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Capacity Enhancement and Performance Analysis of Call Admission and Load Control in Wireless Communication Networks

By

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**A Thesis submitted to
The Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of**

Doctor of Philosophy

**Ottawa-Carleton Institute for Electrical Engineering
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and Research acceptance of the thesis

**Capacity Enhancement and Performance Analysis of Call
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Submitted by Mohamed Hossam Ahmed, M.Sc.
in partial fulfillment of the requirements for
The degree of Doctor of Philosophy

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February, 2001

Abstract

This work focuses on the capacity enhancement and performance analysis of modern wireless cellular communication systems using efficient call admission and load control algorithms for single and multiple service. The proposed algorithms exploit the residual capacity to enhance the system performance.

Overlapping coverage in urban microcells is studied. Area Coverage Probability (*ACP*) is evaluated analytically and by simulation. The results show that the *ACP* is substantially improved by making use of overlapping coverage. A novel algorithm is proposed to enhance system capacity using overlapping coverage. Capacity enhancement is achieved by balancing the loading in the neighboring cells. Performance is evaluated analytically using Markovian analysis, namely, the Birth-Death model and by simulation as well. Then, it is compared with the non-overlapping coverage case and with overlapping coverage using a previous algorithm called directed retry. The results show that the proposed algorithm surpasses the directed retry and achieves a considerable capacity gain by reducing the blocking and dropping probabilities.

The capacity of Time Division Multiple Access (TDMA) networks with Slow Frequency Hopping (SFH) is determined analytically and by simulation. The soft capacity limit and the effect of admission control algorithms are investigated. The outage probability (P_{out}) as one of the measures of the Quality of Service (QoS) is derived as a

function of the loading factor. Then, the network capacity is determined as a function of the maximum loading factor that keeps the outage probability below a certain threshold value. The capacity gain of switched-beam antennas and power control is evaluated. A novel call admission control algorithm is proposed. This algorithm enhances the network capacity by reducing the call blocking and dropping rates without causing any significant degradation in the QoS in terms of the outage probability.

An admission and load control algorithm is developed for multiple service in third generation wireless system. It is designed for a stream mode non-real-time data service such as File Transfer Protocol (FTP) applications taking the voice service into consideration. The algorithm takes advantage of the smart antennas and intermittent nature of the voice service. Furthermore, some features of third generation wireless systems such as the reported pilot measurements, auxiliary pilot for smart antennas and variable spreading gain are considered in the system model. The performance of the proposed algorithm is evaluated analytically using two-dimensional Markovian model and by simulation as well. The results show that a high transmission rate (more than 144 Kbps) can be achieved for vehicular data users without degrading the QoS of the voice service.

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List of Abbreviations

3G	Third Generation wireless systems
ACIS	Advanced Cellular Internet Service
ACP	Area Coverage Probability
AOA	Angle of Arrival
ARQ	Automatic Repeat request
BER	Bit Error Rate
BS	Base Station
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CINR	Carrier to Interference plus Noise Ratio
CIR	Carrier to Interference Ratio
CRC	Cyclic Redundancy Check
DCA	Dynamic Channel Allocation
DOA	Direction of Arrival
DPA	Dynamic Packet Assignment
DTX	Discontinuous Transmission
ETSI	European Telecommunications Standardization Institute
EWMA	Exponential Weighted Moving Average
FDMA	Frequency Division Multiple Access

FER	Frame Error Rate
FL	Fractional Loading
FTP	File Transfer Protocol
GBSBSCM	Geometrically Based Single-Bounce Statistical Channel Models
GoS	Grade of Service
GSM	Global System for Mobile communications
GWSSUS	Gaussian Wide Sense Stationary Uncorrelated Scattering
HCS	Hierarchical Cell Structure
IMT	International Mobile Telecommunication
ITU	International Telecommunications Union
LOS	Line of Sight
MAC	Medium Access Control
MB	Multiple Beam antennas
MS	Mobile Station
MSC	Mobile Switching Centre
MUD	Multi User Detection
NLOS	Non-LOS
OFDM	Orthogonal Frequency Division Multiplexing
OVSF	Orthogonal Variable Spreading Factor
PC	Power Control
QoS	Quality of Service
QPSK	Quadratic Phase Shift Keying
RACH	Random Access Channel

RLC	Radio Link Control
SFH	Slow Frequency Hopping
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TLA	Traffic Load Admission
TPM	Transition Probability Matrix
TRA	Traffic Load Admission
UMTS	Universal Mobile Telecommunications Systems
VAF	Voice Activity Factor

List of Symbols

(D_j, θ_j)	Coordinates of the BS in the j^{th} cell in polar form
(l_j, θ_l)	Coordinates of the MS in cell 0 w. r. t the BS in the j^{th} cell in polar form
(r_m, θ_m)	Coordinates of the MS in cell 0 in polar form
A^c	Total Traffic per cell in Erlang
A_j	Bernoulli random variable representing the activity of the MS in the j^{th} cell
b	Cell border length normalized to S
B_c	Coherence bandwidth
C	Maximum network capacity in Erlang/cell
C_{av}	Average network capacity in Erlang/cell
CH_{cell}	Number of Channels per cell
CIR_{min}	Minimum acceptable CIR
C_r	Receiver carrier power
C_r^d	Targeted received carrier power from data users
C_r^v	Targeted received carrier power from voice users
D	Frequency reuse distance
d	Width of the overlapping arm normalized to S
$E[]$	Mean value
E_b/I_o	Energy per bit to interference density ratio
E_{user}	Traffic per user in Erlang

f	Carrier frequency
$f(r, \theta)$	PDF of the MS lies in the position denoted by (r, θ)
$f(\theta_{bj})$	PMF of θ_{bj}
$g(\theta_j, \theta_{bj})$	Antenna gain as a function of the interferer angle (θ_j) and beam angle (θ_{bj})
h_r	Receiver antenna height
h_t	Transmitter antenna height
$i(k)$	Number of admitted data user at state k
I_{inter_cell}	Normalized Inter-cell interference
I_j	Interference power from the j^{th} cell
$\bar{I}_j$	Mean value of I_j
I_{tot}	Total interference power
L_d	Arrival rate of data traffic
LF	Loading Factor
LF_{max}	Maximum LF
L_{max}	Maximum number of voice users per beam
L_v	Arrival rate of voice traffic
N	Frequency reuse factor
n	Path loss exponent
N_b	Number of beams per cell (sector)
N_d	Number of data users per cell
N_d^b	Number of data users per beam
$N_d^{b\_max}$	Maximum number of data users per beam
N_j^{EWMA}	EWMA of the number of active users in the j^{th} cell

N_{max}	Maximum number of active channels per cell
N_q^b	Number of queued users per beam
N_{sc}^b	Number of the supplemental channels per beam
N_v	Number of voice users per cell
N_v^b	Number of voice users per beam
P_b	Call blocking probability
P_d	Call dropping probability
P_{est}	Estimated value of β or P_b in the iterative solution
P_h	Handover failure probability
P_i	Probability of the i th state in the Markovian chain
p_{ij}	Transition probability from the i^{th} state j^{th} state in the Markovian chain
P_{init}	Initial value of β or P_b in the iterative solution
P_m	Probability of call moving in the load balancing algorithm
p_{max}	Maximum acceptable outage probability
P_{on-off}	Talking to silence transition probability
P_{off-on}	Silence to talking transition probability
P_{out}	Outage probability
P_r	Received power
P_R	Received power in dBW
P_t	Transmitted power
P_T	Transmitted power in dBW
P_{th}	Threshold received power level for coverage
P_{TH}	Threshold received power level for coverage in dB

q	Probability of the interferer activity
Q	Truncation value of the two dimensional Markovian chain
r	Distance between the MS and BS
R	Cell radius
R_b	Bit rate
r_c	New call arrival rate with overlapping coverage
r_d	Handoff call departure rate with overlapping coverage
R_f	Bit rate of the fundamental channel
r_h	Handover call arrival rate with overlapping coverage
R_m	Radius of the scatterer circle
r_n	New call arrival rate with overlapping coverage
R_s	Bit rate of the supplemental channel
S	Side length of square cells
S_d	Mean value of the data message size
SG_f	Spreading gain of the fundamental channel
SG_s	Spreading gain of the supplemental channel
T	Frame duration
T_q	Queuing delay
W	Signal bandwidth
w	Updating parameter of N_f^{EWMA}
Y	Overlapping arm length normalized to S
$1/\mu_v$	Average call duration
$1/\mu_d$	Average call dwelling time

$1/\mu$	Average call residence
ΔN_j^{EWMA}	Quantization step size N_j^{EWMA}
ΔP_{est}	Relative error of P_{est}
Δs	Loading factor offset in the load balancing algorithm
α	Constant value that equals to $\ln(10)/10$
α_f	Normalized received power of the fundamental channel
α_s	Normalized received power of the supplemental channel
β	Probability of cell full loading
ϕ_n	Possible values of θ_{bj}
γ_f	CIR_{min} of the fundamental channel
γ_s	CIR_{min} of the supplemental channel
γ_v	CIR_{min} of the voice service
λ	Wavelength
λ_h	Handover call arrival rate
λ_n	New call arrival rate
θ_{bj}	beam angle of MS in the j^{th} cell
θ_{bm}	beam angle of MS in cell 0
σ	Standard deviation of the lognormal shadowing
ξ	Shadowing parameter
$\zeta_{i(i-1)}$	Data call departure rate with i active data calls

Chapter 1

Introduction

1.1 Introduction

During the last two decades, a rapid growth of wireless and mobile communication popularity has taken place around the globe. It is anticipated that the demand for mobile communications will keep increasing. This includes voice services and non-voice services as well.

The increasing traffic of voice and data services over wireless networks can cause overloading. Network overloading degrades the Quality of Service (QoS) in terms of the Carrier to interference Ratio (*CIR*) and the Grade of Service (GoS) in terms of the blocking and dropping probabilities for the voice service and the transmission rate and delay for the data service. High call blocking and dropping rates in addition to intolerable interference levels are experienced in many wireless networks. Thus, efficient resource management is crucial to overcome such problems. Some techniques have been devised

to boost the network capacity and enhance the system performance. Examples of such techniques include cell splitting, Hierarchical Cell Structure (HCS), Dynamic Channel Allocation (DCA), Power Control (PC), Discontinuous Transmission (DTX), Slow Frequency Hopping (SFH), Fractional Loading (FL) and smart antennas.

With the introduction of third generation (3G) wireless systems based on wideband CDMA technology, some new services such as File Transfer Protocol (FTP) applications, image and video transmission, and the Internet access should be considered in radio resource management. Radio resource management for multiple services is a challenging problem since each service has its specific profile in terms of traffic patterns and QoS requirements.

Performance analysis and capacity dimensioning tools are needed in the design, planning and optimization process of new and operating wireless networks. These tools should be simple, flexible and accurate. A set of simulation tools has been developed for this purpose. Analytical methods based on stochastic models, namely Markovian models, are also used in most of the cases for verification purposes.

These tools are used to characterize the system performance and capacity enhancement obtained using techniques such as overlapping coverage, slow frequency hopping and smart antennas.

Cellular networks with interference-limited capacity such as CDMA and SFH-TDMA systems can provide higher capacity figures than bandwidth-limited cellular networks. However, call admission and load control must be employed in the cellular networks having interference-limited capacity to guarantee the signal quality offered by the network. The call admission and load control algorithms constitute an essential part in

the resource management process. These algorithms aim to efficiently assign the radio resources for new and ongoing voice and data calls to achieve the maximum possible capacity.

1.2 Thesis Contribution

The main theme of this thesis is the capacity enhancement of wireless systems using efficient call admission and load control algorithms for single and multiple services. The capacity enhancement and system performance is evaluated analytically and by simulation. The main contributions of this thesis are the following:

1. A set of simulation tools has been developed for analyzing the performance of wireless networks using several capacity enhancement techniques. These tools are based on realistic models and parameters. The software tools are designed in a modular structure. Hence, changes and modifications can be easily included in the system model.
2. Call admission and load control has been studied in urban microcells with overlapping coverage as presented in chapter 4. A novel algorithm called load balancing is proposed to enhance the network capacity. The system performance is evaluated analytically and by simulation. A comparison with a previous algorithm called directed retry as well as with no overlapping coverage is given to estimate the capacity gain [Ahm98].
3. Area Coverage Probability (*ACP*) as one of the important measures of the

network planning and optimization process has been determined as discussed in chapter 4. *ACP* is evaluated in urban microcells with and without overlapping coverage analytically and by simulation [Ahm97].

4. Capacity enhancement in GSM networks as an example of TDMA systems with Slow Frequency Hopping (SFH) and switched-beam antennas is determined analytically and by simulation [Ahm2000-1, Ahm2000-2]. As shown in chapter 5, the system performance is determined with and without power control to estimate its effect on the system capacity.

5. A novel call admission control algorithm is developed for SFH-TDMA systems. This algorithm is designed to enhance the network capacity without causing any degradation to the QoS. The capacity gain is determined as demonstrated in chapter 5 using Markovian analysis and computer simulation [Ahm2000-2].

6. An admission and load control algorithm for stream-mode non-real-time data service such as FTP applications is developed for third generation wireless system as presented in chapter 6. The algorithm takes the voice service into consideration and gives it higher priority over the data service [Ahm99].

7. The performance of the proposed call admission and load control algorithm for stream-mode non-real-time data service is determined analytically and by simulation in chapter 6. The system model includes both switched-beam antennas and power control.

1.3 Thesis Organization

An overview of wireless and mobile communications is presented in chapter 2. Chapter 3 provides a review of the related studies to the radio resource management and capacity enhancement using the call admission and load control algorithms published in the literature. Chapter 4 presents the coverage analysis and load control in urban microcells with overlapping coverage. The capacity enhancement in GSM systems with slow frequency hopping and smart antennas is discussed in chapter 5, which also includes the Markovian analysis to determine the system performance with the proposed admission control algorithm. Chapter 6 presents an admission and load control algorithm for multiple services in third generation wireless networks. Finally, chapter 7 presents the main conclusions and recommendations for future research work.

Chapter 2

Wireless and Mobile Communication Systems

2.1 Introduction

The fundamentals of wireless and mobile communications are briefly discussed in this chapter as an essential background for the topics presented in the next chapters.

Section 2.2 overviews the classical wave propagation and channel models. Then, the quality of service expressed in terms of the Carrier-to-Interference Ratio (*CIR*) is discussed in section 2.3. This section also illustrates the *CIR* calculation for different multiple access schemes.

Section 2.4 presents the notion of cellular network capacity with a numerical example for a better insight into this topic.

Smart antennas as effective means of performance improvement and capacity enhancement are discussed in section 2.5. This section discusses the basic structure, the

implementation techniques and the modern channel models developed solely for smart antennas.

Section 2.6 reviews the wireless data and multimedia services particularly in third generation systems.

Wireless network planning is discussed in section 2.7. This section highlights the main items in the wireless network planning methodology.

Finally, section 2.8 presents the radio resource management and its interdependence on the wireless network planning.

2.2 Propagation Characteristics and Channel Modeling [Jak74, Rap96]

Channel modeling is an essential part in wireless network planning, design, and performance characterization. A channel model is a set of formulas and/or graphs that describe the wave propagation from the transmitter (Tx) to the receiver (Rx). There are numerous models that estimate the signal strength as a function of the Tx-Rx separation (r), carrier frequency (f), and the environment type (densely urban, urban, sub-urban, rural, ...etc.). One of the most popular models which estimates the received power P_R in dBW is expressed as

$$P_R = P_T + K + 10n \log(r) + F1 + F2 \quad (2.1)$$

where P_T is the transmitted power in dBW, K is a constant that depends on the antenna gain and carrier frequency, n is the path loss exponent that ranges from 2 to 6 depending

on the environment and area type, $F1$ represents the slow fading and $F2$ represents the fast fading.

Slow fading (shadowing) is usually modeled as a lognormal random process with a zero mean and a standard deviation ranges from 6-10 dB depending on the environment type and the carrier frequency. The fast fading is usually modeled by a Rayleigh distribution. Rice distribution is also used to describe the fast fading. Fast fading is a function of the frequency such that two spaced enough carriers will have uncorrelated fading profile. The minimum spacing between two carriers to have 0.5 fading cross-correlation coefficient is called the coherence bandwidth (B_c).

In mobile communication, the received power can be modeled by a more accurate model based on empirical data collected from different sites and under different conditions. Okumura's model is a family of curves that gives the path loss as a function of the distance between the Tx and Rx for different frequencies and environments. Hata's model is just a mathematical formulation of Okumura's model and it is usually used to model the propagation in macrocells.

More detailed and accurate models are sometimes needed. These models require a detailed description/maps of the covered area. Ray tracing (which is based on Electromagnetic wave reflection, diffraction, ...etc.) is an example of these detailed and accurate models. These models are appropriate for indoor and microcells.

2.3 Carrier to Interference Ratio

In wireless voice communication systems, the QoS mainly refers to the quality of the signal received at/from the Mobile Station (MS). Basically the signal quality is a function of the Bit Error Rate (BER) or the Frame Error Rate (FER) which are determined from the Carrier-to-Noise-plus-Interference Ratio (CINR). Since the interference in cellular networks is more severe than the background noise, the *CIR* is used as a measure of the QoS in voice communications. In this section, the *CIR* is evaluated in the main multiple access techniques used in wireless communications (FDMA, TDMA and CDMA) in the uplink. The downlink *CIR* can be calculated using the same methodology.

In FDMA and TDMA without frequency hopping, the *CIR* calculation procedure is the same. The user in the central cell has 6 cochannel interferers in the first tier and 12 interferers in the second tier. The interference from the second (and higher tiers) is usually neglected because it is much less than that of the first tier. As mentioned in the previous section, the received power is proportional to r^{-n} where r is the distance from the transmitter to the receiver and n is the path loss exponent. Considering the path loss only the *CIR* can be written as

$$CIR = \frac{r^{-n}}{\sum_{i=1}^6 d_i^{-n}} \quad (2.2)$$

where d_i are the distances from the interferer MSs to the Base Station (BS) in the central cell. Assuming that the MS is at the cell boundary and approximating d_i to D (where D is the frequency reuse distance) the CIR expression is simplified to [Cox82]:

$$CIR = \frac{R^{-n}}{6 D^{-n}} \quad (2.3)$$

where R is the cell radius. This calculation corresponds to the worst case because it is assumed that the MS in the central cell is at the cell border and that all the six cochannel interferers are active.

The CIR in TDMA with slow frequency hopping is derived analytically and by simulation in chapter 5. In CDMA, the interference comes from all active users inside and outside the cell of that MS. A simplified expression for the CIR in the uplink in the CDMA is given as follows [Gil91]

$$CIR = \frac{1}{I_{inter\_cell} + DTX (N_v - 1)} \quad (2.4)$$

where N_v is the number of users in the same cell, DTX is the discontinuous transmission factor and I_{inter_cell} is the normalized inter-cell interference. Perfect power control is assumed in deriving this equation such that the received power at the BS from each user is constant and does not depend on the user location. Due to the spectrum spreading, the bit energy to interference density ratio (E_b/I_o) is more relevant to the signal quality in the CDMA and it is expressed as

$$\frac{E_b}{I_o} = (W/R_b) CIR \quad (2.5)$$

where W is the signal bandwidth, R_b is the bit rate and (W/R_b) is the spreading gain.

2.4 Capacity of Cellular Networks

There are various definitions for the cellular wireless network capacity. The total value of carried traffic in Erlang divided by the total allocated spectrum in MHz divided by the total area in km^2 (Erlang/MHz/ km^2) is the most popular definition of the network capacity for voice service. It is sometimes called the spectrum efficiency. Another related definition is the maximum number of users divided by the total allocated spectrum in MHz divided by the total area in km^2 (User/MHz/ km^2). It is determined by dividing the spectrum efficiency by the traffic intensity per user. With the inclusion of data services, the system capacity is usually measured as the maximum throughput divided by the total allocated spectrum in MHz divided by the total area in km^2 (bps/MHz/ km^2).

There are several factors that affect the cellular network capacity; the first one is the spectrum size allocated to the system. The larger the allocated spectrum for the cellular network, the higher the capacity of that network. Although the capacity measures are usually normalized to the spectrum size, the system capacity is still a function of the spectrum size because of the trunking efficiency dependence on the spectrum size.

The resources allocation is another factor that highly influences the network capacity. The infrastructure and radio resources must be utilized efficiently to maximize the capacity. For instance, a high capacity gain can be achieved through tight frequency planning. However this might deteriorate the QoS in terms of the *CIR*. Therefore, some constraints are included in the optimization of the design and planning process to guarantee the QoS as explained in the next sections.

Other factors including the design parameters, the environment and terrain type, and the fixed network performance are very important in the evaluation of the cellular network capacity.

The blocking and dropping probabilities are significant measures of the system capacity from the point of view of the end user. These two measures are inversely proportional to the system capacity so that the blocking and dropping probabilities decrease with the increase of the network capacity. However, both blocking and dropping probabilities are functions of other factors such as the admission control scheme, the area coverage probability, the reserved resources for the handover calls, and the cell size. The condition that both the blocking and dropping call probabilities do not exceed a certain threshold (e.g. 2%) is one of the most important constraints in the design and planning process.

To cope with the growing demand for mobile communication systems, several techniques have been devised to enhance the system capacity such as reducing the cell size through cell splitting, power control, smart antennas and slow frequency hopping [Fru96, Deh97, Mad97].

A numerical example is presented here to clarify the notion of the cellular network capacity. For example, if a TDMA (GSM-like) cellular network is assigned a total spectrum (W) of 2x9.6 MHz for both up link and down link, then the carrier spacing is 200 kHz with 8 users time multiplexed. Each cell is divided into 3 sectors with a frequency reuse factor N of 4/12 and 1 km cell radius. Assume that the control channels have their own band so the 2x9.6 MHz band is entirely allocated for traffic channels. Hence, each sector is assigned 4 carriers, which is equivalent to 32 channels. At 2% blocking probability this gives 23.74 Erlang per sector with 75% trunking efficiency.

Therefore, the network capacity (spectrum efficiency) is equal to 1.24 Erlang/MHz/km². It is straightforward to show that using this frequency planning, the worst case CIR is greater than 12 dB without considering the shadowing, while 90% of the MSs have $CIR > 12$ dB when the fading is taken into consideration.

This relatively high capacity is achieved because of the large allocated spectrum and the small cell size assumed in the example above. This simple example demonstrates the notion of system capacity. The typical value of the system capacity in GSM networks ranges from 0.2 to 0.6 Erlang/MHz/km².

Discontinuous Transmission (DTX) and half-rate speech encoders that are widely employed in most of the existing cellular wireless network are not included in these calculations. Each can double the network capacity. However, higher capacity gain can be achieved by combining them with other capacity enhancement techniques such as smart antennas.

2.5 Smart Antennas

Smart antennas consist of a set of M omnidirectional antenna elements. The received signal is obtained by combining the received signal at each element weighted by a complex value. The weights are adjusted according to the implementation technique as explained below.

Smart antennas have been proposed as an effective means for providing high capacity associated with an improved performance. In the last few years many studies and field measurements have shown that the impact of the smart antennas arrays is promising, but with a considerable additional cost and complexity. The key element in smart antennas is the antenna directivity used at the base station to reduce the cochannel interference and maximize the *CIR*.

2.5.1 Implementation Techniques [Gdr97-1, Gdr97-2, Lit96]

In this subsection, four implementation techniques of smart antennas are briefly discussed along with the pros and cons of each. The last three techniques are just different forms of the adaptive antenna arrays. They have the same structure but with different objective functions.

a) Multiple Beam Antennas

M fixed beams are used at the BS. For instance, 12 beams with 30° beamwidth each can cover the whole cell. The MS is to be connected to the beam that provides it with the highest power (or *CIR*) level. Hence a switching from one beam to another is needed when the MS crosses the boundary between two beams. Thus, it is also called "Switched-Beam Antennas". This implementation technique does not need any complex hardware or sophisticated dynamic weight adjustment algorithms. Consequently it is considered as the simplest technique.

b) Adaptive Beam Forming

In this technique, the direction of the MS is estimated using Direction of Arrival (DOA) algorithms. Then the weights are adjusted to direct the beam into the MS. Since a continuous tracking of the MS is needed, it is also called "User Tracking Antennas". It is possible to cover more than one user by a single beam provided that they are close enough to each other and they do not use the same channel. Direction estimation and weight adjustment is a sophisticated process and needs additional hardware and complex algorithms for accurate tracking and pointing.

c) Null Forming

As the objective of the smart antennas is interference reduction, this can be achieved by directing the nulls of the antenna pattern towards the cochannel interferers. This is applicable in both the uplink and downlink. Using M elements, it is possible to cancel $(M-1)$ interferers using null forming. However this technique is not effective in mobile communication environment because of the multipath propagation and the frequent change of MS locations. This technique cannot be used with SFH-TDMA or CDMA because with the former, the cochannel interferer locations are changing every frame (4.614 ms in GSM) while with the latter the number of interferers inside and outside the MS cell is extremely large.

d) Optimal Combining

In this technique, the weights are adjusted to maximize the CIR . The estimation of the user direction is not required. It is sufficient to know the desired signal or even a correlated reference signal. The weights are adjusted such that all interfering signals (which are uncorrelated with the reference signal) will be suppressed and as a result the CIR is maximized.

The complexity of this system is moderate but if a special signal is used for weight adjustment this will reduce the throughput of the network. In CDMA, the channel code can be used for this purpose. Some recent studies show that the use of the training

sequences in TDMA systems (such as GSM and IS-136) for the weight adjustment is also possible.

The multiple beam antennas and optimal combining techniques are the most promising ones. The adaptive beam forming technique is very effective in maximizing the *CIR*. However the system complexity and the necessity of the DOA estimation are significant factors that might slowdown the utilization of adaptive beam forming in cellular systems. The null forming technique has many difficulties and complications in mobile communication systems especially in CDMA and SFH-TDMA networks as mentioned above. However the null forming technique can be a good candidate in fixed wireless systems.

2.5.2 Channel Models [Ert98, Win98]

Considering the inclusion of smart antenna with its promising effect on the system capacity improvement and service quality enhancement, the classical channel models mentioned above are sometimes not adequate for analyzing the performance and determining the signal quality. Spatial and temporal information such as Angle of Arrival (AOA), Time of Arrival (TOA), ...etc. are needed because different techniques and algorithms of smart antenna implementation use this spatial and temporal information in the weight adjustment.

Modern models have been developed to cope with these new requirements. Some of those models have been developed and modified from the old models of the space diversity.

In the last few years, microcells are widely used and deployed in most of the cellular networks as one of the effective means to increase system capacity and improve service coverage. The propagation models for microcells are quite different from those of the macrocells. The base station antennas of the former are always placed at the same height of the surrounding buildings, which means that the scatterers are around the MS and the BS as well. In the latter, the BS antennas are much higher than the surrounding buildings. Thus, it is acceptable to assume that there are no scatterers around the BS in macrocells. This introduces large variations between micro- and macrocells in the signal level, AOA, and TOA.

a) Time-Varying Vector Channel Model (Raleigh's Model)

In this model, it is assumed that there are dominant reflectors in the propagation environment. The received signal is given as the sum of all the reflected signal components weighted by the array response.

b) Geometrically Based Single-Bounce Statistical Channel Models (GBSBSCM)

These models are characterized by a spatial scatterer density function. The form of the scatterer density function depends on many factors such as the cell type (macro or micro), environment type (urban or rural), and many other factors. The scatterers are randomly placed according to this scatterer density function and then the signal amplitude, the AOA, and TOA are determined.

1-Macrocells GBSBSCM : In Macrocells GBSBSCM the scatterers are assumed to be distributed uniformly in a circle centered around the MS with a radius R_m which is less than the BS-MS separation (r). Several measurements suggested different values for R_m . It is shown that for $r=1$ km, the best value for R_m is 200m.

2-Microcells GBSBSCM : The difference in this case is that the scatterers are assumed to be around both the BS and MS. This model assumes that the scatterers are distributed uniformly in an elliptical area while the BS and MS are located at the foci of this ellipse. The selection of the elliptical shape can be well justified by noting that for any point inside this ellipse (which is a potential place of a scatterer) the delay τ of the path passing by this point is less than some threshold value τ_m . Thus the choice of τ_m determines the ellipse size. The GBSBSCM models are simple and well suited to the simulation purposes. The comparison with field measurements shows a good agreement between these models and the measured values.

c) Typical Urban - Bad Urban Models

These models are essentially developed for simulation purposes of GSM networks in urban areas. In the typical urban model, 120 scatterers are uniformly distributed within 1 km radius about the mobile. The position of the scatterers are updated after each five-meter movement of the MS. Random phases and random shadowing are assigned to each scatterer after updating the location.

In the bad urban model, an additional scatterer cluster is introduced. This cluster is shifted by 45° from the first one. This additional cluster increases both the angle spread and the delay spread.

There are some other models such as the Lee's model which places the scatterers in a circular ring about the MS, and the Gaussian Wide Sense Stationary Uncorrelated Scattering (GWSSUS) in which N scatterers are grouped into clusters in space such that the delay differences within each cluster are not resolvable within the transmission signal bandwidth.

2.6 Wideband Wireless Communication Systems

Wideband Wireless Communication Systems can be considered as an evolution of the narrowband services offered by second-generation wireless systems (GSM, IS-136 and IS-95). The need for high-speed data services, global roaming and worldwide compatibility is the main driving force for 3G wireless systems. The success and maturity of the existing cellular system in addition to the rapidly growing popularity of the Internet motivates the research institutes, the standardization bodies and leading companies to plan and pave the road for the technologies and standards of the third generation wireless systems. IMT-2000 and UMTS are third generation wireless systems standardized by the International Telecommunication Union (ITU) and the European Telecommunication Standardization Institute (ETSI) respectively. The main system requirements, capabilities and key features of the IMT-2000 and UMTS are as follows:

- High-speed data services encompassing circuit and packet switched mode transmission tailored particularly for Internet access services such as Web browsing, FTP, E-mail and multimedia applications.
- Hierarchical Cell Structure (HCS) including picocells, microcells, and macrocells.
- Portable pocketsize terminals.
- Improved voice-quality service compared to that of the current second-generation wireless systems.
- Fast power control and seamless inter-frequency handover.
- Support of smart antennas and multi-user detection.

Wideband CDMA has been chosen as the multiple access technique for the IMT-2000/UMTS. TDD-CDMA and OFDM are also approved as standards for third generation. W-CDMA, the European and Japanese proposal, is briefly presented below. Other proposals can be found in [Zen98, Oja98-1, Oja98-2, Kni98-1, Kni98-2].

The channel bandwidth is 5 MHz at 2 GHz with a chip rate of 4.096 Mcips/s. This bandwidth can support data rates from 144 kb/s to 384 kb/s for wide area coverage and up to 2 Mb/s for local area coverage. Larger bandwidth (10,15 or 20 MHz) is also proposed for higher data rates.

Orthogonal Variable Spreading Factor (OVSF) and code aggregation are considered for variable bit rate services. Either time multiplexing or code multiplexing can be used for service multiplexing emerging from the same source.

Control channel data is time multiplexed with the traffic data in the downlink. In

the uplink, the control channel data is transmitted in parallel to the traffic data in a separate dedicated channel.

In the downlink, data is modulated as quaternary phase shift keying (QPSK) using a channelization code and then scrambled by a cell-specific code. In the uplink, the data is modulated in dual-channel QPSK using two different codes in the I and Q rails. Then it is scrambled using complex scrambling coding.

Radio Link Control (RLC) layer divides the data messages into smaller packets with a fixed size. A header is added to each packet. It contains a sequence number for the ARQ and CRC for error detection.

There are two methods for packet transmission. In the first one, packets are transmitted in the Random Access CHannel (RACH) using slotted ALOHA technique. This is suitable for short and non-frequent messages. For longer or more frequent messages, a request has to be sent by the MS first. The BS/MSC estimates the interference that will be experienced by other users if that user is accepted and the interference that will be experienced by that user from the current active users. Then, it decides to admit that user or not. If admission is granted, the user is informed about the power and data rate levels to be used in the resource allocation message. The user still cannot transmit before it gets the starting time from the network. At that time, the user can start transmitting. The allocated rates are not fixed and they can be dynamically changed during the session depending on the network loading and propagation conditions.

2.7 Wireless Network Planning

Wireless network planning is a complex process that involves considerations of a large number of interdependent parameters and variables. Furthermore, cost considerations make it essential to optimize the network structure and the infrastructure deployment.

The wireless network planning and infrastructure deployment is based on five steps. The procedures and processes associated within each step are iterative. The main steps are:

I-Radio Coverage Optimization

The first step in the planning process is to determine the radio coverage. Radio coverage is a function of both propagation characteristics and the traffic/capacity relationship. The coverage function is determined using the channel models presented above. The main result of this step will be the identification of a feasible set of BS sites and the cell boundaries such that coverage requirements are met. The selected sites and number of cells are to be modified in later steps to take into account the required network capacity and interference considerations.

II-Traffic Distribution Analysis

This analysis represents the second step of the planning process and involves

assembling the essential input data related to expected network traffic. This data includes the area of coverage, user profiles and distributions, the coverage planning target and the range of services to be provided. The user mobility should be incorporated in the traffic analysis.

III-Network Resource Dimensioning

This step accepts as input the results of the traffic distribution analysis, the frequency allocation plan, the cell sites determined in the radio coverage optimization analysis, and the BS radio parameters. The main task is to compute the capacity of the macrocells and to determine if the network performance requirements are met. Then the actual traffic distribution can be considered to determine the number of required microcells.

IV-Validation of Network Dimensioning

The previous steps provide feasible network architectural options. It is essential to analyze the impact of mixed services and traffic variations using simulation and analytical tools. These tools can be used to examine the performance under different loading conditions. If the performance measures are found unsatisfactory, another iteration for the first three steps is performed.

V-Rollout Plan Consideration

In practice, network deployment takes place in stages. Several technical and economical considerations are included in this process such as the probable delays associated with the site acquisition, the expected traffic density, and the infrastructure cost factors. The wireless network is likely to be activated first in major user and population centres.

In the next chapters, wireless network performance analysis and capacity determination based on simulation and analytical tools are discussed and addressed in different environments and operating conditions. These tools are essential in wireless network planning particularly in the third and fourth steps (network resource dimensioning and network validation) discussed above.

2.8 Radio Resource Management

The wireless network planning and radio resource management are highly interdependent since both deal with the efficient allocation of network resources. The wireless network planning, as mentioned above, mainly aims to optimize the allocation of network infrastructure such that the coverage and capacity requirements can be met with minimum cost. Then, the radio resource management complements the network planning by optimizing the radio resources allocation to achieve the highest possible capacity. Wireless network planning has a strong impact on the radio resource management since

the amount of the available resources and the flexibility in managing these resources are essentially determined by the network planning. For instance, the number of BSs and their spatial distribution throughout the served area can influence to a great extent the number of channels per cell as well as the utilization of these channels. Furthermore, the radio resource allocation policy can influence the capacity demands, which affects the requirements of the network infrastructure in the network planning process.

The main function of the radio resource management is to assign for each requested call (in both the uplink and downlink) a waveform (channel/code), a transmit power, an access port (BS), and a transmission rate (if a variable rate data service is considered) [Zan97]. This assignment process is optimized such that rejection of the call requests is minimized to keep the rejection rate as low as possible. Meanwhile, the resource allocation algorithm must take the QoS (represented by the *CIR*) constraints into consideration in the assignment procedure.

The problem of the channel allocation has been given a great deal of attention in FDMA/TDMA systems. Various channel allocation techniques are proposed for cellular radio communications such as static channel schemes, dynamic channel techniques, handover-reservation policies, random channel allocation methods such as frequency hopping, and spectrum sharing/partitioning strategies for multi-layer structures. Each of these channel allocation techniques suits certain traffic patterns, network structures, and loading conditions.

Power control algorithms essentially aim to regulate the transmitter power of the MSs and BSs to achieve less interference, better signal quality and/or longer battery life (in the MS terminals). Power control is also required to combat the near-far problem

especially in CDMA. *CIR* and received signal strength are usually used as criteria for power control. Slow power control techniques are commonly used to compensate for the path loss and shadowing. Fast power control is included in 3G systems to compensate for the fast fading. Power control algorithms can be either open loop or closed loop depending on the symmetry between the uplink and downlink. For example, in TDD-CDMA 3G systems, there is a notable symmetry between the propagation conditions and channel characteristics in the uplink and downlink, and as a result open loop power control schemes can be utilized.

The access port assignment is usually considered as the simplest function in the radio resource management. The MS is usually connected to the BS providing it with the best quality (in terms of the *CIR* or received signal strength). However, when there is overlapping coverage the problem is no longer straightforward. Some techniques such as directed retry, load sharing and soft handover are capable of enhancing the system capacity as discussed in chapter 3.

If the network design is based on multi-layer structures, then the assignment of users to the BSs in the different layers becomes a challenging task. Some algorithms proposed the user speed as a criterion for layer assignment. Some issues like traffic overflow and take-back between different layers should be taken into consideration in resource management. With overflow, the mobile user can be directed to the other layer (macro-cell layer for low mobility users or micro-cell layer for high mobility users) if the proper layer (macrocell layer for high mobility users or micro-cell layer for low mobility users) has not enough resources. The take-back option tries to redirect the mobile user to its proper layer after this layer restores enough resources due to a call completion or a call

handoff departure. The take-back aims to eliminate the possibility of keeping the high mobility user in the micro-cell layer which leads to a high handoff rate and can eventually cause call dropping. Also, to avoid the possibility of keeping the low-mobility user in the macro-cell layer, which is considered an inefficient utilization of the macro-cell resources. It is imperative to consider the multiple-service scenario and its interaction with multi-layer structure. In this scenario, voice and data services coexist with different QoS requirements, mobility patterns, and service coverage.

In third generation wireless systems, some data services such as web browsing, file transfer services, and video transmission can tolerate the variability of the transmission rate. Hence, the radio resource allocation algorithm is required to control the transmission rate assigned to each data user. The objective of the data rate control is to assign the highest possible data rate for most (or all) of the data users. However, high data rate calls are associated with high transmission power and are likely to cause high interference to other calls. Therefore, the QoS constraints and the capacity demands of other services (such as voice service) must be taken into consideration in the rate control procedure. Thus, the more information acquired for the rate control, the better it performs. In 3G systems, auxiliary pilots are used to estimate the interference level, the spatial distribution, and propagation conditions. Data rate control can be implemented in CDMA using variable spreading or multiple code assignment.

Call admission and load control is considered as the core of the radio resource management. The call admission control deals with the call arrival (new or handover) to decide whether the call can be admitted to the system. This decision is based on the availability of the resources. For instance, the call request can be rejected if the admission

control algorithm has no enough resources or cannot find a feasible power assignment. Admission control algorithms are either based on a threshold value of the resources utilization or the QoS constraints. The call admission control is optimized such that erroneous decisions (by admitting calls when the QoS constraints will be exceeded or rejecting calls while some resources can be afforded) are minimized. The admission of data calls is a formidable process particularly with mixed services provision. The load control handles the network loading and its allocation to the BSs. Also, the data rate assignment for data users is an essential part in the load control. Thus, the main task of the load control is to maintain the availability of the radio resources and the QoS requirements for the admitted users.

Call admission and load control has a direct impact on the system capacity and QoS. Hence, the enhancement of the call admission and load control is one of the most vital goals in cellular radio systems. In the next chapters, this problem is investigated in different environments.

Chapter 3

Call Admission and Load Control Algorithms in Wireless Networks

3.1 Introduction

The capacity of wireless networks depends -to a great extent- on the performance of the call admission and load control. In this chapter, a review of the call admission and load control algorithms in wireless communication systems and their impact on the system capacity is presented. In section 3.2, the system capacity of cellular networks is discussed through publications covering the interference-limited capacity concept, *CIR* analysis, and capacity enhancement techniques for networks with soft capacity. The call admission and load control algorithms of a single service in SFH-TDMA and CDMA system are then discussed in section 3.3. Also, the call admission and load control algorithms for cellular networks with overlapping coverage are discussed in this section.

Call admission and load control algorithms constitute an essential part of the radio resource management layer in 3G wireless systems, particularly in wideband CDMA systems. Several admission and load control algorithms proposed for 3G wireless networks with multiple service are discussed in section 3.4. Finally, section 3.5 presents the problem statement.

3.2 Wireless Network Capacity Analysis

Frequency reuse planning has a direct impact on system performance and network capacity. There are two main approaches for frequency planning. In the first one, a large frequency reuse factor N (between 7 and 12) is used. This sparse allocation of the radio resources can guarantee the QoS in terms of CIR . However, this approach limits the number of allocated channels per cell, and as a result a high blocking rate is encountered particularly at high traffic loads. The network loading must then be restricted to keep the blocking rate under a certain threshold (e.g. 2%). Hence, the wireless network capacity is considered blocking-limited rather than interference-limited.

In the second approach, a tight frequency planning is used. For instance, N can be reduced down to 3 or even 1. In this case, a large number of channels are available per cell. This reduces the blocking rate dramatically. On the other hand, high cochannel interference can be experienced unless the network loading is restricted. Accordingly, the wireless network capacity in such a case is interference-limited. Since only a fraction of the available radio resources can be used simultaneously, this approach is usually called (fractional loading technique). Slow frequency hopping is always employed with

fractional loading to achieve interference averaging as explained in section 2.4. As the system capacity is interference-limited, it is essential to analyze the interference and outage performance.

In [Lee95], the *CIR* of TDMA systems is determined analytically in the uplink as well as the downlink. Perfect power control, frequency hopping, and discontinuous transmission are employed with and without sectorization. The average *CIR* is plotted versus the reuse factor N at different values of the Voice Activity Factor (VAF). It is found that for a GSM-like network, N can be reduced to 3 with sectorization (3 sectors/cell). It is assumed in this study that the system is fully loaded. The first approach of the frequency planning (sparse channel allocation) is adopted in this study. However, the analysis can be readily modified to consider the second approach of the frequency planning (fractional loading).

The capacity of GSM networks using fractional loading is studied by simulation in [Joh95]. Frequency hopping, power control and discontinuous transmission are also included. However, a more realistic power control technique is used in this study. A power control algorithm based on the received signal with a 20 dB dynamic range is utilized. It is found that the power control increases the *CIR* by 3.5 dB. The gain due to the discontinuous transmission with 0.5 activity factor is 3 dB. A static simulation is used first to analyze the effect of some design parameters such as the antenna pattern and the path loss exponent. Then a detailed dynamic simulation is used to consider the system dynamic behavior including the frequency hopping, power control and discontinuous transmission. It is found that the optimum reuse pattern is 1/3 (N is equal to 1 and number of sectors per cell is 3). This frequency reuse plan gives 74% capacity gain compared to

the 4/12 reuse pattern (N is equal to 4 with 3 sectors per cell). It is shown that the soft capacity limit is significantly higher than the hard capacity limit particularly when frequency hopping is employed combined with power control and discontinuous transmission.

An analytical approach for the same problem –the capacity analysis of TDMA cellular system with frequency hopping- is presented in [Chen96]. Imperfect power control is assumed by modeling the received power as a Log-normal random process. The performance is measured by determining the probability of code word error using Reed-Solomon coding. Discontinuous transmission with 0.5 voice activity factor is included in the analysis. Omni-directional antennas are employed at both the MSs and the BSs. The results indicate that a spectral efficiency of 17.5 user/MHz/cell can be achieved with a 1% worst case of code word error probability over 95% of the cell area.

The capacity improvement in GSM cellular networks due to frequency hopping with a limited number of carriers is investigated in [Tun97]. Neither power control nor discontinuous transmission is included in the system model. The system performance with slow frequency hopping is compared with the intra-timeslot handover technique. Computer simulation is used to estimate the outage probability in urban and suburban environments. The results show that intra-time slot handover provides better performance than 2 channel frequency hopping when the mean CIR is less than 16 dB. If 4 carriers or more are used, slow frequency hopping surpasses the intra-timeslot handover in both urban and suburban environments and at any value of the mean CIR .

The capacity of GSM networks and the main factors influencing the system performance are outlined from a practical perspective in [Wor97]. Capacity enhancement

techniques are discussed with approximate figures of their impact on the system capacity. Many techniques are included in this study such as frequency hopping, power control, discontinuous transmission, half rate encoding and smart antennas. The average gain of the *CIR* from utilizing power control -determined by simulation- ranges from 1.5 to 2.5 dB. It is also shown that the minimum required *CIR* can be reduced from 16 dB to 8.5 dB by including the slow frequency hopping. Queuing and routing of new calls to neighbor cells are proposed as an effective method to improve the trunking efficiency.

Smart antennas have a strong impact in network capacity and system performance in terms of signal quality and area coverage. In [Nag94], a semi-analytical study of the smart antennas in cellular CDMA is presented. It is assumed that the BS is code locked onto every user, but DOA is not known and the power control is perfect such that the received power at the BS from all mobiles are equal. An optimum combining scheme is used by estimating the array response vector (steering vector) from the pre-correlation and post-correlation covariance arrays. Some approximations are used to simplify the analysis. For instance, it is assumed that the optimum combining beam-forming process is perfect such that any user will not introduce any interference to the desired MS unless it lies within its beam area. The inter-cell interference (for a large number of users) is approximated as a Gaussian random process. The results show that a substantial increase in the system capacity is achieved by incorporating antenna arrays at the BS.

In [Ho98], the performance enhancement is analyzed for TDMA (IS-54) cellular systems using switched-beam smart antennas. A perfect beam-switching antenna is utilized with 12 beams (30° beamwidth). Hexagonal cells with 3 sectors are used to cover the served area. Two trunkpool techniques are used. In the sector-trunkpool, all the

channels assigned to a sector are shared by all four beams in that sector, while in the omni-trunkpool technique, any of the channels assigned to a cell can be used by any of the twelve beams in the cell. The channel utilization is taken as 100% (fully loaded). Both perfect and practical power control techniques are employed in this work. The main difference between the uplink and downlink analysis is the number of cochannel interferers, and the unfeasibility of having diversity at the MS. Two performance criteria are used in this study. The first one is the area-averaged probability P_1 that the received CIR exceeds a target value (CIR_{min}), while P_2 is defined as the percentage of the cell area where the received CIR exceeds the target value 75% of the time. It is shown that for switched-beam smart antennas the performance with the first criterion is considerably improved, but with the second criterion the improvement is much less. It is also shown that the bad areas (areas with $CIR < CIR_{min}$) are concentrated in radial sectors because this area corresponds to the radial sectors that point directly to the first-tier of cochannel cells. It is found that the performance is almost the same for both perfect and practical power control.

In [Iva98], upper bounds of the capacity gain are estimated for various smart antenna techniques in GSM networks. Perfect beam-selection and beam-forming techniques are assumed to simplify the simulation. It is assumed that DOA of the desired user and the cochannel interferers is known. Ideal beams (for beam switching and beam forming) have been introduced such that its width shrinks to zero while pointing to the MS. Interference canceling using notch (or null) forming is also assumed to be employed perfectly. Random slow frequency hopping is used while the channel utilization is taken as 50%. A considerable capacity gain is remarked especially when frequency hopping is

utilized. Ideal adaptive beam forming is also used, and it is found that its capacity gain is comparable to that achieved by fixed beams. Because of the complexity of the adaptive beam forming, the switched beam technique is more practical and cost efficient for capacity enhancement.

In [Oja98-1], a capacity analysis based on system level simulation is given. The simulator contains 19 macrocells and 128 overlaid microcells for W-CDMA system. Fast power control based on the *CIR* level is used to compensate for the fast fading. Soft handover, antenna diversity and Multi User Detection (MUD) are utilized in the simulation, while sectorization and smart antennas are not included in the system model. The system capacity is defined as the spectrum efficiency in bps/MHz/cell at 5% outage probability.

In the uplink, the estimated capacity with a conventional RAKE receiver (without MUD) is 2.0 users/MHz/cell, and with MUD (with 65% interference cancellation efficiency) the capacity can reach 4.7 users/MHz/cell with a 74-Kbps service. The system capacity is also determined analytically for verification. It is shown that there is a good agreement between the simulation and theoretical results with a small offset due to the Gaussian approximation of the inter-cell interference.

In the downlink, less capacity figures are achieved. For instance, with the 12-Kbps service, the uplink capacity is 192 kbps/MHz/cell, while the downlink capacity is only 108 kbps/MHz/cell. For the 144 kbps service, the uplink capacity is 388 kbps/MHz/cell, while the downlink capacity is still 108 kbps/MHz/cell. The downlink capacity is almost 40-50% of the uplink capacity since both the MUD and the antenna diversity cannot be

utilized in the downlink. A 2-Mbps service is also simulated, but the downlink capacity does not exceed 80 kbps/MHz/cell.

A proposal for a wireless Internet access service, Advanced Cellular Internet Service (ACIS) is given in [Chua98]. ACIS is designed primarily for Web browsing with a peak rate up to 2 Mbps in the downlink using TDMA. Multicarrier modulation using Orthogonal Frequency-Discrete Multitones (OFDM) is used to overcome the difficulty of the equalization of the wideband signal. Antenna diversity and error correction coding are used to reduce the required CIR. A dynamic channel algorithm, called Dynamic Packet Assignment (DPA), is designed based on two techniques: interference measurement and channel segregation. In the DPA algorithm, the BS broadcasts the IDs of the MSs, number of packets for each MS and a list of the available downlink channels. Next, each MS scans the pilot carriers and sends the results of this measurement to the BS. Then the BS assigns channels to all packets and sends packets to the MSs.

The system performance is evaluated using computer simulation. The simulated network consists of 36 BSs with 3 sectors per cell. A frequency reuse of 1 is used with the possibility of reusing the same channel in the same cell in another sector. ARQ is used with a perfect feedback.

From the simulation, the spectrum utilization is determined as a function of the probability of packet retransmission. A 3-4% retransmission probability is accepted as the target level. It is shown that 25-50% spectrum utilization can be achieved with two carriers if multiple-beam smart antennas are used. Without multiple-beam smart antennas, three carriers are needed to achieve the same spectrum utilization.

3.3 Call Admission and load Control in Cellular Networks with Single Service

As mentioned in chapter 2, the call admission and load control algorithms play an important role in allocating the radio resources efficiently and maintaining the signal quality at an acceptable level. In [Bem97], an admission control algorithm for frequency hopping GSM networks is proposed. The proposed algorithm -Traffic Load Admission (TLA)- considers the traffic loading in the cell of the incoming call and its cochannel neighboring cells. Each cell with its six cochannel interferers in the first tier constitutes together what is called interference area. When a call is attempted in a cell, the loading factors in all interference areas that include that cell are checked. If all of them are less than the threshold value (e.g. 60% in this study), the call is admitted, otherwise the call is rejected. Slow frequency hopping, discontinuous transmission and power control are employed. Computer simulation is used to assess the system performance and the capacity gain. Two reference systems are used for comparison. The first one does not use admission control at all, and thus, the system can be fully loaded (100% utilization) while the second one uses a local admission control criterion where the loading factor in each cell individually is limited to 60%. It is found that the offered traffic is increased from 11.9 Erlang/cell to 15.7 Erlang/cell with acceptable signal quality when TLA is used. This is almost 32% increase in the capacity. It is also shown that capacity gain can be increased to more than 49% if hot spots are considered.

Two call admission strategies are investigated in [Ish97]. The first one is based on the number of users, while the other is based on the interference level. Although this study is for narrow band CDMA systems, the presented analysis and conclusions are still

applicable for any wireless network with soft capacity. Theoretical expressions for the QoS and GoS as functions of the traffic intensity are derived. Then the call admission threshold for both techniques is determined. Computer simulations are used to validate the results and to derive the pdf of the intra-cell interference. The dependence of both the blocking rate and the outage probability on the admission threshold is determined to find the optimum threshold value. The results show that the system capacity of these two admission techniques is almost the same. The admission control based on the interference level has the advantage that its threshold is not highly dependent on the system parameters, unlike the case of the admission algorithm based on the number of users. However, the former algorithm requires more complex hardware for interference measurements.

The inevitable overlapping coverage in wireless networks can be exploited to increase the system capacity by reducing the probabilities of call blocking and dropping. In [Kar89], a call admission and load control called load sharing is proposed. Load sharing is an extension of a preceding algorithm called directed retry. In directed retry, users access the best serving cell (not necessarily the nearest cell). If the best serving BS is fully loaded, those users who can access more than one BS are directed to the neighbor BS to avoid call blocking or dropping. Note that users in non-overlapping coverage areas do not take advantage from the overlapping among the neighbor cells and experience more blocking and dropping than those in overlapping areas. With load sharing, the users access the best serving BS. If the loading factor exceeds a certain threshold F_1 ($F_1 < 100\%$) all the active users as well as the new users in that cell are advised to check the signal quality in the neighbor cells. After receiving the measurements from the users, the BS

directs the new users or/and some active users to move to a neighbor cell provided that that cell has a load factor less than F_2 , where $F_2 < F_1$. The cell loading can be modeled by a Markov chain with states equal to the number of occupied channels. The results show that a considerable reduction in the blocking probability can be achieved by using load sharing. The main drawback of this algorithm is the increased number of hand-offs because of the switching of the ongoing calls.

In order to reduce the number of hand-offs, another algorithm called channel rearrangement is proposed [Chu95]. This algorithm tries to capture the advantages of both techniques the directed retry and load sharing. Like the directed retry algorithm, the channel rearrangement minimizes the number of handovers by not directing the users to move to the neighbor cell as long as the loading factor is less than 100%. Like the load sharing algorithm, the BS directs the users in the overlapping areas to move to a neighbor cell to avoid blocking a user in a non-overlapping area when the BS is fully loaded. The results show that both the blocking probability and the hand-off rate are considerably reduced due to the use of the channel rearrangement algorithm.

3.4 Call Admission and Load Control in Cellular networks with Multiple Service

The design and analysis of admission and load control policies for multiple service in CDMA systems have been studied in some published work, e.g. [Ish97, Ram98]. Although most of these studies are developed for narrowband CDMA, some of the design concepts and performance analyses given in these studies can be extended to suit the wideband CDMA systems.

In [Yan94], two service classes are studied, voice service and delay-tolerant data service. Packet transmission is used for both services. The discontinuous transmission (DTX) is not considered in the voice traffic model. However, the DTX is taken into account by increasing the threshold value of the voice user number from (K_v) to $(E_v=K_v/VAF)$, where VAF is the voice activity factor. The number of arriving data packets is assumed to follow the Poisson distribution with mean rate λ_d . The admission policies are studied in the downlink (forward link) with the possibility of data packet queuing at the BS. Voice packets are given high priority over data packets to preserve the GoS of the voice service.

Two admission control algorithms are used for the voice service. In the first one, called direct admission policy, the voice call is accepted as long as there is an available channel (code), otherwise the call is blocked. The second admission algorithm, called optimal admission policy, is based on semi Markovian decision process. A cost function, which is equal to the number of the blocked calls, is minimized using the value-iteration algorithm. The optimum admission decision is the solution of such minimization problem. The blocking probability of the voice calls using both techniques is determined analytically by solving the Markov chain representing the cell status.

In order to analyze the packet data service, it is assumed that the voice traffic is quasi-static with respect to the data traffic. Two techniques are used for data packet admission. The first one, called threshold model, sets a maximum (threshold) value for the number of data packets ($K_d < E_v$). If the number of the voice users (N_v) is less than K_d , $(K_d - N_v)$ channels can be allocated for data users, otherwise no channels will be available to the data users and all data packets are queued. In the second technique, called graceful

degradation, all arriving data packets are allocated channels as long as the total number of packets (data and voice) does not exceed K_v .

It is shown that the reduction factor in the blocking probability of the voice calls can be as high as 15% due to the use of the optimum admission policy compared to the direct admission algorithm. The data throughput, data-packet delay, data-packet loss probability and packet error probability are determined analytically as a measure of the algorithm performance under heavy and light voice loading conditions.

The results show that the graceful degradation model has a better performance particularly at high data loading rates. At high data rate ($\lambda_d > 2$ packet/slot), the graceful degradation model increases the throughput, reduces the data-packet delay and loss probability substantially. However, this enhancement comes at the expense of a higher packet error probability, which is considered as the main disadvantage of the graceful degradation model.

In [Dzi96], a framework for adaptive traffic admission is presented. In order to accommodate variable rate services with a nonstationary and nonuniform traffic, a good estimation of the interference level of the incoming calls has to be utilized. Three call admission strategies for the uplink in CDMA system are proposed in this study. These admission algorithms mainly differ in the amount of information used for deciding to admit/reject the incoming call. The first one, called fixed strategy, considers only the traffic parameters of all sources in the cell of the incoming call. The second technique, called local adaptive strategy, uses the traffic parameters and the channel characteristics in the cell. The third technique, named global adaptive strategy, extends the scope of the information sources to include all the neighboring cells.

There are two main parts of the proposed framework, the estimation part and the decision part. In the estimation part, the mean and variance of the interference level are estimated using the mean and variance of the interference level of the active calls from the measurements using a Kalman filter. The mean and variance of the interference due to the new call are also predicted. The total interference is assessed by adding the estimated interference of the active calls, the predicted interference due to the new call plus and the reservation threshold (a reservation for the estimated interference variance and errors). Then, the decision part decides whether to admit the new call or not by comparing the total interference to the maximum interference threshold $I_{\max}$.

The admission algorithm performance is analyzed by simulation. The modeled cellular network consists of 49 (7x7) square cells. However, the performance metrics are evaluated in the central nine cells. A homogenous traffic sources with a Poisson distribution is used for the sake of the simplicity. A spatial traffic distribution within each cell is assumed. However, different traffic densities are assumed in the central nine cells. The user mobility and handover process are not taken into consideration. Two power control techniques are utilized in this simulation; perfect power control and SIR-based power control.

The results show that the Kalman filter reduces the estimation error, and as a result a better utilization of the system resources can be achieved by using a smaller reservation parameter. The local strategy with *CIR*-based power control gives a capacity gain in the order of 10-27% compared with the fixed strategy depending on the traffic spatial distribution. The local strategy with perfect power control gives a capacity gain in the order of 3-20% compared with the fixed strategy. The global strategy with *CIR*-based

power control gives a capacity gain in the order of 17-33% compared with the fixed strategy. The global strategy with perfect power control gives a capacity gain of the order of 7-22% compared with the fixed strategy.

It is evident that the global strategy surpasses the other two techniques since the algorithm takes advantage of the extra information obtained from the neighboring cells. It is also shown that power control based on the *CIR* gives better results than the perfect power control. Additional gain is achieved by giving higher priority for calls in neighboring cells over than the calls on the cell. This gain comes from the fact that when the BS is close to its maximum loading, it is better to reject one call in its cell to be able to accept several calls in the neighbor cells.

A combined power and admission control algorithm for the reverse link in W-CDMA systems is presented in [Par99]. Three stream-mode traffic categories are defined with a bit rate (R_b) of 9.6, 64 and 128 kbps. The first traffic category is suitable for a voice service, while the second and third categories are suitable for data services with medium and relatively high rate transmission.

An optimum power allocation scheme has been developed to determine dynamically the power level for each MS in the three traffic categories. The algorithm calculates the optimum power levels that satisfy the outage probability constraints for all users iteratively. Both the inter-cell interference and the intra-cell interference are assumed to follow Gaussian distribution.

When a call arrives to the network, the optimum power levels are determined using the proposed power allocation scheme. Then, the constraint of the total power (P_{tot}) is checked assuming that P_{tot} follows Gaussian distribution. If the user can be assigned

the power level without violating the constraint, the user is admitted to the network, otherwise this call is blocked.

The system performance and capacity per cell are determined by solving the power constraint numerically. The Voice Activity Factor (VAF) is 0.375 and the bandwidth is 10 MHz. The results show that convergence speed is considerably high. It is shown that the power level has to be updated dynamically and the capacity limit in all traffic categories is highly dependent on the P_{tot} constraint.

A similar work has been given in [Kur99]. A call admission control algorithm has been proposed for the reverse link in W-CDMA systems. The total received power P_{tot} at the BS is utilized as a quantitative measure of the resources utilization. When a user sends a request, the BS estimates the 95 percentile of P_{tot} and compares it with the maximum allowable value (P_{max}). If the 95 percentile is less than P_{max} the user is admitted, otherwise it is blocked. It should be noted that the estimated total power includes the estimated effect of the attempting call. Two stream-mode services are supported, a voice service with a peak rate of 8 kbps and a video service with 64 kbps peak rate. The power control scheme is based on the *CIR* level. At each time frame, the BS estimated the *CIR* and sends a PC command to the MS to increase/decrease the transmitted power. Since the video transmission rate is 8 times the transmission rate of the voice service, the *CIR* threshold of the video service is set 8 times (9 dB) higher than that for voice.

The maximum number of users for each service is determined by static simulation (without call arrival or departure). The simulator consists of 25 (5x5) cells. Exponential path loss, lognormal shadowing and Rayleigh fading are included in the propagation

model. Poisson traffic with exponential call duration is used for both kinds of traffic. The results show that up to 176 voice users can be supported if there is no video users. If 2 video users are active, only 144 voice users can be supported. 11 video users can be supported provided that no voice users are active.

In order to assess the performance of the proposed admission algorithm, a dynamic simulation is used to include the call arrival and departure, user mobility and hard handover. The results show that the maximum number of users determined by static simulation can be achieved by using the proposed admission algorithm.

An admission and load control algorithm for integrated service over W-CDMA is presented in [Guo94]. Stream-mode voice and data services are supported by the system. Both have Poisson distribution with exponential call duration. BER formulae for the voice service as well as the data service have been derived as functions of the number of active voice and data calls. It is assumed that perfect power control is utilized in this system.

Voice calls are given high priority over data calls so that an active data call can be interrupted and forwarded back to the waiting queue if an arriving voice call does not find enough resources. When a call arrives at the system, the BER is estimated. If it is lower than the maximum allowable threshold, the call is admitted. Otherwise the call is either rejected if it is a voice call and no data calls can be interrupted, or queued if it is a data call.

This algorithm also investigates the possibility of rate control for data users to reduce the queuing time for data users. When a data call is attempted and it is found that the BER is higher than the threshold value, the algorithm reduces the rate of some active

data calls to allow the new call to meet the BER requirement. The performance of the algorithm is assessed using the derived BER formulae. The chip rate is assumed to be 9.83 Mcps while both the voice and data transmission rates are equal to 9.6 kbps. The results are given as BER plots as function of the number of active voice and data calls. The maximum BER of voice service is assumed to be equal to 10^{-3} while the BER of the data service is 10^{-9} . Contours of BER for both voice and data services are used to determine the permissible loading values. The results show that a high throughput can be achieved (more than 2 Mbps) by using this admission and loading control scheme.

An admission and load control algorithm that takes the loading and interference level into consideration has been proposed in [Lin96]. The algorithm considers the loading and the interference in the cell of the incoming call and its neighbor cells to decide whether to admit this call or not. The pilot strength of the surrounding BSs is measured by the MS and reported to the best serving BS. Then the BS estimates the interference that would be caused by admitting this user. The high transmission rate required for data users is achieved by using multiple code assignment.

Three algorithms have been investigated in this study. In the first one, the data user reports the pilot measurements to the best serving BS. If the pilot measurements from all neighboring cells are less than the threshold value T_M , the data user is granted M codes, otherwise it is allowed only to transmit at the basic rate. In the second algorithm, multiple thresholds (T_i , $i=1,2,\dots, M$) are determined from the loading information in the cell of the incoming call. The pilot measurements are compared with the M threshold values and according to that comparison, the MS is assigned m codes, where m ranges from 1 to M . In the third algorithm, the M threshold values are determined from the

loading information in the cell of the incoming call and the neighboring cells as well. Then, the MS is assigned up to M codes. In this algorithm, the loading information has to be exchanged periodically between neighbor cells. The system performance has been analyzed by applying the proposed algorithm for a simplified cell structure that consists of 3 cells. Perfect power control, sectorization and soft handover are included in the system model. The maximum loading values for both voice and data services (with different transmission rates) are determined using the three algorithms mentioned above. The results show that transmission rates (up to 52 kbps) can be achieved by IS-95 for data users particularly if the data user is not close to the cell boundary.

A refined version of the previous algorithm has been given in [Kni98-1]. A two-phase evolution plan for IS-95 towards the third generation proposal cdma2000 is the main theme of this work. The intermediate phase (IS-95B) which is fully compatible with the current phase (IS-95A) has been presented with an emphasis on an admission control for packet-mode data service.

The data user is assigned up to 8 codes depending on the loading and interference information as discussed above. The maximum data rate is 64 kbps, which is suitable for many data services and Internet access applications such as E-mail, FTP and Web browsing. The MS sends a request to originate a data call to the BS. The BS negotiates with the MS the number of allocated codes in the forward and reverse links. By the end of the negotiation process, the MS goes into an active state. When there are some packets for transmission, a burst request is sent from the MS to the BS. The BS decides to allocate from 0 to 8 codes for this burst depending on the previous negotiation and the current loading in the cell. By assigning 0 codes, the BS denies this burst request. The BS sends

to the MS the starting instant for the packet transmission. Then, the MS goes to active-burst mode and starts to send at this time instant. If more packets have arrived during the transmission period, the MS can keep sending. After sending all packets, the MS returns to the active mode so it can send a request for another burst assignment if some packets arrive during this temporary state. If no more packets arrive, the MS returns to the dormant mode. Capacity and coverage analysis has been performed by simulation. Perfect power control and soft handover are included in the simulation. Neither sectorization nor smart antennas are considered in the system model. It is found that more than 80% area coverage probability is achievable for the high data transmission service even at high loading values in adjacent cells. The burst admission probability is inversely proportional with distance between the MS and BS until the distance reaches $0.7R$ (where R is the cell radius) where the probability starts to increase after that. The reason for this change in the trend is the use of soft handover.

In [Liu98], a joint admission/congestion control for integrated services over W-CDMA is presented. The proposed admission control algorithm for the voice and packet-mode data services in the reverse link is quite simple. The incoming calls are accepted as long as the number of active voice users is less than a maximum threshold value M_v^{max} . The admission of data calls is performed in the same way using a threshold value M_d^{max} . All the voice users are permitted to send once they are admitted to the system. The first M_d data users are allocated C_d codes each, but they start to send only during the silent periods of the voice transmission. During these silent periods, the data users start to send with a probability p_{start} which is adapted according to the network loading and utilization. But once the data user starts to send, it does not stop until it finishes all backlogged

packets. The rest of the admitted users are queued waiting the completion of some active data calls. The system is modeled as a three-dimensional Markov chain. The results show that a high data throughput (up to 4 packets/slot) can be achieved with a considerably low packet error rate (1×10^{-2}). The system performance shows some dependence on the design parameters such as M_d , C_d and M_v .

Finally, a study that addresses the impact of adaptive call admission control on the spatial distribution of blocking probability has been given in [Car99]. A W-CDMA system with a simple admission control based on the estimated CIR in the reverse link has been proposed in this work. Two services are considered, voice service with a voice activity of one and a stream-mode data service with a transmission rate of 144 kbps. Monte-Carlo simulation is used for the spatial blocking analysis. Two cellular structures are used, a regular hexagonal layout with macrocells and a realistic structure in an urban area with microcells in Munich city. An adaptive power control based on the *CIR* is included in the system model. The blocking probability estimation is repeated many times in different user locations to determine the spatial distribution of the blocking probability. In the regular hexagonal structure, the results show that the blocking probability of the voice users is slightly increased (from 1.5% to 3%) as the distance between the MS and the BS increases from 0.1 km to 0.5 km. A further increase of the distance does not lead to any significant change in the blocking probability.

3.5 Problem Statement

The last three sections present the capacity analysis in wireless networks emphasizing on the impact of call admission and load control algorithm on the system performance. Also, the effect of some capacity enhancement techniques such as power control and smart antennas has been discussed through the published work in the literature. The capacity analysis in most of the published studies is performed by computer simulation. Computer simulation requires more computational burden and time compared with analytical tools. Analytical tools are vital for validation and better insight into the system performance.

Several call admission and load control techniques are presented in the literature. These algorithms can be classified into two main classes. The first class includes the interference-based call admission and load control techniques, while the second one includes the loading-based call admission and load control algorithms. Algorithms belong to the first class are more complicated because they require continuing measurement of the interference level used as a criterion for call admission and load handling. Loading-based call admission and load control algorithms are simpler and do not require any measurements. However, a considerable portion of the system capacity is usually not exploited which is considered as a loss of the system resources. This residual capacity loss takes place in wireless networks particularly interference-limited capacity networks such as CDMA and FH-TDMA because the hard capacity limit imposed by the loading-based call admission and load control algorithms has to be lower than the soft capacity limit under all circumstances. Hence the hard capacity limit is always chosen

less than or equal to the soft capacity limit at the worst-case scenario. Thus, the hard-capacity limit causes the residual capacity loss at different scenarios (other than the worst-case scenario).

The objective of this work is to propose efficient loading-based call admission and load control algorithms avoiding the residual capacity problem without adding much complexity to the system. By doing so, these algorithms will have the simplicity of loading-based techniques and the high efficiency of interference-based ones. These algorithms are proposed for three specific cases, namely the overlapping coverage in urban microcells, FH-TDMA networks with fractional loading, and wideband CDMA networks with mixed service.

In order to determine the capacity enhancement of the proposed algorithms, computer simulation and analytical tools must be developed and used for performance analysis and verification of the results. Other capacity enhancement techniques and modern features of wireless networks are to be included in the system models to study their impact on the system capacity.

Chapter 4

Call Admission and Load Control in Urban Microcellular Networks with Overlapping Coverage

4.1 Introduction

In this chapter, the overlapping coverage in urban microcells is studied with an emphasis on capacity enhancement using efficient admission and load control. Section 4.2 introduces the basics of this topic including the propagation models. The Area Coverage Probability (*ACP*), as one of the important measures in wireless cellular networks, is determined analytically and by simulation in section 4.3. The results of the *ACP* analysis is given in section 4.4. Section 4.4 also includes the *CIR* distribution with and without overlapping obtained by simulation. This is helpful in estimating the degradation in the QoS due to the overlapping coverage. Section 4.5 includes a detailed analysis of the system performance using two admission and loading control algorithms,

namely, the directed retry and the load balancing techniques. A Markovian analysis is used in this section to assess the system performance using the overlapping coverage. Then the results of the performance analysis are given in section 4.6.

4.2 Urban Microcellular Systems

Microcells are widely used in cellular networks as an efficient solution for the high capacity needs in urban areas. In microcells, the transmitted power is much smaller than that in macrocells because of the small cell size. The microcell radius (or cell side length for square cells) normally ranges from 100 to 500 meters. Accordingly, more cells are needed to cover a certain area compared with the conventional cellular system. The BS antennas are usually mounted in the light posts near the intersection of streets. In this case, the BS is much simpler and cheaper than that used in macrocellular system, so that the large number of base stations will not add a substantial cost.

Several measurements show that the propagation characteristics of microcells are quite different from those of macrocellular networks. In cities with rectilinear streets, it is found that the cell shape tends to be square rather than circle. The propagation is either Line of Sight (LOS) or Non-LOS (NLOS) propagation mode depending on the environment and obstacles between BS and MS. High rise buildings and dense constructions affect the propagation characteristics in urban areas. LOS propagation is normally unattainable in most of the cell area, while NLOS propagation applies in most of the cell area with the exception of the two streets intersected at the centre of the cell as

shown in Fig. 4.1. It is reported that the LOS received power P_r can be modelled by [Cla97]:

$$P_r = \frac{P_t A \xi}{r^2 \left[1 + \left(\frac{r}{B} \right)^2 \right]} \quad (4.1)$$

where P_t is the transmitted power, $A = (\lambda / 4\pi)^2$, $B = (4h_t h_r / \lambda)$, λ is the wavelength, h_t and h_r are the transmit and receive antenna heights, r is the distance between the MS and the BS, and ξ is a lognormal shadowing parameter with zero mean and σ standard deviation. On the other hand, the NLOS received power P_r is modeled by [Cla97]:

$$P_r = P_t A \frac{\xi}{z^n} \quad (4.2)$$

where $A = 0.16$ for $f = 900$ MHz and 0.0015 for $f = 2$ GHz, z is the projection of r in the x direction as shown in Fig. 4.1, and n is the path loss exponent, which ranges from 3.5 to 5 depending on the environment.

Overlapping coverage occurs in some regions in the cell particularly around the cell borders. This can be exploited to reduce the call blocking and dropping probabilities as explained later.

One of the most important performance measures in cellular wireless networks is the ACP , which is defined as the percentage of the cell area where P_r exceeds some specified threshold (P_{th}) that depends on the receiver sensitivity, noise floor and expected

interference level. Due to the propagation anomalies, P_r in some locations might drop below P_{th} . Thus, these locations are considered as uncovered areas, which degrades the service quality and can even cause call blocking and dropping.

4.3 Coverage Analysis [Ahm97]

From the definition of the ACP given above, ACP can be expressed as follows

$$ACP = \frac{1}{area_{cell}} \int Pr(P_r > P_{th}) dA \quad (4.3)$$

where $area$ is the cell size. Since part of the cell area is covered by LOS propagation, while the rest of the cell area is covered by NLOS propagation, ACP can be rewritten as

$$ACP = c_1 ACP_1 + c_2 ACP_2 \quad (4.4)$$

where c_1 and c_2 are the percentages of the cell area covered by the LOS and NLOS propagation respectively, while ACP_1 and ACP_2 are the *area coverage probability* in the areas covered by the LOS and NLOS propagation respectively. Indeed, the LOS propagation is much stronger than the NLOS as shown by Eq (4.1) and Eq (4.2). Consequently, it is acceptable to consider that ACP_1 is equal to 1. Thus, to determine ACP it is only required to find ACP_2 using the NLOS propagation model given by Eq (4.2). Then the coverage probability can be given as

$$Pr(P_r > P_{th}) = 1 - Q\left(\frac{E[P_R] - P_{TH}}{\sigma}\right) \quad (4.5)$$

where $E[P_R]$ is the mean value of the received power in dBW, σ is the standard deviation of P_R , while P_{TH} is the received power threshold in dBW. Thus, ACP_2 is expressed as:

$$ACP_2 = \frac{8}{area} \int_0^{\frac{\pi}{4}} \int_0^{\frac{S}{2\cos\theta}} \left[1 - Q\left(\frac{E[P_R] - P_{TH}}{\sigma}\right) \right] r \, dr \, d\theta \quad (4.6)$$

where S is the cell side length and (r, θ) are the polar coordinates of the MS as shown in Fig. 4.1. $E[P_R]$ can be expressed as

$$E[P_R] = P_T + 10\log A - 10 n \log z \quad (4.7)$$

where P_T is the transmitted power in dBW. As shown in Fig. 4.1, z is equal to $r \cos \theta$. After some manipulation, it can be shown that ACP_2 can be expressed as follows:

$$ACP_2 = 1 - Q(K) + \exp\left(\frac{2(KL+1)}{L^2}\right) Q\left(\frac{2+KL}{L}\right) \quad (4.8)$$

Where $K = (S E[P_r(0.5S)] - P_{TH})/\sigma$ and $L = (10 n \log(e))/\sigma$. This expression is similar to that of the circular cells, which is not unexpected since all the points on the path loss

contour have the same z from the base station. Although all these points are physically displaced at different distances from the BS, they have the same effective displacement (z) from the base station.

As mentioned above, the overlapping coverage is unavoidable in such small cells. Hence, it is also important to evaluate ACP with overlapping coverage. In order to simplify the derivation of ACP with overlapping coverage, we assume that the overlapping from each cell is limited to the cells in the first tier (the eight shaded cells surrounding cell A) as shown in Fig. 4.2. Firstly, we calculate the area coverage probability in these eight cells due to the base station in cell A (ACP_o) as done for one cell above but the limits of the inner integral will be from $S/(2\cos\theta)$ to $3S/(2\cos\theta)$. Therefore, ACP_o is expressed as

$$ACP_o = G_1 + G_2 \exp\left(\frac{2(ML+1)}{L^2}\right) \quad (4.9)$$

where $M=(S E[P_r(1.5S)]-P_{TH})/\sigma$, $G_1 = Q(M+3)-Q(M)$ and G_2 is given by

$$G_2 = Q\left(\frac{2+ML}{L}\right) - Q\left(\frac{2+ML+L^2 \log(3)}{L}\right) \quad (4.10)$$

Since each cell has eight neighbor cells, the area coverage probability with overlapping (ACP_o) at any cell is the union of the following events: The cell area is covered by its BS (with probability ACP) or by one of the eight-neighbor cells (with probability ACP_o). Thus the ACP_o is given by [Gar94]:

Fig. 4.1 MS coordinates in a square microcell

Fig. 4.2 Urban Microcellular Network Layout

$$ACP_{-O} = \sum_{i=1}^9 P_i - \sum_{i < j} P_i P_j + \sum_{i < j < k} P_i P_j P_k - \dots + \prod_{i=1}^9 P_i \quad (4.11)$$

where $P_i = ACP$ and $P_i = ACP_o$ ($i = 2, 3, \dots, 9$). To validate these results, computer simulation is used to compute ACP with and without overlapping. Monte-Carlo simulation is used by generating the random variables such as the mobile locations and shadowing parameter (ξ) to compute the percentage of the cell area covered by the base station. The mobile locations are uniformly and independently distributed. Both LOS and NLOS are taken into consideration.

To assess the effect of the overlapping coverage on the QoS, the CIR distribution of the downlink is estimated by simulation. The mobile users are uniformly distributed throughout the network area while the shadowing parameter (ξ) is lognormally distributed as started above. The CIR is estimated using static simulation. Thus the user mobility and the channel dynamic behavior are ignored for the sake of analysis simplicity.

4.4 Results

Using Eqs (4.4)-(4.11), and the simulation results, ACP is plotted vs. the cell side length S for $n = 4.5$ and 5 . ACP is evaluated analytically and by simulation for non-overlapping and overlapping coverage at different values of P_{TH} .

Fig. 4.3-a shows ACP vs. S for $n = 4.5$ at $P_{TH} = -140$ and -150 dBW, while Fig. 4.3-b shows the same relationship for $n = 5$. Figs. 4.4-a and 4.4-b show the same relationships but with overlapping coverage.

The results obtained analytically are in a good agreement with the simulation results. The maximum difference in ACP does not exceed 5%, and the difference in more than 90% of the results is less than 2%. The agreement in the non-overlapping coverage is better than that in overlapping coverage. The dependence of the ACP on n is obvious. For instance, at $n = 4.5$ and $S = 250$ m for non-overlapping coverage $ACP = 100\%$ and 97.5% for $P_{TH} = -150$ dBW and -140 dBW respectively, while at $n = 5$ and $S = 250$ m, $ACP = 96\%$ and 73% for $P_{TH} = -150$ dBW and -140 dBW respectively. The dependence on n increases as S increases as shown in Figs. 4.3 and 4.4.

The results show that the overlapping coverage improves the coverage probability. For example, with non-overlapping coverage at $S = 300$ and $n = 5$ ACP is equal to 92% and 57% for $P_{TH} = -150$ dBW and -140 dBW respectively. While with overlapping coverage and with the same values of S and n , ACP is increased to 97.5% and 64% for $P_{TH} = -150$ dB and -140 dBW respectively. Y , the length of the overlapping arm normalized to the cell side length S , is chosen as 0.5 and 0.707 . These two values are depicted in Fig. 4-7. It is evident that larger values of Y will lead to longer overlapping arms, and as a result the overlapping will be extended to the second tier cells, which complicates the analysis.

(a)

(b)

Fig. 4.3 ACP without overlapping coverage for $P_{TH} = -140$ dBW (lower curve) and -150 dBW (upper curve) at (a) $n=4.5$ (b) $n=5$.

(a)

(b)

Fig. 4.4 ACP with overlapping coverage for $P_{TH} = -140$ dBW (lower curve) and -150 dBW (upper curve) at (a) $n=4.5$ (b) $n=5$.

The *CDF* of the *CIR* with a frequency reuse factor N equals to 4 is depicted in Fig. 4.5. At $CDF = 10\%$, the reduction in the *CIR* is 3.5 dB and 6 dB for $Y=0.5$ and $Y=0.707$ respectively. At higher values of the *CDF*, the reduction is much less. For instance, at $CDF=30\%$ the reduction in the *CIR* is 2.8 dB and 4 dB for $Y=0.5$ and $Y=0.707$ respectively. This shows that the overlapping coverage can degrade the signal quality. However, in some cellular networks the overlapping coverage is inevitable because of the propagation characteristics particularly in urban microcells. Therefore, the overlapping can be exploited in such areas to enhance the system capacity as explained in the next section.

4.5 Capacity Enhancement¹ [Ahm98]

The overlapping coverage can be utilized to reduce the call blocking and dropping probabilities. This capacity improvement can be achieved using different approaches as explained below.

In order to determine the capacity enhancement from the overlapping coverage using analytical methods, the system is represented with a discrete Markovian model, namely, the birth-death process. The state of each cell is defined as the number of active mobile users served by the BS of this cell. The state transition occurs by the following four events: new call arrival, handover call arrival, normal call departure, and handover departure.

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¹ The derivation of the formulae used in this section is given in Appendix A.

Two techniques are used to take advantage of the overlapping coverage in minimizing the blocking and dropping probabilities. The first one is called directed retry [Chu95, Kar89], in which the MS accesses the best serving BS. If all channels are busy in that BS, the user is directed to retry in another BS provided that the user is in an overlapping coverage area, otherwise this call will be blocked. The second technique is called load balancing which aims to even up the loading in all cells. The MS accesses the best server as long as the loading in this BS does not exceed a certain loading threshold (e.g. 50%). If the loading is higher than this threshold and the MS is in a non-overlapping coverage area, the MS is admitted as long as the BS is not 100% loaded. If the loading is higher than loading threshold value and the MS is in an overlapping coverage area, the MS is encouraged to access the other BSs provided that at least one of these BS has a loading factor less than the loading of the best server with a certain offset (Δs). In this case, the user is moved to the other BSs with a probability (P_m), which is a linearly-increasing function of the loading factor as shown in Fig. 4.6. Therefore, more users are moved to the neighbor cells when the cell becomes more loaded and vice versa. The overlapping is restricted to the first tier and to the LOS propagation areas as shown in Fig. 4.7. In the next two subsections, the system performance of these two techniques is determined analytically and by simulation.

4.5.1 Performance Analysis of Overlapping Coverage using Directed Retry

In order to calculate the blocking and dropping probabilities, the state probabilities are to be determined first. This can be obtained from the global balance

condition using the transition probabilities. With overlapping coverage, the new call arrival rate per cell r_n is given by

$$r_n = (1 + \beta p_2 + 2p_3\gamma_1 + 3p_4\gamma_2) \lambda_n \quad (4.12)$$

where β is the probability that a base station is fully loaded. In other words, it is the probability that the cell state (s) is equal to C ($\beta = Pr(s = CH_{cell})$), where CH_{cell} is the number of channels per cell), p_2, p_3 , and p_4 are the percentages of the cell area covered by two, three, and four base station respectively as depicted in Fig. 4.7, λ_n is the new call arrival rate per cell without overlapping, $\gamma_1 = \beta^2 + 0.5\beta(1 - \beta)$, and $\gamma_2 = \beta^3 + 0.5\beta^2(1 - \beta) + 0.33\beta(1 - \beta)^2$. On the other hand, the call completion rate per cell (r_c) is given by

$$r_c = s\mu_v \quad (4.13)$$

where $(1/\mu_v)$ is the average call duration. The handover departure rate per cell r_d is given by

$$r_d = s\mu_d \quad (4.14)$$

where $(1/\mu_d)$ is the average call dwelling time in the cell. The handover arrival rate per cell r_h is given by

$$r_h = 4 \sum_{s_1=0}^C \sum_{s_3=0}^C P(s_1, s_3) \lambda_h(s_1, s_3) \quad (4.15)$$

Fig. 4.5 CDF (CIR) for the Downlink at $N=4$ with and without overlapping.

Fig. 4.6 Probability of moving to another BS versus the (percentage) loading factor.

(a)

(b)

Fig. 4.7 Urban microcell with overlapping coverage (a) $Y=0.5$ and (b) $Y=0.707$

where $P(s_1, s_3)$ is the joint probability that cell I is in state s_1 and cell B is in state s_3 . Assuming independence between the neighbor cell states, $P(s_1, s_3)$ is equal to $P(s_1)P(s_3)$ while $\lambda_h(s_1, s_3)$ is the handover arrival rate from cell I and cell B to cell A, and it is given by

$$\lambda_h(s_1, s_3) = \frac{\mu_d}{b} [s_3(1 - \sqrt{2d} + 2d\varepsilon) + s_1(2Y + d)] \quad (4.16)$$

where b is the cell border length, d is the width of the overlapping arm, both normalized to S , and $\varepsilon = \beta + 0.5(1 - \beta)$. Hence, the transition probabilities can be expressed as

$$P_{ij} = \begin{cases} r_n + r_h & j = i + 1 \\ r_c + r_d & j = i - 1 \\ -(p_{i(i+1)} + p_{i(i-1)}) & j = i \\ 0 & \text{otherwise} \end{cases} \quad (4.17)$$

Then the state probabilities is determined using the global balance condition

$$P(i) \sum_{j=0}^C P_{ij} = \sum_{j=0}^C p_{ji} P(j) \quad i = 0, 1, \dots, C \quad (4.18)$$

Subject to the condition

$$\sum_{j=0}^C P(j) = 1 \quad (4.19)$$

The above $C+2$ equations are non-linear since the transition probabilities are function of the state probabilities as shown by Eqs (4.12)-(4.17). By solving this system of non-linear equations iteratively as explained in Appendix B, the state probabilities are determined. Then, the blocking probability (P_b) is evaluated by

$$P_b = \beta p_1 + \beta^2 p_2 + \beta^3 p_3 + \beta^4 p_4 \quad (4.20)$$

while the dropping probability (P_d) can be determined from the following expression

$$P_d = \frac{HOR P_h}{[1 - HOR(1 - P_h)]} \quad (4.21)$$

where HOR is the handover rate, which is equal to $\mu_d/(\mu_d + \mu)$ and P_h is the handover failure probability and it is given by

$$P_h = \frac{(1 + (1 - \sqrt{2})d + 2Y)\beta + 2d\beta^2}{b} \quad (4.22)$$

4.5.2 Performance Analysis of Overlapping Coverage using Load Balancing

In order to calculate the blocking and dropping probabilities, the state probabilities are calculated using the same methodology used for directed retry in

subsection 4.5.1. The new and hand off arrival rates are modified according to the proposed technique. Using this algorithm, the new call arrival rate is given by

$$r_n = [1 + (M_1 - N_1) + (M_2 - N_2) + (M_3 - N_3)] \lambda_n \quad (4.23)$$

where M_i (N_i), $i=1, 2, 3$, are the normalized added (reduced) new call rate in the areas covered by two cells, three cells, and four cell respectively. These are given by the following formulae:

$$M_1 = p_2 \sum_{s_1=s_L}^C P(s_1) P_m(s_1) u(s_1 - s - \Delta s) \quad (4.24)$$

$$N_1 = p_2 \sum_{s_1=0}^C P(s_1) P_m(s) u(s - s_1 - \Delta s) \quad (4.25)$$

$$M_2 = p_3 \sum_{s_1=s_L}^C \sum_{s_2=s_L}^C P(s_1) P(s_2) \left[\begin{array}{l} P_m(s_1) u(s_1 - s - \Delta s) u(s_2 - s) + \\ P_m(s_2) u(s_2 - s - \Delta s) u(s_1 - s) \end{array} \right] \quad (4.26)$$

$$N_2 = p_3 \sum_{s_1=s_L}^C \sum_{s_2=s_L}^C P(s_1) P(s_2) P_m(s) \left[\begin{array}{l} u(s - s_1 - \Delta s) u(s_2 - s_1) + \\ u(s - s_2 - \Delta s) u(s_1 - s_2) \end{array} \right] \quad (4.27)$$

$$M_3 = p_4 \sum_{s_1=s_L}^C \sum_{s_3=s_L}^C \sum_{s_4=s_L}^C P(s_1) P(s_3) P(s_4) \left[\begin{array}{l} P_m(s_1) u(s_1 - s - \Delta s) u(s_4 - s) u(s_3 - s) + \\ P_m(s_3) u(s_3 - s - \Delta s) u(s_1 - s) u(s_4 - s) + \\ P_m(s_4) u(s_4 - s - \Delta s) u(s_1 - s) u(s_3 - s) \end{array} \right] \quad (4.28)$$

$$N_3 = p_4 \sum_{s_1=s_L}^C \sum_{s_3=s_L}^C \sum_{s_4=s_L}^C P(s_1) P(s_3) P(s_4) P_m(s) \left[\begin{array}{l} u(s-s_1-\Delta s)u(s_4-s_1)u(s_3-s_1)+ \\ u(s-s_3-\Delta s)u(s_1-s_3)u(s_4-s_3)+ \\ u(s-s_4-\Delta s)u(s_1-s_4)u(s_3-s_4) \end{array} \right] \quad (4.29)$$

where $u(.)$ is the unit step function, s_2 is the state of cell G, s_4 is the state of cell H, and s_L is cell state corresponding to the minimum loading factor at which the MS can access other BS. Recall that s is the state of the central cell (cell A), s_1 is the state of cell I, s_3 is the state of cell B. The handover arrival rate is modified as follows

$$\lambda_h(s_1, s_3) = \frac{\mu_d}{b} \left[s_3 (1 - \sqrt{2}d + 2d u(s-s_1)) + 2s_1 Y \right] \quad (4-30)$$

The call completion and the hand-off departure rates are unchanged, therefore Eqs (4-13) and (4-14) are still applicable. Using the iterative method explained in Appendix B, the state probabilities can be determined. Then, the blocking and dropping probabilities are evaluated using Eqs (4-20) and (4-21).

4.6 Results

The blocking and dropping probabilities are determined using the analysis presented in section 4.5 without overlapping ($Y=0$) as a reference and with overlapping coverage ($Y=0.5$ and 0.707) using both the directed retry and the load balancing

techniques. The following numerical values are used in the analysis: $S=200\text{m}$, $C=18$, $\mu_v=0.01 \text{ sec}^{-1}$ and $\mu_r=0.04 \text{ sec}^{-1}$.

Figs. 4.8 and 4.9 depict the blocking and the dropping probabilities versus the new traffic in Erlang per cell. It is evident that a substantial reduction in both the blocking and dropping probabilities is achievable with overlapping coverage. The reduction due to the load balancing algorithm is slightly higher than that of the directed retry technique. For instance, at $\lambda_n=11$ Erlang/cell the blocking probability is 1.1×10^{-2} without overlapping. By exploiting the overlapping at $Y=0.5$, the blocking probability is reduced to 1.8×10^{-3} with directed retry and 1.3×10^{-3} with load balancing. At $Y=0.707$, the blocking probability can be further reduced to 6.7×10^{-4} using directed retry and down to 5×10^{-4} with load balancing. At high values of λ_n , the reduction in the blocking probability became less. For example, at $\lambda_n=19$ Erlang/cell the blocking probability drops from 7.5×10^{-2} to 4.5×10^{-2} using directed retry and to 3.8×10^{-2} using the load balancing technique at $Y=0.5$. Even at $Y=0.707$, the blocking probability is reduced to 3.3×10^{-2} and 2.9×10^{-2} with directed retry and load balancing respectively. The dropping probability has also the same trend. At low traffic values, the dropping probability is highly reduced using overlapping coverage particularly with the load balancing technique. At high traffic values the reduction in the dropping probability with $Y=0.5$ is very limited, e.g. at $\lambda_n=20$ Erlang/cell, the dropping probability is reduced from 2.7×10^{-1} to 1.9×10^{-1} and 1.8×10^{-1} using directed retry and load balancing. At $Y=0.707$, the dropping probability can be considerably reduced with almost one order.

The maximum new traffic per cell can be estimated from these curves. It can be found as the value of the new traffic at which either the blocking or the dropping

probabilities exceed a certain threshold (e.g. 2%). Using this definition, the maximum new traffic in Erlang per cell is found to equal to 9.9, 12.1, 13, 16.6 and 17.5 without overlapping, with overlapping ($Y=0.5$) using directed retry, with overlapping ($Y=0.5$) using load balancing, with overlapping ($Y=0.707$) using directed retry and with overlapping ($Y=0.707$) using load balancing respectively.

It can be concluded that the system capacity is enhanced by utilizing the overlapping coverage. Both techniques, the directed retry and load balancing, are capable of achieving a considerable capacity enhancement. While the latter technique can achieve higher capacity, it needs more information exchange and mutual arrangement compared to the former one.

Fig. 4.8 Blocking probability with and without overlapping versus the new traffic arrival rate per cell.

Fig. 4.9 Dropping probability with and without overlapping versus the new traffic arrival rate per cell.

Chapter 5

Admission Control in TDMA Systems with Soft Capacity

5.1 Introduction

As mentioned in section 3.3, the admission control plays an important role in achieving high capacity without degrading the QoS in TDMA systems with soft capacity. This trade-off between the system capacity and the QoS is the main theme of this chapter.

In section 5.2, the soft capacity in TDMA wireless networks is discussed. The guidelines of the capacity analysis are also presented in this section.

Admission control algorithms normally consider the network-loading factor as a criterion for call admission since the network loading is related to the *CIR* of the active calls. In order to determine the maximum acceptable loading in TDMA systems with soft capacity, a software simulation tool and mathematical analysis are used to estimate the

effect of the network-loading factor on the outage probability. The wireless network simulation tool is described in section 5.3 followed by the mathematical analysis of the outage probability in section 5.4. The results obtained analytically and by simulation from these two sections are presented in section 5.5.

In section 5.6, a new call admission algorithm is proposed. This algorithm aims to enhance the system capacity without causing degradation to the QoS. Section 5.7 presents the performance analysis of the proposed algorithm analytically using Markovian analysis and by simulation. Section 5.8 presents the numerical results of the performance analysis for the proposed algorithm compared with a conventional admission technique based on the instantaneous loading factor.

5.2 TDMA Wireless Networks with Soft Capacity

The use of the soft capacity concept can enhance the system capacity in TDMA systems [Carn94, Chen96, Jov97]. Soft capacity can be implemented in TDMA systems using fractional loading combined with frequency hopping. This combination makes the TDMA systems quite similar to CDMA in many aspects. An admission control algorithm must be employed to preserve the signal quality by limiting the network loading factor. The admission control can be performed in different ways (central or distributed), based on different criteria (number of users or interference level) and in individual basis or combined with other control algorithms like power control [Bem91, Ish97].

The maximum capacity of the interference-limited network can be evaluated by first determining the maximum loading factor (LF_{max}). Then the maximum network capacity in Erlang/cell (C) is evaluated as follows

$$C = LF_{max} CH_{cell} \quad (5.1)$$

where CH_{cell} is the number of channels per cell. Indeed the average network capacity (C_{av}) is less than C because of the call blocking and dropping and it is given by:

$$C_{av} = C (1 - P_b) (1 - P_d) \quad (5.2)$$

where P_b is the blocking probability and P_d is the dropping probability. As shown in Eq (5.2), if admission control is not employed both P_b and P_d will be dropped to zero, and as a result C_{av} will be equal to C . However this will be at the cost of the QoS since the CIR requirements will be unachievable.

The maximum loading factor can be determined by several ways depending on the admission control strategy. In the interference-based call admission control techniques, users are admitted as long as the interference level does not exceed the specified threshold values. In this case, the maximum loading is variable whose value depends on the propagation conditions and the spatial distribution of the users. In the loading-based admission control techniques, the relationship between the outage probability and the network loading factor is determined off line analytically by simulation or from statistics based on previous measurements. The maximum Loading Factor (LF_{max}) is defined as the

loading factor at which the CIR is equal to the minimum acceptable value (CIR_{min}). Then the admission control algorithm uses this value to admit or reject any access request depending on the instantaneous network-loading factor. The two approaches are equivalent and can achieve almost the same capacity figures. However, the second technique is simpler particularly at the implementation level.

In this study, we adopt the second approach. Since the CIR is a stochastic process which is dependent on the locations of the user and its cochannel interferers as well as the propagation conditions, this equality ($CIR=CIR_{min}$) is replaced with this stochastic condition ($Pr(CIR < CIR_{min}) > p_{max}$) which corresponds to p_{max} outage probability. It has to be emphasized here that the CIR used in this inequality is the carrier to the average interference ratio because of the interference averaging property due to the use of frequency hopping.

Interference reduction/cancellation techniques such as DTX, PC and smart antennas can boost the system capacity by tolerating higher network loading. Additional capacity gain can be accomplished by enhancing the admission control algorithm. Multiple beam antennas are adopted in the system model because of its simplicity and efficiency compared to other techniques.

5.3 Simulation

A dynamic simulation tool for cellular networks has been developed to analyze the performance using different capacity enhancement techniques. This simulator, which is developed in MATLAB, is constructed as a set of independent modules so that any

module can be modified, enhanced or even replaced without affecting the other modules. Fig. 5.1 shows a snapshot of the simulator graphical output. This figure shows the BSs distributed uniformly through the covered area while the MSs are linked to the best servers (links are shown as a line from the BS to the MS). The blocking and dropping probabilities are also displayed in the graphical output as shown in Fig. 5.1. They are updated every multiframe. In the sequel, the different modules used in the simulator will be explained with an emphasis on their characteristics and functionality.

1-TRAFFIC GENERATION MODULE

The traffic generation module generates the call inter-arrival times using the Poisson traffic model and call duration using the exponential distribution. Then, it schedules and saves the arrival times and the call duration in a data file. Uniform spatial traffic distribution is assumed, however hot spot traffic can also be included. This module generates these values off line to reduce the simulation time. When the dynamic simulation starts these values are loaded and retrieved by another module as explained below.

2-INITIALIZATION AND PARAMETERS SETTING MODULE

This module initializes the variables used in the simulator such as the statistics collection variables. It also generates and sets the user profile for each user including its position, speed, and direction of movement in addition to the system parameters such total

available radio resources and the discontinuous transmission factor (DTX). This module also works off line prior to the starting of dynamic simulation.

3-CALL START UP MODULE

The call start up module can be considered as the first part of the dynamic simulation. Once the simulation starts this module retrieves the call arrival time, the call duration and the users profile from the schedule stored in the data file. Subsequently, it initiates the calls according to the simulator clock.

4-ADMISSION CONTROL AND CHANNEL ASSIGNMENT MODULE

The admission control module admits (or rejects) the generated (new) calls as well as the handover calls based on the admission criterion. Thereafter, it assigns channels for the admitted users according to the available resources and the allocation algorithm. The received power (P_r) from the best serving base station is measured before granting the network access to that user. The connection is not established unless the received power P_r exceeds the receiver sensitivity with a certain margin ΔP .

5-BEAM SELECTION MODULE

Since the multiple beam antennas are utilized at the BS, this module selects the best serving beam (based on the absolute power or *CIR*) for each user in the network. 12

beams are assumed to cover each cell site (4 beams per sector). The channels allocated to each sector can be used by any of the 4 beams covering the sector area. However, the same channel cannot be used by more than one beam simultaneously. Both ideal and practical beam patterns (with sinc^2 shape) can be used in the simulator.

6-USER MOVEMENT MODULE

This module moves all the active users in linear directions using the parameters generated in the initialization and parameter settings module including their initial location, direction and speed. A wraparound grid is used to avoid the boundary effect of the served area. For instance, when a mobile user reaches the most right side of the simulation area it will return on the most left side.

7-HANDOVER MODULE

The handover module determines the received power P_r and CIR of each active user from its serving cell and its neighboring cells in addition to P_r and CIR at the BS from each MS. Based on these measurements (P_r and CIR) the mobile user might be switched to another serving cell if it can provide the user with a better quality. The handover process can be performed based on the distance between the MS and the BS.

8-FREQUENCY HOPPING MODULE

The carrier frequency of each user is changed every time frame using a random or cyclic hopping algorithm to achieve interference averaging and frequency diversity. The GSM random hopping algorithm is employed in this simulation tool. At least 4 carriers per cell are necessary to achieve the gain of the frequency hopping.

9-CALL TERMINATION MODULE

The call termination module terminates any active call if its arrival time plus the call duration is equal to the simulation clock value. It releases the channel occupied with that user and removes the user from the active user list.

10-STATISTICS COLLECTION MODULE

This module collects and updates the statistics required to estimate the system performance such as the call blocking rate, call dropping rate, hand over rate and the *CIR* cumulative density function (CDF). This updating process is done every time frame. A final report describing the final statistics is generated at the end of the simulation.

Fig. 5.1 A snapshot of the graphical output of the simulator tool.

5.4 Outage Probability Analysis

Fig. 5.2 illustrates the downlink interference to an MS in sector 1 in cell 0 as well as the uplink interference to the BS in sector 1 in cell 0. The interference from the six base stations in the first tier and the five base stations facing sector 1 in the second tier is taken into consideration.

5.4.1 Downlink Analysis [Ahm2000-2]

a) Multiple Beam Antennas with no Power Control

The interference power at an MS in cell 0 from the j^{th} cell is expressed as

$$I_j = A_j P_t l_j^{-n} 10^{\frac{\xi_j}{10}} g(\theta_i, \theta_{bj}) \quad (5.3)$$

where

P_t is the transmit power

j is the cochannel interferer index ($j=1,2,\dots,N_{int}$)

l_j is the distance between the BS in the j^{th} cell and the MS in cell 0

n is the path loss exponent

A_j is a Bernoulli random variable representing the activity of the j^{th} interferer MS

where $A_j=1$ with probability q that is equal to the product of LF and DTX

ξ is the shadowing parameter of the j^{th} interferer

$g(\theta_i, \theta_{bj})$ is the antenna gain as a function of the interferer angle (θ_i) and beam angle. It is defined as $g(\theta_i, \theta_{bj}) = \text{sinc}^2(1.65(\theta_i - \theta_{bj}))$.

Due to the interference averaging from the frequency hopping, we are interested in the mean value of the interference power rather than the instantaneous value. The mean value of the interference power from the j^{th} cell is given by

$$\bar{I}_j = E[I_j] = E[A_j] P_i E[10^{\frac{\xi}{10}}] I_j^{-n} \sum_{n=1}^{N_b} f(\theta_b) g(\theta_i, \theta_{bj} = \varphi_n) \quad (5.4)$$

where $E[]$ is the mean value of the random variable, $f(\theta_{bj})$ is the PMF of the beam angle and it is equal to $1/N_b$ if users are uniformly distributed, φ_n ($n=1, 2, \dots, N_b$) are the possible values of θ_{bj} [Pet98]. It can be readily shown that $E[10^{\xi/10}] = \exp((\alpha\sigma)^2/2)$ where $\alpha = \ln(10)/10$. By substituting in Eq (5.4)

$$\bar{I}_j = q P_i I_j^{-n} \exp\left(\frac{(\alpha\sigma)^2}{2}\right) \frac{1}{N_b} \sum_{n=1}^{N_b} g(\theta_i, \theta_{bj} = \varphi_n) \quad (5.5)$$

As shown in Fig. 5.2, θ_i and I_j are functions of r_m , θ_m , D_j and θ_j where (r_m, θ_m) are the coordinates of the MS in cell 0 in polar form, while (D_j, θ_j) are the coordinates of the BS in the j^{th} cell in polar form. Therefore the total interference (I_{tot}) can be expressed as

$$I_{tot}(r_m, \theta_m) = \sum_{j=1}^{N_{tot}} \bar{I}_j \quad (5.6)$$

while the received carrier power at the MS in cell 0 is

$$C_r = P_t r_m^{-n} 10^{\frac{\xi}{10}} g(\theta_m, \theta_{bm}) \quad (5.7)$$

where θ_{bm} is the beam angle serving this MS. The outage probability (P_{out}) is defined as:

$$P_{out} = P(CIR < CIR_{min}) = CDF(CIR = CIR_{min}) = P\left(\frac{C_r}{I_{tot}} < CIR_{min}\right) \quad (5.8)$$

By substituting for C_r from Eq (5.7) the outage probability is expressed as

$$P_{out} = P\left(\left(\frac{P_t r_m^{-n} 10^{\frac{\xi}{10}} g(\theta_m, \theta_{bm})}{I_{tot}}\right) < CIR_{min}\right) = P\left(10^{\frac{\xi}{10}} < \frac{CIR_{min} I_{tot}(r_m, \theta_m)}{P_t r_m^{-n} g(\theta_m, \theta_{bm})}\right) \quad (5.9)$$

Using the total probability law the outage probability is given by

$$P_{out} = \int_0^R \int_0^{2\pi} P\left(10^{\frac{\xi}{10}} < \frac{CIR_{min} I_{tot}(r_m, \theta_m)}{P_t r_m^{-n} g(\theta_m, \theta_{bm})} \middle| (r_m, \theta_m)\right) f(r_m, \theta_m) r_m dr_m d\theta_m \quad (5.10)$$

where $f(r_m, \theta_m)$ is the PDF of the MS to be at the location defined with (r_m, θ_m) . When users are uniformly distributed $f(r_m, \theta_m)$ is equal to $3/\pi R^2$. Since ξ follows Gaussian distribution, the first term in the integrand in Eq (5.10) is determined as follows

$$P\left(10^{\frac{\xi}{10}} < \frac{CIR_{min} I_{tot}(r_m, \theta_m)}{P_t r_m^{-n} g(\theta_m, \theta_{bm})} \middle| (r_m, \theta_m) \right) = 1 - Q\left(\frac{\beta}{\sigma}\right) \quad (5.11)$$

where

$$\beta = 10 \log \left[\frac{CIR_{min} I_{tot}(r_m, \theta_m)}{P_t r_m^{-n} g(\theta_m, \theta_{bm})} \right]$$

Therefore the outage probability is evaluated using the following expression

$$P_{out} = \int_0^{\frac{2\pi}{3}} \int_0^R \left(1 - Q\left(\frac{\beta}{\sigma}\right) \right) f(r_m, \theta_m) r_m dr_m d\theta_m \quad (5.12)$$

b) Sectorization with no Power Control

This case can be considered as a special case of the multiple beams antenna with $N_b=1$. It is assumed that the antenna main lobe gain is 0 dB, while the side lobe gain is – 20 dB. Thus, $g(\theta)$ is defined as follows

$$g(\theta) = \begin{cases} 1 & 0 < \theta < \frac{\pi}{2} \\ 0.01 & \text{otherwise} \end{cases} \quad (5.13)$$

The outage probability can still be determined from Eq (5.12) taking into account the new definition of the antenna directive gain.

c) Multiple Beam Antennas with Perfect Power Control

With perfect power control, each mobile must receive a constant power (C_r^v) from its BS regardless of its location. Consequently, the transmitted power from the BS becomes a function of the MS coordinates (r, θ) as follows

$$P_t = C_r^v r^n 10^{\frac{\xi}{10}} g^{-1}(\theta, \theta_b) \quad (5.14)$$

Using Eq (5.3) the interference from the j^{th} BS is given by

$$I_j = A_j C_r^v \left(\frac{r_j}{l_j} \right)^n 10^{\frac{\xi_j - \xi_{ij}}{10}} \frac{g(\theta_i, \theta_{bj})}{g(\theta_{ij}, \theta_{bj})} \quad (5.15)$$

where ξ_{ij} is the shadowing parameter inside the j^{th} cell while r_j and θ_{ij} are the coordinates of the MS in the j^{th} cell. Then the mean value of the interference is

$$\bar{I}_j = q C_r^v l_j^{-n} \exp((\alpha\sigma)^2) \frac{3}{\pi R^2} \int_0^R \int_0^{2\pi} r_j^n \frac{g(\theta_i, \theta_{bj})}{g(\theta_{ij}, \theta_{bj})} r_j dr_j d\theta_{ij} \quad (5.16)$$

which can be simplified as

$$\bar{I}_j = \frac{3q C_r^v I_j^{-n}}{\pi R^2} \exp((\alpha\sigma)^2) h_j$$

where

$$h_j = \frac{R^{n+2}}{n+2} \int_0^{\frac{2\pi}{3}} \left(\frac{\text{sinc}(1.65(\theta_{bj} - \theta_i))}{\text{sinc}(1.65(\theta_{bj} - \theta_{ij}))} \right)^2 d\theta_{ij}$$

Thus the total interference is given by

$$I_{tot} = \frac{R^n}{n+2} \frac{3q C_r^v}{\pi} \exp((\alpha\sigma)^2) \sum_{j=1}^{N_{\text{BS}}} \left(I_j^{-n} \int_0^{\frac{2\pi}{3}} \left(\frac{\text{sinc}(1.65(\theta_{bj} - \theta_i))}{\text{sinc}(1.65(\theta_{bj} - \theta_{ij}))} \right)^2 d\theta_{ij} \right) \quad (5.17)$$

Since perfect power control is assumed, the received carrier power at the MS from its BS is constant (C_r^v). Hence, the outage probability is equal to

$$P_{out} = P\left(\frac{C_r^v}{I_{tot}} < CIR_{min}\right) = P\left(I_{tot} > \frac{C_r^v}{CIR_{min}}\right) \quad (5.18)$$

Using the total probability law, the outage probability is given by

$$P_{out} = \int_0^{\frac{2\pi}{3}} \int_0^R P \left(I_{tot} > \frac{C_r^v}{CIR_{min}} \middle| (r_m, \theta_m) \right) f(r_m, \theta_m) r_m dr_m d\theta_m \quad (5.19)$$

which can be rewritten as

$$P_{out} = \int_0^{\frac{2\pi}{3}} \int_0^R u \left(I_{tot}(r_m, \theta_m) - \frac{C_r^v}{CIR_{min}} \right) f(r_m, \theta_m) r_m dr_m d\theta_m \quad (5.20)$$

where $u(.)$ is the unit step function.

d) Sectorization with Perfect Power Control

A similar analysis can be used here but the antenna directive gain has to be redefined as discussed in (b) above.

5.4.2 Uplink Analysis [Ahm2000-1]

The uplink analysis is similar to the downlink one with some modifications to consider the mobility of the cochannel interferers. Thus the same methodology used in the uplink is used here to find an expression for the outage probability. The details of the analysis will not be repeated here because of the similarity with the downlink analysis.

a) Multiple Beam Antenna with no Power Control

The interference power at the BS in cell 0 from an MS in the j^{th} cell is given by

$$I_j = A_j P_i l_j^{-n} 10^{\frac{\xi_j}{10}} g(\theta_i, \theta_{bm}) \quad (5.21)$$

This equation is similar to Eq (5.3) in the downlink analysis but θ_{bj} is replaced with θ_{bm} . Also, the definitions of both l_j and θ_i are changed as illustrated in Fig. 5.3. Then, the mean value of the interference from the MS in the j^{th} cell is given by

$$\bar{I}_j = q P_i \exp\left(\frac{(\alpha\sigma)^2}{2}\right) \int_0^{\frac{2\pi}{3}} \int_0^R l_j^{-n}(r_j, \theta_{ij}) g(\theta_i, \theta_{bm}) f(r_j, \theta_{ij}) r_j dr_j d\theta_{ij} \quad (5.22)$$

where r_j and θ_{ij} are the polar coordinates of the MS interferer and l_j is the distance between the MS in the j^{th} cell and the BS in cell 0. Other variables and parameters are similar to those used in the downlink analysis. Accordingly, the total interference is given by

$$I_{tot}(\theta_m) = \sum_{j=1}^{N_{int}} \bar{I}_j \quad (5.23)$$

Eq (5.23) is similar to Eq (5.6) in the downlink analysis with one difference that is the independence of I_{tot} on r_m unlike the uplink case. The carrier power expression given in Eq (5.7) is still applicable here. Consequently, the expression of the outage probability of the downlink case given by Eq (5.12) is also valid for the uplink considering the difference in the definition of I_{tot} .

b) Sectorization with no Power Control

The expression of the outage probability given by Eq (5.12) is also valid in this case but the directive gain function $g(\theta)$ should be modified as in Eq (5.13).

c) Multiple Beam Antenna with Perfect Power Control

As in the down link analysis, the received power is assumed to be constant and equal to C_r^ν . Therefore, the cochannel interference at the BS in cell 0 from the MS in the j^{th} cell is still given by Eq (5.15). From Eq (5.15) and Fig. 5.3, it can be shown that the mean value of the interference from the cochannel interferer MS in the j^{th} cell is given by

$$\bar{I}_j = q C_r^\nu \exp((\alpha\sigma)^2) \int_0^{\frac{2\pi}{3}} \int_0^R \left(\frac{r_j}{l_j(r_j, \theta_{ij})} \right)^n f(r_j, \theta_{ij}) \frac{g(\theta_i, \theta_{bm})}{g(\theta_{ij}, \theta_{bj})} r_j dr_j d\theta_{ij} \quad (5.24)$$

Then, the total interference I_{tot} is given by Eq (5.23) and it is a function of θ_m only.

Thus, the outage probability is given by

Fig. 5.2 Downlink cochannel interference at the MS in cell 0 from the j^{th} cell.

Fig. 5.3 Uplink cochannel interference at the MS in cell 0 from the j^{th} cell.

$$P_{out} = \sum_{i=1}^{N_b} u \left(I_{tot}(\theta_{bm} = \phi_i) - \frac{C_r^v}{CIR_{min}} \right) \quad (5.25)$$

d) Sectorization with Perfect Power Control

A similar analysis to the multiple beam antennas with perfect power control can be used here. However the antenna directive gain must be redefined as expressed in Eq (5.13). Therefore, the same expression of the outage probability can be used here.

5.5 Results

In this section, the results of the *CIR* analysis are presented for both the downlink and the uplink based on the simulation described in section 5.3 as well as the analytical method discussed in section 5.4. The following numerical values are used in the simulation and the analysis:

- Cell radius (R)=2 km
- Discontinuous Transmission Factor (DTX)=0.5
- Traffic per user in Erlang (E_{user})=0.02 Er/user
- Frequency reuse factor (N)=1/3

The outage probability is evaluated analytically and by simulation using Eqs (5.12), (5.20), and (5.25) at different values of the loading factor. Figs. 5.4 and 5.5 show the $CDF(CIR)$ with Multiple Beams (MB) antennas and with sectorization only (SC) with and without power control at 20%, 40% and 60% loading factor for the downlink and the uplink as well. In both figures, it is evident that there is a good agreement between the results evaluated by simulation and those evaluated analytically. The difference between the CIR values of the two methods does not exceed 1dB for most of the results. It can also be noticed that the power control changes the distribution of the CIR . Without PC, the CDF has a smooth monotonically increasing shape as shown in Figs. 5.4(a), (c) and (e) for the downlink and Figs. 5.5 (a), (c) and (e) for the uplink. With PC, as expected, the high values of the CIR are emphasized while the low values are de-emphasized. Therefore, the CDF of the CIR takes very low values (approaches zero) at low CIR values while it takes very high values (approaches one) at high CIR values. An abrupt change from the low values to high values can be remarked in Figs. 5.4 and 5.5. The value of the CIR at this abrupt transition is function of the loading factor. For example in the downlink, the transition starts at $CIR=6$ dB and 13 dB at 20% loading with and without MB respectively, while it starts at $CIR=4$ dB and 8 dB at 60% loading with and without MB respectively.

Using Figs. 5.4 and 5.5, the outage probability ($CDF(CIR=9$ dB)) is computed for the four cases mentioned above (with/without multiple beams and with/without power control) and then plotted versus the loading factor in Figs. 5.6 and 5.7 for the downlink and the uplink respectively.

Figs. 5.6 and 5.7 show that significant enhancement in performance can be achieved by employing multiple beam antennas combined with power control. It is shown that the outage probability can be reduced by 40-65% without power control while the reduction is more than 95% with power control, particularly at low and medium loading factors. The reduction in the outage probability due to the PC is obvious in Figs. 5.6 and 5.7. With PC, it can also be shown that beyond a certain threshold value for the loading factor the outage probability starts to increase rapidly. It is evident that the outage probability can be higher than that without PC at high loading factor values particularly if MB antennas are not employed. This happens since the perfect power control used in this analysis might degrade the system performance under heavy loading conditions.

Tables (5.1) and (5.3) list the outage probability for the four cases mentioned above at loading factor values ranging from 10% to 60% for the downlink and the uplink respectively. It is apparent that the outage probability can be significantly reduced using the multiple beam antennas combined with power control. For example, for the downlink, with MB antennas at 60% loading factor, P_{out} is reduced from 1.2×10^{-1} to 6.7×10^{-2} without power control and it can be reduced to 2.0×10^{-2} when MB antennas are combined with perfect power control.

Tables (5.2) and (5.4) list the maximum loading factor at different maximum outage probability requirements (p_{max}). For example, in the downlink, when $p_{max}=2\%$, the maximum loading factor is increased from 7% to 20% (which is almost 300% enhancement) by including the MB antennas without power control, and it is increased to 18% (which is more than 250% enhancement) by employing power control without MB.

(a)

(b)

(c)

(d)

(e)

(f)

Fig. 5.4 CDF(*CIR*) for the downlink without PC (with PC) a(b), c(d), e(f) at 20%, 40% and 60%LF.

Fig. 5.5 CDF(CIR) for the uplink without PC (with PC) a(b), c(d), e(f) at 20%, 40% and 60%LF.

Fig. 5.6 Outage probability versus loading factor with MB and SC with and without PC for downlink.

Fig. 5.7 Outage probability versus loading factor with MB and SC with and without PC for uplink.

Table 5.1 Outage Probability (CDF(CIR = 9 dB)) for downlink at different loading factor values.

	Antenna Type	CDF (CIR = 9 dB)					
		LF = 10%	LF = 20%	LF = 30%	LF = 40%	LF = 50%	LF = 60%
no PC	3 sectors	2.9×10^{-02}	5.7×10^{-02}	8.1×10^{-02}	9.0×10^{-02}	1.0×10^{-01}	1.2×10^{-01}
	Multiple Beam	7.5×10^{-03}	1.9×10^{-02}	3.3×10^{-02}	4.5×10^{-02}	5.6×10^{-02}	6.7×10^{-02}
with PC	3 sectors	1.0×10^{-05}	6.0×10^{-02}	1.3×10^{-01}	2.5×10^{-01}	4.1×10^{-01}	6.3×10^{-01}
	Multiple Beam	1.0×10^{-05}	1.0×10^{-05}	1.0×10^{-05}	1.0×10^{-05}	1.0×10^{-05}	2.0×10^{-02}

Table 5.2 Maximum loading factor for downlink with various outage probability requirements

Antenna type	Maximum Loading Factor (LF_{max})					
	$P_{max}=2\%$		$P_{max}=4\%$		$P_{max}=10\%$ Outage	
	with PC	No PC	with PC	No PC	with PC	No PC
3 sectors	18%	7%	19%	15%	26%	40%
Multiple Beam	60%	20%	70%	36%	100%	90%

Table 5.3 Outage Probability (CDF(CIR = 9 dB)) for uplink at different loading factor values

	Antenna Type	CDF (CIR = 9 dB)					
		LF = 10%	LF = 20%	LF = 30%	LF = 40%	LF = 50%	LF = 60%
no PC	3 sectors	2.9×10^{-02}	5.0×10^{-02}	7.9×10^{-02}	1.0×10^{-01}	1.2×10^{-01}	1.4×10^{-01}
	Multiple Beam	6.5×10^{-03}	2.0×10^{-02}	3.3×10^{-02}	4.5×10^{-02}	5.3×10^{-02}	6.1×10^{-02}
with PC	3 sectors	1.0×10^{-05}	5.0×10^{-02}	1.6×10^{-01}	3.2×10^{-01}	4.5×10^{-01}	6.0×10^{-01}
	Multiple Beam	1.0×10^{-05}	1.0×10^{-05}	1.0×10^{-05}	1.0×10^{-05}	1.0×10^{-05}	1.0×10^{-05}

Table 5.4: Maximum loading factor for the uplink with various outage probability requirements

Antenna type	Maximum Loading Factor (LF_{max})					
	$P_{max}=2\%$		$P_{max}=4\%$		$P_{max}=10\%$ Outage	
	with PC	No PC	with PC	No PC	with PC	No PC
3 sectors	18.5%	8.0%	19.7%	17%	26.8%	40%
Multiple Beam	69%	20%	72%	36%	100%	100%

By combining both techniques the maximum loading factor jumps to 60%. However, the capacity gain that can be achieved in practice might be less than that because of the difficulty of realizing perfect power control. By comparing the maximum allowed loading factors in these two tables we can conclude that the downlink loading is the limiting factor. For example, with $p_{max}=2\%$ and when MB antennas are used combined with PC, the network can tolerate loading factor values up to 69% in the uplink while it can tolerate up to 60% in the downlink. Hence, the admission control must consider the smaller value and limits the loading factor to 60% even though the uplink can accept more loading with acceptable QoS.

5.6 Call Admission Control for GSM Networks [Ahm2000-2]

As mentioned before, the call admission control algorithms can use the instantaneous network-loading factor as the criterion for the call admission. This criterion is selected since it guarantees the QoS (in terms of the outage probability) through limiting the network loading at certain threshold (the maximum loading factor LF_{max}). This threshold is determined either from the outage analysis of the cellular network like that given in section 5.4 or from a software simulation similar to that described in section 5.3. When such an algorithm is used the average network capacity is simply determined from Eqs (5.1) and (5.2) where the blocking probability is evaluated from the Erlang-B formula as follows

$$P_b = \frac{\left(\frac{A^c}{N_{max}!} \right)}{\sum_{k=0}^{N_{max}} \frac{A^k}{k!}} \quad (5.26)$$

where A^c is the total traffic intensity per cell (including the new traffic and the hand over traffic as well) and N_{max} is the maximum number of channels to be utilized simultaneously per cell and it is equal to $CH_{cell} \times LF_{max}$. The dropping probability is expressed as a function of the blocking probability (P_b) and the Hand Over Rate (HOR) as follows:

$$P_d = \frac{HOR P_b}{[1 - HOR (1 - P_b)]} \quad (5.27)$$

A new admission control algorithm that aims to increase the average network capacity (C_{av}) is proposed here. This algorithm takes advantage of the residual capacity discussed in section 3.5. Looking carefully at Eqs (5.1) and (5.2), we can realize that if the maximum available network capacity (C) is kept constant, the only means to increase C_{av} is to reduce P_b and P_d . This can only be accomplished by modifying the admission control algorithm to admit more users. Nevertheless, the QoS should be kept in consideration to avoid any degradation of the signal quality.

Fig. 5.8 depicts realizations of the stochastic processes describing the number of active users in cell 0 and its first tier neighbor. It is worth noting that the average number of users per cell is less than N_{max} and it is equal to $N_{max}(1-P_b)(1-P_d)$. Basically the outage

probability is dependent on the average loading factor rather than the instantaneous loading factor. Hence, It is possible to allow the loading factor to exceed LF_{max} provided that the average loading factor does not exceed LF_{max} .

The proposed admission algorithm takes advantage of this fact to enhance the average network capacity. The proposed admission control algorithm takes into consideration the temporal loading information in each cell separately. The permission for such an overloading status reduces the call blocking and dropping as shown in Fig. 5.8. However, the permission of the overloading status is conditional on the value of the Exponential Weighted Moving Average (EWMA) of the number of active users in the i^{th} cell ($N_i^{EWMA}(t)$) defined by

$$N_i^{EWMA}(t) = (1-w) N_i^{EWMA}(t-T) + w N_i(t) \quad (5.28)$$

where w is the updating parameter which ranges from 0 (no updating) to 1 (memoryless updating) and T is the frame duration. The exponential weighted moving average is chosen since it has an adjustable gradual averaging window rather than the abrupt averaging window as in the truncated average. The call admission condition is simply presented by the following statement: "The i^{th} cell can accept the arriving users (new or hand over calls) as long as $N_i^{EWMA}(t) < N_{max}$ ".

The overloading status is only permitted for some time bursts in each cell (when there is high traffic and the admission condition is satisfied).

Fig.5.8 Number of users at the first tier neighbor cells of cell 0 versus time frame index. The arrows show the overloading instants when users can be admitted with the proposed admission scheme, while they are rejected with the conventional one.

As the random processes describing the number of active users in different cells are mutually independent, an overloading status in the i^{th} cell can be tolerated since the probability of having simultaneous overloading in all the neighboring cells of the central cell is almost negligible. Even if this case happens it can be tolerated since this additional undesirable interference will be distributed over many users because of the interference averaging property. Moreover, this overloading status will last for a short duration until N_i^{EWMA} grows to N_{max} and then no more users can be admitted.

5.7 Performance Analysis of the Admission Control Algorithm

In order to study the performance of the proposed algorithm analytically, a stochastic analysis based on the state transition model has been developed. When time averaging is not employed it is enough to define the system (cell) state (ST) as the number of active users ($ST=N_v$). Then, the system is described as a *Lost Call Cleared System* or M/M/C/C queuing system and the blocking probability is determined by the Erlang-B formula as mentioned above. By introducing the EWMA of the active users number (N^{EWMA}) as a criterion of call admission, we have to redefine the system state to include N^{EWMA} . Thus, each state is determined by a two-element vector ($ST=(N_v, N^{EWMA})$) and we will have a two-dimensional state transition model. Since the transition from one state at instant (t) to another at instant ($t+dt$) depends solely on the current state ($ST(t)$) and not the previous states, the system still has the Markovian property.

By rearranging the Markov chain, it can be represented as a one-dimensional chain as shown in Fig.5.9. It is assumed that the transition occurs at each time interval

(dt) which is so small that no more than one event can occur during this interval. Hence, at state ($ST=(N_v, N^{EWMA})$) the three possible events are as follows:

- 1-One user arrives to the cell
- 2-One user departs from the cell
- 3-No users arrive to or depart from the cell.

The probability of the first event ($Q1$) is equal to $L_v dt$ where L_v is the call arrival rate and the probability of the second event ($Q2$) is equal to $N\mu dt$ where μ is the average residence time of users in the cell while the probability of the third event ($Q3$) is $1-(\lambda + N\mu)dt$. Assuming that the initial state of the system ST_1 is equal to $(0,0)$, we can study the system evolution based on Eq (5.28) in addition to the possible events listed above. The system may remain in state ST_1 with probability $Q3$ or move to state $ST_2=(1,w)$ with probability $Q1$. Another user may arrive to the cell in the next interval with a probability $Q1$, and hence the system will move to state $ST_3=(2,3w-w^2)$. Otherwise the system either moves to state $ST_4=(0,w)$ or $ST_5=(1,2w-w^2)$ if the first arrived user departs from or stays at the cell with probabilities $Q2$ and $Q3$ respectively.

Following this procedure, we can determine all the states of the Markov chain. However the chain size is too large to be determined manually. Thus, a software routine has been developed to find all the possible states associated with its Transition Probability Matrix (TPM). Obviously, N is a discrete variable, which takes nonnegative integer values. On the other hand, N^{EWMA} is a discrete variable that takes nonnegative values but not necessarily integers.

Fig. 5.9 Markov chain representing the cell state transition.

In order to reduce the computational burden N^{EWMA} is quantized with a quantization level ΔN^{EWMA} which implicitly means that some states are merged to reduce the number of the states and consequently the size of the TPM. Nevertheless, ΔN^{EWMA} should be chosen to reduce the computation burden without compromising the accuracy.

A new user is blocked if the number of active users (N) is already equal to the maximum number of channels per cell CH_{cell} or when N^{EWMA} is greater than or equal to a certain threshold value N_{max} . Therefore the blocking probability (P_b) is expressed as

$$P_b = \Pr(N_v = CH_{cell} \text{ or } N_i^{EWMA} \geq N_{max}) \quad (5.29)$$

The TPM is evaluated as a function of the arrival rate (L_v) and the average call residence time ($1/\mu$). The arrival rate $L_v = \lambda_n + \lambda_h$ where λ_n is the new call arrival rate and λ_h is the handover call arrival rate and it is a function of λ_n and P_b as follows [Jab96]:

$$\lambda_h = \frac{HOR (1 - P_b)}{[1 - HOR (1 - P_b)]} \lambda_n \quad (5.30)$$

The average call residence time ($1/\mu$) is equal to $1/(\mu_v + \mu_d)$ where $1/\mu_d$ is the average dwelling time of the MS in the cell which is function of the average speed of the MSs and the cell size, while $1/\mu_v$ is the average call duration. Since the TPM is a function of the blocking probability, it is possible to determine the state probabilities and then the blocking probability P_b iteratively as explained in Appendix B.

5.8 Results

CH_{cell} is limited to 3 channels to reduce the problem size. LF_{max} is assumed to equal 33.33%. Both the updating parameter w and the quantization step size ΔN_i^{EWMA} are chosen to be equal to 0.01. Other parameters are identical to those used in the simulation analysis in 5.4.

Fig. 5.10 depicts all the possible states for this problem. Using these values we found that the chain consists of 992 states. This number grows exponentially and jumps to hundreds of thousands by reducing ΔN_i^{EWMA} and/or increasing CH_{cell} and it becomes too tedious to solve this problem particularly with this iterative method.

Fig. 5.11 shows the blocking rate as a function of the offered traffic using the conventional and the proposed call admission control algorithms. P_b is evaluated for both algorithms by simulation as well as by stochastic analysis. Several remarks can be noticed from this figure. First of all, there is a good agreement between the simulation results and the analytical results. The relative error in P_b does not exceed 3% for both algorithms. Fig. 5.11 also shows that the blocking probability is considerably reduced using the proposed algorithm. For instance, when the offered traffic=15 Erlang/cell and $N_{max}=16$ channel, the blocking rate is 0.09 for the conventional algorithm while it is reduced to 0.05 using the proposed algorithm. At 2% blocking rate the offered traffic can be increased from 10.5 Erlang/cell to 12.7 Erlang/cell, which is more than 20% enhancement.

This capacity enhancement is obtained by admitting more users to the system in such a way that the average number of users per cell does not exceed N_{max} to maintain the

quality of service in terms of the *CIR*. Fig. 5.12 depicts the $CDF(CIR)$ for the proposed and the conventional algorithms. It can be shown that the reduction of the *CIR* does not exceed 0.5 dB for the proposed algorithm. Another advantage of this algorithm is that it is a distributed admission control so that there is no need for any exchange for loading information between the base stations.

Fig. 5.10 (a) The cell possible states using the proposed algorithm.

Fig. 5.10 (b) some of the possible states using the proposed algorithm with zooming in.

Fig. 5.11 (a) Blocking probability versus the offered traffic (Analytically and by Simulation at $N_{\max}=1$).

Fig. 5.11 (b) Blocking probability versus the offered traffic (at $N_{\max}=16$)

Fig. 5.12 CDF(CIR) for the proposed and the conventional admission algorithms.

Chapter 6

Call Admission and Load Control of Multiple Service in Third Generation Wireless Networks

6.1 Introduction

The demand for data and multimedia applications in wireless and mobile communications networks continues to grow at accelerating pace. Services such as World Wide Web (WWW), Electronic mail (E-mail), File Transfer Protocol (FTP) and video transmission are to be offered along with enhanced voice services in third generation wireless systems.

Standardization bodies such as ITU and ETSI have been developing the essential framework of the supporting technology, which includes many aspects such as the physical layer, multiple access techniques, media access control and network structure [Dah98, Oja98-1].

Wideband CDMA has been chosen as the access technique for 3G wireless systems because of its superiority to other multiple access techniques in terms of system capacity and performance.

Efficient admission and load control algorithms are required in CDMA wireless systems because the network capacity is interference limited. Therefore, an admission policy is required to maximize the available capacity and guarantee the Quality of Service (QoS) in terms of the Energy per bit to Interference density ratio (E_b/I_o).

With multiple services, fixed resource allocation is not suitable due to the bursty nature of the data traffic. As a result, data services are to be based on dynamic resource allocation that considers the propagation path loss, network loading, and interference conditions derived and estimated from the reported pilot measurements, and the exchanged data between each cell and its neighbors [Ejz97, Zan97]. Short and infrequent messages are transmitted over a random access channel using the slotted ALOHA protocol to avoid large overheads. For larger and frequent messages, a connection request is first sent to the BS that determines the possibility of establishing this connection and decides how much resources can be assigned to it. The BS might reject this request due to the loading conditions or the high interference expected from the user requesting the service. Since most of the data services are delay tolerant, the rejected user can be queued until some users (voice or data) depart.

Admission algorithms mainly differ in the amount of information used for deciding to admit/reject the incoming call. Fixed strategy techniques consider only the traffic parameters of all sources in the cell of the incoming call. Local adaptive strategies use the traffic parameters and the channel characteristics in the cell. On the other hand,

global adaptive strategies extend the scope of the information sources to include all the neighboring cells. The local strategy gives higher capacity compared with the fixed allocation techniques while the global strategy surpasses both techniques at the expense of a higher signaling and information exchange rate.

In this chapter, an admission and load control algorithm for 3G wireless systems is presented. A modified model that combines the advantages of the local and global strategies is adopted in the proposed algorithm. The algorithm considers the loading and propagation information in each cell and its first tier neighbors to exploit the residual capacity discussed in section 3.5. In 3G systems, the pilot signal is measured at the serving BS and the BSs of the first tier neighbors as well. Hence, the intercell interference can be accurately predicted without any extra information exchange requirements. It is assumed that voice and switched-mode data services are to be provided over wideband CDMA system. The proposed algorithm controls the admission of voice and data users, the data rate of the data users, and the transmit power assigned for voice/data users taking the QoS requirements for voice and data services into consideration. Switched-beam antennas are included in the system model exploiting the auxiliary pilot option proposed in 3G systems.

This chapter is organized as follows: section 6.2 introduces the system model. The proposed algorithm is explained in subsection 6.3.1. Then the Markovian model describing the system performance is presented in subsection 6.3.2. The performance measures are given in subsection 6.3.3. Finally, the results obtained analytically and by simulation are discussed in section 6.4.

6.2 System Model

1-Basic Features: It is assumed that the system is time slotted with a time frame of 10 ms divided into 16 slots of 0.625 ms. The number of bits per time slots is variable. Data users admitted to the system are assigned a fundamental (code) channel which carries data rate (R_f) of 14.4 kbps. They are also assigned 1 (or 0 depending on the network loading as discussed below) supplemental (code) channel that carries data rate up (R_s) to 144 kbps. The system bandwidth (W) is 5MHz with a 34.7 spreading gain for voice and fundamental data channels and a variable spreading gain for the supplemental data channels. The assigned bit rate is determined by the BS and sent to the data users through the dedicated control channels. Perfect Power Control (PC) is assumed such that the received power at the BS from voice users (C_r^v) and data users (C_r^d) are constant.

2-Smart Antennas: 3G systems support the utilization of smart antennas using an auxiliary pilot on both the uplink and downlink. As mentioned in chapter 2, switched-beam antennas use N_b beams to cover the entire cell area, and the MSs use the beams providing them with the best quality in terms of the received power or signal-to-interference ratio. Ideal beam patterns with no overlapping are employed at the BS as shown in Fig. 6.1. The arrow represents the uplink interference from the MSs at the six beam areas in the neighbor cell to one of the beam areas (shaded) in the central cell.

3-Voice Traffic: Voice traffic is modeled as a Poisson process with an arrival rate (L_v) and an exponential call duration with mean value ($1/\mu$). DTX is included by modeling the

voice source as an On/Off source depicted in Fig. 6.2. The source has two states (on and off) corresponding to talking and listening and the source state is changed with probabilities P_{on-off} and P_{off-on} .

4-Data Traffic: Data user arrivals are also modeled as a Poisson traffic with an arrival rate (L_d) and an exponential message size with a mean value (S_d). Data traffic is assumed to be totally independent of the voice traffic.

The call admission and load control can be modeled by a fixed number of parallel servers for the voice service. On the other hand, the data service is modeled by a variable number of servers with a waiting queue as illustrated in Fig. 6.3.

6.3 Stream-mode Non-Real-Time Data Service [Ahm99]

Since the data service is non-real-time, it can tolerate both the queuing delay and the variable transmission rate. Also, there is no guaranteed minimum bit rate, and the assigned bit rate is determined according to the network loading condition. Hence, it can be considered as a best effort service. This suits some applications such as FTP. In the proposed algorithm, voice users are given higher priority so that at first voice users are assigned channels. Then, the remaining resources are assigned to some (or all) of the data users on a first-come-first-serve basis as explained below.

6.3.1 The Proposed Algorithm

When a voice user requests a service from the nearest (or best serving) BS, it is granted a particular code (channel) provided that the number of existing voice users in this cell (N_v) does not exceed the maximum value (L_{max}), otherwise this voice call will be rejected. L_{max} is determined from the simulation as the maximum number of voice users per cell at which the QoS requirements can be met.

The QoS requirements are summarized as: $(E_b/I_o)_v > \gamma_v$, $(E_b/I_o)_f > \gamma_f$, and $(E_b/I_o)_s > \gamma_s$ where γ_v , γ_f , and γ_s are the minimum E_b/I_o of the voice channel, fundamental data channel, and supplemental data channel respectively.

The admission of data users is performed at the beam area level. As illustrated in Fig. 6.4, when a BS receives a request from a data user, the BS determines the maximum number of data users that can be served in this beam area $(N_d^{b-max}) = (1/\alpha_f)[(L_{max}/N_b) - N_v^b]$. If N_d^{b-max} is greater than the number of the existing data users in this beam area (N_d^b), the data user is admitted, otherwise it will be queued. Each admitted data user is granted a fundamental channel. Supplemental channels are also assigned to some of the admitted data users depending on the availability of more resources. In the proposed algorithm, we take advantage of the intermittent nature of the voice sources by determining the active voice users in the beam area ($N_v^b(m)$) where m is the frame number. Thereupon, the residual resources due to the inactivity of some voice users are allocated to the data users as supplemental channels. The admitted data users are assigned in this beam area are ordered according to their arrival time. Then, the first $N_{sc}^b(m+1)$ data users in this beam area are assigned supplemental channels. If $N_d^b > N_{sc}^b(m+1)$ the remaining data users are

only assigned the fundamental channels. The number of the supplemental channels in this beam area ($N_{sc}^b(m+1)$) and the associated spreading gain ($SG_s(m+1)$) are determined as illustrated below. The derivation of the formulae given below is provided in Appendix C.

- a) An initial estimate of the number of the supplemental codes ($N_{sc}^b(m+1)$) is evaluated by

$$N_{sc}^b(m+1) = \min \left(\left\lfloor \frac{(L_{max}/N_b) - DTX N_v^b(m) - \alpha_f N_d^b}{\alpha_f} \right\rfloor, N_d^b \right) \quad (6.1)$$

where $\lfloor x \rfloor$ is the largest integer less than or equal to x .

- b) The rate control is performed by determining the spreading gain using the (E_b/I_o) constrains as follows:

$$SG_s(m+1) \geq \frac{N_{sc}^b(m+1) A + B}{A - B} \quad (6.2)$$

where $A = (SG_v/\gamma) + DTX$ and $B = N_v^b + \alpha(N_d^b - 1) + I_{inter\_cell}$. The inter-cell interference (I_{inter_cell}) is estimated from the exchanged information (including the number of active voice users in the current frame, the number of data users, and the number of supplemental channels used in that frame) between each cell and its neighbor cells in addition to the reported

pilot measurements from the MS in the interfering areas used to estimate the distance and propagation conditions between those MSs and the serving BS.

c) The spreading gain $SG_s(m+1)$ is adjusted to keep the transmission rate of the supplemental channel between 14.4 kbps and 144 kbps. If $SG_s(m+1)$ is increased, then more supplemental channels can be used and vice versa. And as a result, $N_{sc}^b(m+1)$ must be modified and given by

$$N_{sc}^b(m+1) = \min \left(\left[\left(1 - \frac{B}{A} \right) \left(1 + \frac{SG_s(m+1)}{\gamma_s} \right) \right], N_d^b \right) \quad (6.3)$$

d) The normalized received power levels of the fundamental and supplemental channels are determined as follows

$$\alpha_f = \frac{A}{\left(1 + \frac{SG_f}{\gamma_f} \right)} \quad (6.4)$$

$$\alpha_s = \frac{A}{\left(\frac{SG_s(m+1)}{\gamma_s} + 1 \right)} \quad (6.5)$$

Accordingly, power control commands are sent by the BS to all MSs to adjust the transmit power based on the required received power values.

6.3.2 Performance Measures

The voice and data admission and load control can be modeled as depicted in Fig. 6.4. The voice service is modeled as L_{max} parallel servers (per cell). If a voice service request arrives and one or more servers are available, it will be admitted, otherwise it will be rejected. The data service is modeled using N_d^{b-max} parallel servers per beam area. It should be noted that the number of servers and the service rate are variable and their values depend on loading conditions of the voice service. Furthermore, the spreading factor of the supplemental channel is a function of network loading in the beam area as well as in its neighboring areas. Thus, if a data user arrives and one or more servers are available, it will be admitted and the service rate will be determined in a frame by frame basis as discussed in the previous section; otherwise it will be queued until the loading conditions change.

The performance of the proposed algorithm is estimated using the following performance measures:

1-Number of data users per beam area N_d^b : It is the average number of admitted data users per beam area. This value is function of the available traffic as well as the allocated resources.

2-Transmission Rate (R_b): It is the average transmission rate allocated for the data users.

Fig. 6.1 The central cell covered by 12 beams.

Fig. 6.2 Voice On/Off model.

Fig. 6.3(a) Voice admission control model

Fig. 6.3(b) Data admission control model

Fig. 6.4 The admission and load control of data calls

3-Number of queued data users (N_q^b): The average number of queued data users per beam area is an important measure since it can show the average number of data calls requests arrived to the system and placed in the waiting queue because of the resources unavailability.

4-Queuing Delay (T_q): It is the average waiting time of the data users starting from the arrival time until the start of transmission.

5-Energy per bit to interference density ratio (E_b/I_o): It is the average energy per bit to interference density ratio for voice and data services (including the fundamental and supplemental channels).

In order to analyze the performance of the proposed algorithm, the system performance is evaluated analytically and by computer simulation. A dynamic time-driven simulation is utilized to study the performance of the proposed algorithm. The time resolution of the simulation tool is set equal to the frame length (10 ms). The simulator is built as a modular structure using the models presented in section 6.2. The traffic parameters are provided as inputs to the simulator. Then, the performance measures are estimated using the statistics collection module. The performance of the proposed algorithm is studied analytically using Markovian model. Each state is defined by two variables: N_d^b and N_v^b . Fig. 6.4(a) shows the state transition model of the proposed algorithm. At any state ($ST=(N_d^b, N_v^b)$), there are four possible events:

1-A voice call arrives to the cell with a transition rate L_v .

2-A data call arrives to the cell with a transition rate L_d .

3-A voice call departs from the cell with a transition rate μ .

4-A data call departs from the cell with a transition rate $\zeta_{i(i-1)}$.

$\zeta_{i(i-1)}$ is a function of both state variables, and i is the number of admitted data users. $\zeta_{i(i-1)}$ is expressed as

$$\zeta_{i(i-1)} = \frac{i R_f + N_{sc}^b (m+1) R_s(i, N_v^b)}{S_d} \quad (6.6)$$

Since the number of data calls per beam (N_d^b) includes the admitted data call as well as the queued data calls, the Markov chain extends horizontally to infinity as indicated in Fig. 6.5(a). In order to determine the state probabilities using the transition rates, it will be transformed to a one-dimensional chain as depicted in Fig. 6.5(b). In order to do this transformation, the Markov chain must be truncated horizontally. Thus, the number of states in each horizontal line in Fig. 6.5(b) is restricted to $N_d^{d-max} + Q$, where Q is a constant whose value is selected as a tradeoff between the result accuracy and computation burden.

Using the one-dimensional chain shown in Fig. 6.5(b) and the transition probabilities listed above, the Transition Probability Matrix (TPM) is determined. Then the state probabilities (P_k , $k=1,2,\dots,[(1+L_{max})(N_d^{d-max}+Q)]$) are calculated using the global balance condition:

$$P_k \sum_{j \neq k} p_{kj} = \sum_{j \neq k} p_{jk} P_j \quad \forall k \quad (6.7)$$

Subject to the condition

$$\sum_k P_k = 1 \quad (6.8)$$

By solving the state transition model and calculating the state probabilities, the performance measures can be determined as follows:

The average number of data users per beam (N_d^b) is given by

$$N_d^b = \sum_k P_k i(k) \quad (6.9)$$

where $i(k)$ is the number of admitted data users at state k . The average transmission rate (R_b) is given by

$$R_b = \sum_k P_k \zeta_{i(k)[i(k)-1]} S_d \quad (6.10)$$

while the average number of queued data users (N_q^b) is

$$N_q^b = \sum_k P_k \left(N_d^b(k) - i(k) \right) \quad (6.11)$$

Fig. 6.5 (a) A two-dimensional Markov chain representing the system state transition.

Fig. 6.5 (b) A one-dimensional Markov chain approximating the system state transition.

where $N_d^b(k)$ is the number of all data users (admitted and queued) at state k . The average queuing delay time is given by

$$T_q = \sum_k P_k \left(N_d^b(k) - i(k) \right) \frac{S_d}{i(k) R_f} \quad (6.12)$$

Finally, E_b/I_o of the voice channel, fundamental data channel, and supplemental data channel are given by

$$\left(\frac{E_b}{I_o} \right)_v = \sum_k P_k \left(\frac{SG_f}{\alpha_s(k) N_{sc}^b(k) + \alpha_f i(k) + DTX [N_v^b(k) - 1] + I_{inter\_cell}} \right) \quad (6.13.a)$$

$$\left(\frac{E_b}{I_o} \right)_f = \sum_k P_k \left(\frac{\alpha_f SG_f}{\alpha_s(k) N_{sc}^b(k) + \alpha_f [i(k) - 1] + DTX N_v^b(k) + I_{inter\_cell}} \right) \quad (6.13.b)$$

$$\left(\frac{E_b}{I_o} \right)_s = \sum_k P_k \left(\frac{\alpha_s(k) SG_s(k)}{\alpha_s(k) [N_{sc}^b(k) - 1] + \alpha_f i(k) + DTX N_v^b(k) + I_{inter\_cell}} \right) \quad (6.13.c)$$

6.4 Results

A numeral example is used to explore the proposed algorithm and its performance analytically and by simulation as explained above. The numerical values of the systems parameters are chosen as follows:

$$L_v=0.14 \text{ sec}^{-1} \cdot \text{km}^{-2}, 1/\mu=220 \text{ sec}, L_d=0.02:0.04 \text{ sec}^{-1} \cdot \text{km}^{-2}, S_d=5\text{Mb}, L_{\max}=576, N_b=12, R=2 \text{ km}, \gamma_s=6.3 \text{ dB}, \gamma_f=9 \text{ dB}, \text{ and } \gamma_r=3.1 \text{ dB}, Q=100.$$

It is apparent that there is a good agreement between the results of the simulation and the analytical method particularly at low to medium values of (L_d).

As shown in Fig. 6.6, the average number of data users (N_d^b) increases linearly with L_d because more data users arrive to the system and lower transmission rate can be assigned for them. As depicted in Fig. 6.7, the transmission rate (R_b) decreases linearly with L_d since the available number of the supplemental channels and the associated transmission rates are reduced when more data calls are to be admitted as explained in section 6.3. However, the transmission rate drops from 158 to 141 kbps, so the reduction in the transmission rate is less than 10% of the maximum rate at the highest data arrival rate $L_d=0.04$.

The dependence of the queuing delay and the number of queued data users on L_d is depicted in Figs. 6.8 and 6.9. Both T_q and N_q^b have the same trend and dependence on the data arrival rate (L_d). A relatively steep increase is noticeable from $L_d=0.02$ to 0.35. Then both T_q and N_q^b grow gradually (less steep) approaching a saturation region. This

change in the trend is due to the higher priority proposed in the load control algorithm to the queued data users over the new call arrivals.

Fig. 6.10 plots (E_b/I_o) for the voice and data services (fundamental and supplemental channels) versus the data traffic arrival rate. It is evident that the QoS requirements can be met even at high loading conditions. (E_b/I_o) is higher than the threshold values of the voice and data services (fundamental and supplemental channels) for all values of L_d . The outage probability is determined by simulation and it ranges from 5-10% for both the voice and data services.

From these results, it can be concluded that integrating the voice service with data services can be realized even for vehicular users using efficient utilization of the radio resources. It is shown that using the proposed algorithm, it is possible for each cell to serve more than 360 voice users with a high voice quality along with more than 18 data users with a high rate (around 144 kbps) and with acceptable QoS measures.

The QoS measures including E_b/I_o for different channels (voice, fundamental, and supplemental) and the queuing delay are computed by simulation and using Markovian analysis. It is shown that the E_b/I_o requirement can be met even at high loading conditions for the voice and data traffic. The queuing delay does not exceed 4.5 seconds for the data service, which is acceptable for many data services.

In order to achieve less queuing delay, the condition of the higher priority for voice calls must be relaxed. Nonetheless, the negative impact on the voice service should be considered. This case is studied by simulation. It is shown that both T_q and N_q^b can be reduced by 80-95%. For instance, at $L_d=0.04$, T_q is reduced from 4.5 sec to 0.412 sec.

Fig. 6.6 Average number of data users per beam area.

Fig. 6.7 Average allocated bit rate for data users.

Fig. 6.8 Average queuing delay per data call.

Fig. 6.9 Average number of queued data users per cell.

Fig. 6.10 Average Energy per bit to Interference Ratio of Voice Users.

Similarly, at $L_d=0.04$, N_q^b is reduced from 0.142 to 0.0174. The drawbacks of this policy is that a fraction of the voice calls must be blocked in order to preserve the QoS for both voice and data services. For example, at $L_d=0.04$, the blocking probability of the voice calls is increased from 0 (no blocking) with high priority for the voice service to 2.3×10^{-3} without high priority for the voice service. However, the blocking rate can be reduced by directing the call to one of the neighbor cells to take advantage of the overlapping coverage particularly if soft handover is considered.

Chapter 7

Summary, Conclusions and Future Work

7.1 Introduction

In this chapter, the work discussed in the previous chapters is briefly presented highlighting the important derived conclusions and contributions. This chapter also includes a summary of suggested future work.

7.2 Thesis Summary and Conclusions

This thesis focused on the capacity enhancement and performance analysis of modern wireless cellular communication systems using efficient call admission and load control algorithms for single and multiple service. Capacity enhancement techniques such as smart antennas, power control and overlapping coverage are considered in this study to

explore their impact on the system performance and to estimate the capacity gain due to the utilization of such techniques.

In order to evaluate the performance of the proposed algorithms, some performance measures are computed throughout this work using computer simulation and analytical methods. These measures include the blocking and dropping probabilities for voice calls, the area coverage probability, the queuing and transmission rate for data users, the outage probability and the average transmission rate. These measures give a deep insight into the system performance and show the effect of the different algorithms and techniques on the system capacity and the provided QoS.

A set of simulation tools has been developed and employed in the performance analysis and capacity dimensioning. These simulation tools are based on realistic and commonly acceptable models for most of the system aspects. These models include the spatial user distribution, user mobility, propagation model, handover criterion, traffic pattern (for voice and data services), smart antenna implementation, power control and radio resource allocation strategies. The simulator tools are built in a modular structure so that any changes or replacement in the system model or the implemented techniques can be readily included.

The simulation software is built as dynamic simulation tools that include the system dynamics and temporal variations in the different models (for example, the channel propagation model, the user mobility, the traffic pattern model, etc...). Since most of the simulated systems are time slotted, the simulation tools is designed as time-driven simulators with a resolution time equals to the time frame.

The Area Coverage Probability (*ACP*) in urban microcellular networks with overlapping is evaluated analytically and by simulation. The *ACP* is determined with and without overlapping. The results show that the overlapping coverage improves the coverage probability. For example with non-overlapping coverage at cell side length $S = 300$ m and path loss exponent (n) = 5, The *ACP* is equal to 92% and 57% for $P_{TH} = -150$ dBW and -140 dBW respectively. With overlapping coverage for the same values of (S) and (n), *ACP* is equal to 97.5% and 64% for $P_{TH} = -150$ dBW and -140 dBW respectively.

A novel algorithm called load balancing is proposed to make use of the overlapping coverage. The performance of this algorithm is analyzed and compared with the non-overlapping coverage case and with overlapping coverage using a previous algorithm called directed retry. The performance is evaluated analytically using Markovian analysis, namely, the Birth-Death model and by simulation as well. The results show that the proposed algorithm surpasses the directed retry and achieves a considerable capacity gain by reducing the blocking and dropping probabilities. For instance, at $\lambda_n = 11$ Erlang/cell the blocking probability is 1.1×10^{-2} without overlapping. By exploiting the overlapping at overlapping arm length (Y)=0.5, the blocking probability is reduced to 1.8×10^{-3} with directed retry and to 1.3×10^{-3} with load balancing. At $Y=0.707$, the blocking probability can be further reduced to 6.7×10^{-4} using directed retry and down to 5×10^{-4} with load balancing.

In the proposed algorithm, users in areas without overlapping coverage can also get benefit from the overlapping coverage since other users located in the overlapping areas are encouraged to move to less loaded neighboring cell. The proposed algorithm

has another advantage, which is the even load distribution among the neighboring cells to avoid the case when there is an overloaded cell (with an increasing blocking and blocking probability) while its neighbor cells are lightly loaded. It can be concluded that the system capacity can be substantially enhanced by the efficient utilization of the overlapping coverage. Both techniques, directed retry and load balancing, are capable of achieving a considerable capacity enhancement. While the latter technique achieves higher capacity, it needs more information exchange than the former one.

The capacity of GSM networks (as an example of TDMA networks) with SFH is analyzed using simulation and analytical methods. The outage probability as a measure of the QoS is derived as a function of the loading factor. Then, the network capacity is determined as a function of the maximum loading factor that keeps the outage probability below a certain threshold value. Capacity enhancement techniques using interference reduction are considered to study the impact of the inclusion of the smart antennas and power control in the system capacity.

The results show that significant capacity enhancement can be achieved by employing multiple beam antennas combined with power control. It is shown that the outage probability can be reduced by 40-65% using smart antennas even without power control while the reduction is more than 80% using smart antennas and power control, particularly at low to medium values of the loading factor. It is also shown that the outage probability for the uplink is slightly less than that of the downlink particularly when PC is employed. The maximum loading factor at different maximum outage probability requirements (p_{max}) is calculated and listed for the different cases mentioned above for both the uplink and downlink. For instance, at the downlink, when $p_{max}=2\%$, the

maximum loading factor is increased from 7% to 20% by including the MB antennas without power control, and it is increased to 18% by employing power control without MB. By combining both techniques the maximum loading factor jumps to 60%. However, the capacity gain that can be achieved in practice might be less than that because of the difficulty of realizing perfect power control.

By comparing the maximum allowed loading factors of the downlink and uplink, we can conclude that the downlink loading is the limiting factor. For example, with $p_{max}=2\%$ and when MB antennas are used combined with PC, the network can tolerate loading factor values upto 69% in the uplink, while it can tolerate up to 60% only in the downlink. Hence, the admission control must consider the smaller value and limits the loading factor at 60% even though the uplink can accept more loading with acceptable QoS.

A novel call admission control algorithm is developed for GSM systems. This algorithm is aimed to enhance the network capacity without causing any significant degradation in the QoS in terms of the outage probability. The system capacity is determined analytically and by simulation. Results show that the proposed algorithm can achieve more than 20% capacity gain.

An admission and load control algorithm for multiple service in third generation wireless system is designed and tested analytically and by simulation. It is developed for a stream mode non-real-time data service such as FTP applications coexisting with a voice service.

The algorithm takes advantage of the features of third generation wireless system such as the reported pilot measurements, auxiliary pilot for smart antennas and variable

spreading gain. Voice users are given higher priority than data users. Dynamic resource allocation is used in order for the system to adapt to the network loading and propagation conditions. The algorithm allocates the required radio resources for the voice users at first. Then the remaining resources are allocated on a frame by frame basis to the data users following the first-come first-served policy. Accordingly, there is no guarantee for the waiting delay or the transmission rate for the data calls since the number of the admitted data calls and the data rates assigned to them are dynamically varying depending on the network loading conditions.

The performance of the proposed algorithm is evaluated analytically and by simulation. The results show that a high transmission rate (more than 144 kbps) can be achieved for vehicular data users. The signal quality is measured in terms of the energy per bit-to-interference density ratio (E_b/I_o). Although the average E_b/I_o for both voice and data users is reduced by increasing the network loading, it is shown that the proposed algorithm can keep E_b/I_o higher than the threshold values. From these results, it can be concluded that the integration of voice and data services can be successfully implemented provided that an efficient utilization of the network resources is employed.

It is shown that loading-based call admission and load control algorithms can be enhanced to take advantage of the residual capacity to achieve high capacity without adding much complexity. In urban microcells, the load balancing algorithm makes use of the overlapping coverage to enhance the system capacity by more than 30%. It can also be concluded that call admission and load control in FH-TDMA can be enhanced by using average (or generally speaking) statistical measures of the loading factor. It is proved that the integration of voice and high-speed data services in 3G systems can be

accomplished using efficient and simple loading-based call admission and load control techniques.

7.3 Thesis Major Contributions

1. Building a set of modular simulation tools for analyzing the performance of the capacity enhancement techniques. The simulation tools have been used to test the proposed call admission and load control algorithms. As mentioned before, the modular structure facilitates the inclusions of the modifications and model variations.
2. Evaluating the performance of the proposed algorithms analytically for verification. The results of both the simulation and analytical methods compare well for most of the cases. It is shown that the analytical tools, which need less computational burden, can be as accurate as the simulation tools.
3. Proposing a novel admission and load control algorithm in urban microcells with overlapping coverage. This algorithm aims to enhance the system capacity by balancing the load in the contiguous cells. The load balancing is achieved by directing both the new and existing calls to less loaded cells. The performance of the proposed algorithm (load-balancing algorithm) is determined by simulation and analytically using Markovian model. The proposed algorithm has been compared with a previous algorithm (directed retry). Unlike the directed retry

algorithm, the load-balancing algorithm extends the benefit of the overlapping to the users located in non-overlapping areas. It is shown that the load-balancing algorithm can achieve a capacity gain (at 2% call blocking rate) of 30-60% depending on the size of the overlapping area. This gain is achieved without causing any significant degradation to the *CIR*.

4. The Area Coverage Probability (*ACP*) is evaluated in urban microcells with and without overlapping coverage analytically and by simulation. The results show that a 5-13% improvement in the *ACP* can be achieved with overlapping coverage.

5. The system capacity of SFH-TDMA (GSM-like) networks is determined analytically and by simulation. The effect of switched-beam antennas, power control and discontinuous transmission on the network capacity has been investigated. It is shown that the capacity gain of the switched-beam antennas ranges from 200% to 300% depending on the maximum acceptable outage probability.

6. A novel call admission control algorithm is developed for SFH-TDMA (GSM-like) systems. The performance of this algorithm is determined by simulation and analytically using Markovian model. Then, the algorithm is compared with the conventional call admission control technique. It is shown that the proposed algorithm enhances the network capacity without causing any significant

degradation to the *CIR*. The capacity gain is equal to 20% while the reduction in the *CIR* is less than 0.5 dB.

7. Designing an admission and load control algorithm for multiple service in third generation wireless system. This algorithm considers the traffic load information, interference levels, channel propagation conditions and users locations. The algorithm considers both voice and stream-mode non-real-time data services. The algorithm takes advantage of the smart antennas available in 3G systems and the intermittent nature of the voice service.

8. The performance of the proposed call admission and load control algorithm for stream-mode non-real-time data service is determined by simulation and analytically using two-dimensional Markovian model. It is shown that data rate more than 144 kbps can be provided without degrading the voice service quality.

7.4 Suggestions for Future Work

Various non-voice services are to be provided by third generation wireless systems with different traffic patterns, GoS requirements and QoS constraints. Hence, admission and load control algorithms should be extended to consider the coexistence of these various services and their diverse requirements. For instance, stream-mode real-time data service is to be provided by 3G systems since it suits some applications such as video transmission. The requirements of the maximum packet (cell) delay, average

transmission rate, and E_b/I_0 must be taken into consideration in the design of the admission and load control algorithms.

Some assumptions are used in this study to simplify the analysis. For more realistic results and as an extension of this work, these assumptions or some of them can be modified. For example, the perfect power control scheme can be replaced by more efficient *CIR*-based power control techniques. Hard handover included in the system model can also be replaced by soft handover because of its role in enhancing the system performance.

In this study, a first-come first-served queuing policy is adopted. Other queuing policies can also be investigated. For instance, some policies that give higher priority to short messages can lead to better throughput and delay measures. Also, defining several service classes with different priorities based on economical considerations can provide a better performance and fair resources sharing. In order to achieve very low bit error rates required for data service, ARQ protocols are included in 3G systems. The inclusion of such protocols with multiple service is challenging since the retransmission reduces the system throughput and causes a significant delay. Thus, ARQ protocols should be carefully integrated into the admission and load control schemes to avoid any degradation to the GoS.

Appendix A

Explanation of the Performance Analysis of the Admission and Load Control with Overlapping Coverage

As mentioned in section 4.5, the performance of the admission and load control algorithms with overlapping coverage can be determined by solving the birth-death process representing the system model. While the solution methodology is given in sections 4.5.1 and 4.5.2, more explanation of the formulae used in these two sections is given in this appendix.

A.1 Performance Analysis of Overlapping Coverage using Directed Retry

The new call arrival rate in a cell is equal to the sum of the new calls arriving in this cell (λ_n), plus the new calls arriving from the neighbor cells due to the overlapping

areas. The rate of the new calls arriving from the neighboring cells (cells C, E, G, and I) to cell A in areas covered by two cells is equal to the new call arriving rate (λ_n) times the percentage of the area covered by two cells (p_2) times the probability that the neighboring cell is 100% loaded (β) . Similarly, the rate of the new calls arriving from the neighboring cells (cells C, E, G, and I) to cell A in areas covered by three cells is equal to the new call arriving rate (λ_n) times the percentage of the area covered by three cells ($2p_3$) times the probability that the call will be directed to cell A (γ_1) . Also, the rate of the new calls arriving from the eight neighboring cells (cells B-I) to cell A in areas covered by four cells is equal to the new call arriving rate (λ_n) times the percentage of the area covered by four cells ($3p_4$) times the probability that the call will be directed to cell A (γ_2).. Thus, the aggregate new call arrival rate can be expressed as

$$r_n = (1 + \beta p_2 + 2p_3\gamma_1 + 3p_4\gamma_2) \lambda_n \quad (A1)$$

The handover arrival rate is the sum of the handover rate coming from the eight neighbor cells (cells B-I). Due to the symmetry of the problem, the handover arrival rate can be expressed as four times the handover arrival rate from two cells (e.g. Cell I and B) as follows

$$r_h = 4 \sum_{s_1=0}^C \sum_{s_3=0}^C P(s_1, s_3) \lambda_h(s_1, s_3) \quad (A2)$$

$\lambda_h(s_1, s_3)$ is the sum of the handover arrival rate from both cells I and B to cell A provide that cell I and cell B are in the states s_1 and s_3 respectively. Using the fluid flow model, the handover rate from a neighboring cell to cell A is calculated as the product of the neighboring cell state and the ratio of the border length between this cell and cell A divided by the average call dwelling time ($1/\mu_d$). If in parts of the border length the handover arrival calls to cell A can access any base station in neighboring cells in addition to cell A, this portion of the cell border must be weighted by the probability of directing the call to cell A (ϵ). Accordingly, $\lambda_h(s_1, s_3)$ can be expressed as

$$\lambda_h(s_1, s_3) = \frac{\mu_d}{b} [s_3(1 - \sqrt{2}d + 2d\epsilon) + s_1(2Y + d)] \quad (\text{A3})$$

The Transition Probability Matrix (TPM) is calculated using Eq (4.17). Then, the state probabilities are determined using the global balance condition

$$P(i) \sum_{j=0}^C p_{ij} = \sum_{j=0}^C p_{ji} P(j) \quad i = 0, 1, \dots, C \quad (\text{A4})$$

Subject to the condition

$$\sum_{j=0}^C P(j) = 1 \quad (\text{A5})$$

Since we have $C+2$ equation whilst the number of unknowns is $C+1$, one of these $C+2$ equations is considered as redundant. Then, the state probabilities can be solved as explained in Appendix B.

By determining β , the blocking probability is calculated from the following equation

$$P_b = \beta p_1 + \beta^2 p_2 + \beta^3 p_3 + \beta^4 p_4 \quad (\text{A6})$$

This formula is derived as follows: the blocking rate in the area covered by one base station is the probability that base station covering this area is 100% load (β). In areas covered by two base stations, the blocking rate is the probability that two base stations covering this area are 100% load (β^2). Similarly, for areas covered with three base stations, it is β^3 and with four base stations it is β^4 . Thus, the average blocking probability is the weighted sum of the rates given above where the weights are the percentages of areas covered by one, two, three, and four base stations.

Then the dropping probability is then determined from Eq (4-21). The handover failure probability (P_h) is determined as follows: some users who move to cell A (across its borders with cells B, D, F, and H) can access only one base station (of cell A). Therefore, the handover failure rate is just β . On the other hand, other users who move to cell A (across its border with cells C, E, G, and I) can access two base stations (of cell A and one of its neighboring cells). Thus, the handover failure rate is β^2 . Accordingly, the average handover failure probability is the weighted sum of these two rates where the weights are the ratios of the cell border of cell A with the first group (cells B, D, F, and

H) and the second group (cells C, E, G, and I). Hence, the handover failure rate can be expressed as

$$P_h = \frac{(1 + (1 - \sqrt{2})d + 2Y)\beta + 2d\beta^2}{b} \quad (A7)$$

A.2 Performance Analysis of Overlapping Coverage using Load Balancing

The new call arrival rate is modified due to the new call reduction and addition in the Load Balancing algorithm. The new call addition rate M_i , is calculated as the probability of the call moving (P_m) times the unit step function (which represents the condition that the loading in the neighboring cell is higher than the loading in cell A) averaged over all the possible values of the cell state and weighted by the area covered by either two, three, or four base stations. In areas covered by three (four) base stations there is another (two) unit step function(s) representing the condition that cell A is the less loaded cell among the neighboring cells. The new call reduction rate N_i is similarly determined as the call addition rate but the loading condition represented by the unit step function is modified such that the loading in cell A is higher than the loading in the neighboring cell. Accordingly, the call addition and reduction rates are expressed as in Eqs (4.24-4.29).

The handover arrival rate is similar to that of the directed retry case. Only a minor modification is needed in Eq (A5). The probability of directing the call to cell A (when there is one or more additional base station) in the handover process (ϵ) is replaced by a

unit step function that represents the condition that cell A is less loaded than the neighboring cell. Thus, $\lambda_h(s_1, s_3)$ is given by

$$\lambda_h(s_1, s_3) = \frac{\mu_d}{b} \left[s_3 (1 - \sqrt{2}d + 2d u(s - s_1)) + s_1 (2Y + d) \right] \quad (\text{A8})$$

The rest of the formulae and solution steps are similar to the analysis of the directed retry algorithm given above.

Appendix B

Iterative Solution of Markovian Model

If the TPM is function of the state probabilities (p_{ij}), the state probabilities can be solved iteratively as follows:

- 1-Set an initial value for β or $P_b (P_{init})$.
- 2-Calculate the arrival and departure rates using the initial value (P_{init}).
- 3-Determine the transition probability from each state to the other states ($p_{ij} \ i \neq j$) using the events list.
- 4-Determine the state probabilities using the global balance condition:

$$P_i \sum_{j \neq i} p_{ij} = \sum_{j \neq i} p_{ji} P_j \quad \forall i \quad (B1)$$

where P_i is the probability of the i^{th} state, subject to the condition

$$\sum_i P_i = 1 \quad (\text{B2})$$

5-Estimate β or P_b the from the state probabilities (P_{est})

6-Calculate the relative error of the estimated blocking probability as follows.

$$\Delta P_{est} = \frac{P_{est} - P_{init}}{P_{est}} \times 100 \quad (\text{B3})$$

7-If ΔP_{est} is greater than 1% let $P_{init}=P_{est}$ and go back to step 2, otherwise stop and consider the blocking probability β or P_b is equal to P_{est} .

Appendix C

Derivations of the formulae used for Multiple Service Call Admission and Load Control Algorithm

The QoS constraints are expressed for the voice channels, fundamental data channels, and supplemental data channels in terms of (E_b/I_o) as follows

$$\left(\frac{E_b}{I_o}\right)_v = \frac{SG_v}{DTX(N_v^b - 1) + \alpha_f N_d^b + \alpha_s N_{sc}^b + I_{inter\_cell}} \geq \gamma_v \quad (C1)$$

$$\left(\frac{E_b}{I_o}\right)_f = \frac{\alpha_f SG_f}{DTX N_v^b + \alpha_f (N_d^b - 1) + \alpha_s N_{sc}^b + I_{inter\_cell}} \geq \gamma_f \quad (C2)$$

$$\left(\frac{E_b}{I_o}\right)_s = \frac{\alpha_s SG_s}{DTX N_v^b + \alpha_f N_d^b + \alpha_s (N_{sc}^b - 1) + I_{inter\_cell}} \geq \gamma_s \quad (C3)$$

Rewriting Eqs (C1)-(C3)

$$N_d^b \leq \frac{1}{\alpha_f} \left(\frac{SG_v}{\gamma_v} + DTX - I_{inter-cell} \right) - \frac{DTX N_v^b}{\alpha_f} - \frac{\alpha_s N_{sc}^b}{\alpha_f} \quad (C4)$$

$$N_d^b \leq \left(\frac{SG_f}{\gamma_f} + 1 - \frac{I_{inter-cell}}{\alpha_f} \right) - \frac{DTX N_v^b}{\alpha_f} - \frac{\alpha_s N_{sc}^b}{\alpha_f} \quad (C5)$$

$$N_d^b \leq \frac{\alpha_s}{\alpha_f} \left(\frac{SG_s}{\gamma_s} + 1 - \frac{I_{inter-cell}}{\alpha_s} \right) - \frac{DTX N_v^b}{\alpha_f} - \frac{\alpha_s N_{sc}^b}{\alpha_f} \quad (C6)$$

By plotting the admissible region for N_v and N_d^b using Eqs (C4) and (C5) as shown in Fig. C1, we can notice that the optimum value for α_f (that maximizes the admissible region) is obtained by equating the first terms in the right hand side in Eqs (C4) and (C5). Hence, α_f is expressed as

$$\alpha_f = \frac{\left(\frac{SG_v}{\gamma_v} + DTX \right)}{\left(\frac{SG_f}{\gamma_f} + 1 \right)} \quad (C7)$$

Similarly, α_s is determined using Eqs (C4) and (C6) and is given by

$$\alpha_s = \frac{\left(\frac{SG_v}{\gamma_v} + DTX \right)}{\left(\frac{SG_s}{\gamma_s} + 1 \right)} \quad (C8)$$

The number of supplemental channel is initially estimated using Eq (6.1). This value is computed by calculating the remaining resources (the difference between the maximum number of users and the actual number of active users) assuming that all the supplemental channels are allocated the minimum transmission rate (14.4 Kbps).

The spreading gain of the supplemental channels (SG_s) is determined from (C6) using (C8) as given by Eq (6.2). Since the transmission rate of the supplemental channel ranges from 14.4 to 244 Kbps (the maximum transmission rate is increased from 144 to 244 Kbps because of the error correction coding redundancy), SG_s ranges from 20.5 to 347. Hence, SG_s computed from Eq (6.2) must be adjusted to satisfy this condition. Accordingly, n_{sc}^b must be adjusted to satisfy (C8) by deriving N_{sc}^b as a function of SG_s using Eq (2) as follows

$$N_{sc}^b = \left\lceil \left(1 - \frac{B}{A} \right) \left(1 + \frac{SG_s (m+1)}{\gamma_s} \right) \right\rceil \quad (C9)$$

Fig. C.1 Admissible area at different values of α_f where
 $a=DTX$, $b=SG_v/\gamma_v+DTX-I_{inter\_cell}-\alpha_s N_{sc}$, $c=I_{inter\_cell}$, $d=SG_f/\gamma_f+I$, and $\alpha_f^*=(b+c)/d$.

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