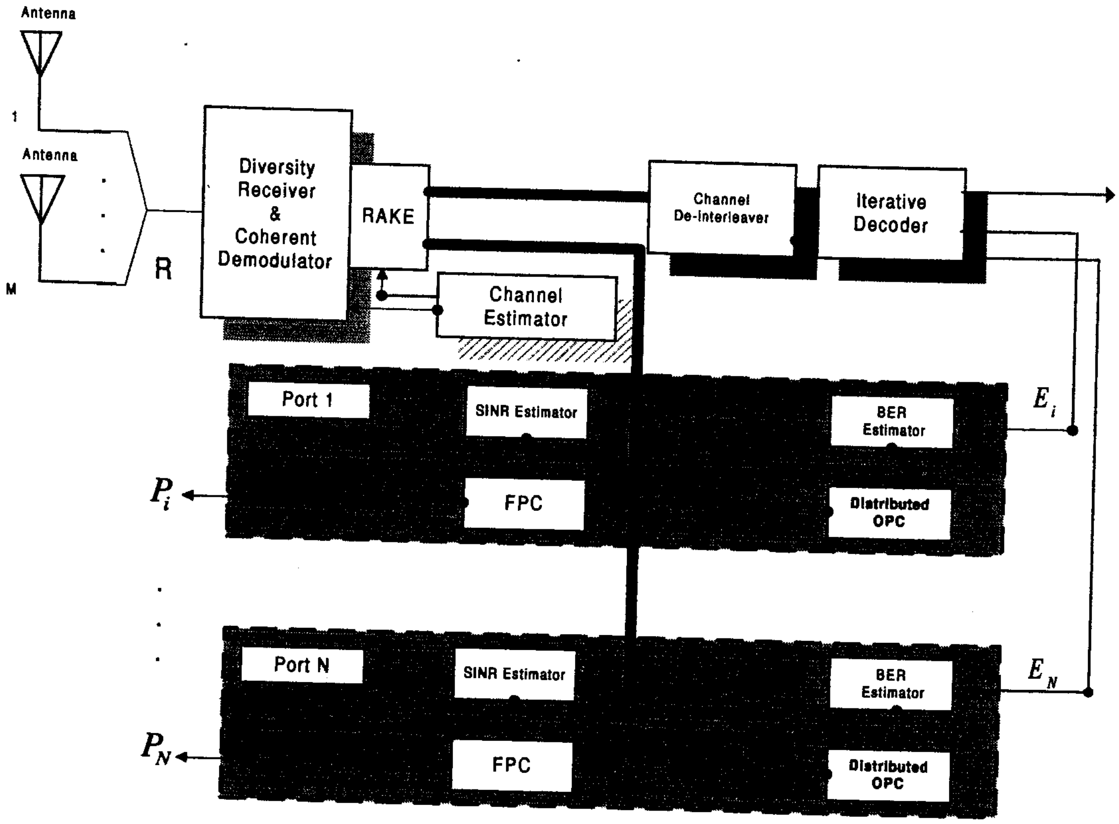


FIGURE 4.12: A multi-target APC with N distributed OPC

- Each base station or zone assigns a power budget, which is determined through the higher layer optimization.
- The zone is to distribute the power budget to each user so that the total cell QoS is maximized. This goal is achieved by computing the optimal power vector for all users.
- Based on the conservation law (section 3.6.4) for iterative FPC algorithms, the power vector for the zone will always converge to the optimal value.
- If the power set does not converge to optimal quickly enough, NPC will reconfigure the networking setting.

Figure 4.12 shows the structure of a typical multi-target APC. The distributed OPC algorithm will generate N sets of desired SINR for the next transmit frame, i.e. N power vectors $\gamma_1 .... \gamma_N$. These N power vectors corresponding to N different QoS (BER) requirements are used to control the transmitted signal in different ports. NPC controls the feasibility of the N power vectors corresponding to N different QoS requirements that may exceed system capacity. In Figure 4.12, $y_1(n), ..., y_N(n)$ are the outputs of ports $1, ..., N$ at the nth iteration, respectively, representing the estimated BER. $\gamma_1, ..., \gamma_N$ are the power vectors of users 1, ..., N, respectively and $p_1, ..., p_N$ are the PC commands of users 1, ..., N, respectively. From Figure 4.12, we see that the MT-PC can be viewed as a complete PC strategy system. We claim that the system design is incomplete if these methods are not considered simultaneously.

4.3.3 A QoS-based Network PC (NPC)

The number of users in the system, N, strongly influences system capacity. From the capacity analysis already presented, decision rules can be defined and implemented in RRM to avoid overloaded situations and for stable system operation. An interesting finding is that the power budget calculation depends on several parameters such as orthogonality factor, $\rho^2_{i,j}$, soft handoff area and gain, $\sum_{j\neq i}^{N} P_{tj}$, $(\frac{E_b}{I_o})_i$ target, and radio-link characteristics, h_{ik}, or, $\sum_{j\neq i}^{N} h_{jk}$. A further finding is that there is a theoretical limit, N_{limit}, [16] which when it reached, the network will fail to deliver satisfactory QoS to any users. Therefore, the number of users should be kept within a safety margin below N_{limit}. PC and admission-control, PC and base station assignment and PC and handoff operations (section 3.4) aim to maximize the system resources by minimizing *inter-cell* interference. At the same time NPC measures the system capacity of current communication systems.

4.3.3.1 NPC Algorithms

Since intercell interference is localized within a finite region, changing the power level of a cell affects only its nearby cells, its "neighbourhood". This observation suggests that we are able to set the power budget for several cells simultaneously. For this discussion we assume only first order interference [14].

Assume a cell topology as shown in Figure 4.13, where a centre cell has six neighbouring cells. Suppose cell k is in the centre and let, $\bar{P}_i = (P^0_k, P^1_k, ..., P^6_k)$, be the total power budget for each of the seven cells. When updating the power budget for cell 0, its power level is chosen so as to maximize its overall neighbourhood QoS is also a function of P_o (minimize the intercell interference), as shown below

$$U_{\text{neighbourhood}}(P_o, P_1, ..., P_6) = U^*_{\text{cell0}}(P_o) + \sum_{i=1}^{6} U^*_{\text{cell0}}(P_i) \tag{4.17}$$

[14] First-order interference means that a base station only interferes with its six immediate neighbouring cells. This assumption is only for illustrative purposes, and is not necessary for our distributed algorithms. If the assumption does not hold, we can increase the neighbourhood size, which will decrease the rate of convergence.

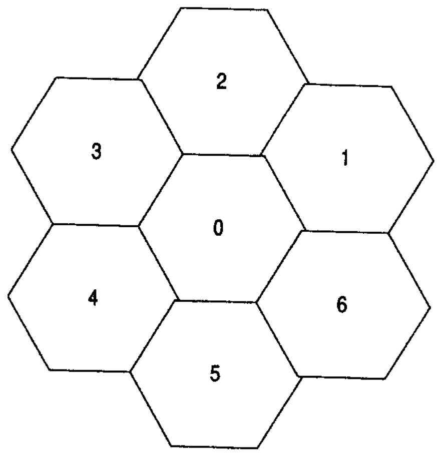


FIGURE 4.13: Cell topology

While P_o is upper bounded by the implementation limit, the objective of adjusting P_o is to maximize the total neighbourhood QoS. Thus, P_o has to satisfy

$$\frac{\partial}{\partial P_0}[U_{\text{neighbourhood}}(P_o, P_1, ..., P_6)] = 0 \tag{4.18}$$

This is equivalent to

$$\frac{\partial}{\partial P_0} U^*_{\text{cell0}}(P_0) = -\frac{\partial}{\partial P_0}\left(\sum_{i=1}^{6} U^*_{\text{celli}}(P_i)\right) \tag{4.19}$$

Notice that the left side of Equ. (4.19) is the marginal QoS of cell #0 as a function of P_0, and on the right is the total marginal QoS of the neighbouring cells. At the optimal point, with respect to P_0, the marginal QoS of cell #0 offsets the marginal QoS of the neighbouring cells. The system QoS optimization algorithm described above is indeed an iterative, one-dimensional (1-D)search algorithm, in which we optimize along each P_i iteratively until the maximum is reached.

Restrict ourselves to changing power levels for the centre cell of these six neighbourhoods only. Firstly, since the effects of changing the power level of a centre cell is limited to the neighbourhood boundary, cells only need to communicate within the neighbourhood. Secondly, since a centre cell faces a fixed interference environment, calculation of the power budget is simplified. Finally, since the remaining cells within the neighbourhood have exactly one interfering cell which changes its power, calculation of intracell and intercell interference coefficients is simplified. So far, we have updated the power budgets for only a cell.

4.4 A SUMMARY OF THE MULTIPLE-TARGET (MT) QOS-BASED PC ALGORITHM

We have presented a QoS-based approach to the overall control problem. Since the policy issues of allocation resources are separate from the design process, the main advantage of this MT, QoS-based PC structure is that it offers a great deal of flexibility to the system control. In other words, we can always choose a QoS function that reflects specific design objectives.

In order to achieve optimal system performance, three control knobs are available to fulfill different BER and bandwidth requirements: FPC; OPC; and NPC. FPC varies the transmit power to adjust the received signal quality. Together FPC and OPC are used to support applications with widely varying QoS and to mitigate excessive interference. Finally, OPC and NPC allocate resources among data types, especially when application demands exceed channel capacity. The MT-PC can be viewed as a complete PC strategy system. We claim that the system design is incomplete if these methods are not considered simultaneously.

However, this advantage of flexibility makes it difficult to quantify and compare system performance with other approaches. Therefore, we have simulated the system using a specific traffic demand, channel conditions and RRM algorithms. Our ultimate goal is to investigate the influence of physical and temporal parameters in a UMTS/UTRA cellular environment. A detailed comparison of the SINR tracking ability, BER stability and performances for different PC algorithms is presented in Chapter 5.