ON THE CAPACITY MODELLING IN 3G MOBILE WIRELESS COMMUNICATIONS SYSTEMS AND BEYOND

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Certificate of Research

This is to certify that, except where specific reference is made, the work described in this thesis is the result of the candidate's research. Neither this thesis, nor any part of it, has been presented, or is currently submitted, in candidature for any degree at any other University.

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Director of Studies

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Abstract

Capacity issue was a major motivation behind the introduction of the present 3G mobile communication systems such as the wideband CDMA (WCDMA). However, the rapid increase in the number of connections and demand for high-speed multimedia communication services supported is contradicting with the limited resources allocated by these systems. WCDMA is an interference-limited system, which means that the capacity bounds of these systems as well as coverage boundaries are continuously changing according to traffic conditions. WCDMA is designed to provide variable data rates, which further complicate the capacity analysis.

Active user capacity analysis in the Universal Mobile Telecommunications System (UMTS) network of WCDMA is essential for different stages ranging from the initial network planning to the proper resource management of the operating network. The determination of upper bounds on the network's active-user capacity is needed to determine the traffic handling capability of the network and later in determining its performance.

Amongst the motivations for WCDMA is the possibility for capacity increase with the use of directional smart antennas to reduce the interference and therefore gain capacity increase. These are typically complex systems. One type that is simple enough yet beneficial in gaining capacity and coverage improvements in the WCDMA environment is called the Switched Beam Smart Antenna (SBSA).

This work is about the analysis of the capacity/ coverage problem of WCDMA in a multiservice environment with the use of omnidirectional antennas at the base stations or with SBSAs. The analysis produced a distinctive model for the capacity and coverage in both cases whereby the number of users in each of the services, their coverage radii, activities, rates and other parameters in a multi-service UMTS environment are related together at the boundaries of operation. The model provides a useful tool to analyse traffic and for radio resource management in UMTS especially that it links the problem of capacity sharing using WCDMA to the well-studied ATM statistical multiplexing theories. The model with SBSA was used as a tool to asses the improvement gains against complexity when the antenna at the base station is of the switched beam type.

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Dedication

I dedicate this work to the one person who contributed much to this work, to my beloved wife, Ola. She suffered a lot because of my absence for either work or study, took over much of my responsibilities and took on her the job of bringing up our two children, Mutasem (14) and Alaa (12). I also dedicate this to them. They are brilliant kids who were also a source of enthusiasm to me, especially at times when research difficulties made "giving up" a valid option in my thoughts but the decision was always not to waste their patience and let them down.

Contents

List of Tables

List of Figures

List of Symbols

A	Traffic in Erlang
B	Number of beams
Bk	Blocking probability
C	System capacity
C_g	Capacity gain
C_p	Propagation constant
C_g	Interference-limited capacity gain
C'_g	Approximation to C_g
c_q	Resource unit for service q
d_{class}	Class coverage
d_{intr}	Intrinsic coverage
d_{max}	Maximum coverage
d_{others}	Reduction of coverage due to other services
E_b/N_o	Energy per bit to noise density
f	Intercellular interference ratio
F	$F = 1/(1+f)$
f_{eff}	Effective interference ratio
h_b	Base station height
h_m	Mobile equipment height
I_{oc}	Other cell interference
I_{sb}	Same beam interference
I_{sc}	Same cell interference
I_t	Total interference
$\square_{gen}$	Subscript to denote using the general path loss model

K_p	Proportionality factor
$\square_{LOS}$	Subscript to denote *LOS* (Line of Sight) model
L_p	Path loss
N	Capacity of a class
N_{class}	Class capacity
N_{max}	Maximum capacity
N_{others}	Reduction of coverage due to other classes
N_{pole}	Pole capacity
N_{power}	Reduction in capacity due to power limit
N_q'	The new number of connections of service q
N_t	Thermal noise
N_{upper}	Upper interference limit on capacity
O	Orthogonality factor
P_{out}	Outage probability
P_r	Received power
P_s	Transmitted power
P_{Smax}	Maximum output power of the UE
R	Data rate
S_q	A state of the number of connection $(n_1, n_2, ..., n_Q)$
T_c	Chip period
T_{upper}	Upper throughput
$\square_{q,\hat{q}}$	$q, \hat{q}$ are indexes /subscripts to denote classes
Q	Number of classes
W	Chip rate
α_q	Self factor for capacity of classes q
$\alpha_{q\hat{q}}$	Mutual factor for capacity between classes q and $\hat{q}$
β_q	Self Factor for coverage of classes q

$\beta_{q\hat{q}}$	Mutual factor for coverage between classes q and $\hat{q}$
γ	Corrected E_b/N_o
Γ	Power control correction factor (Outage factor)
φ	Reliability ($\varphi = 1-P_{\mathrm{out}}$)
ζ	Shadowing random variable
η_{UL}	Uplink cell loading factor
λ	Poisson processes mean rate of arrival
μ	Poisson process service rate
ξ	Up-rating increase ratio
σ	Standard deviation
υ	Activity factor
ψ	MUD factor

List of Abbreviations

1G/2G/3G	First/ Second/ Third Generation
3GPP	Third Generation Partnership Project
ACL	Auto Correlation
AMC	Adaptive Modulation and Coding
AMPS	Advanced Mobile Phone System
AMR	Adaptive Multi-Rate
ARQ	Automatic Repeat Request
ATM	Asynchronous Transfer Mode
AUC	Authentication Centre
BER	Bit Error Rate
BLER	Block Error Rate
BW	Band Width
CAC	Call Admission Control
CCL	Cross Correlation
CDMA	Code Division Multiple Access
cdmaOne	Narrow Band CDMA (IS-95)
CPCH	Common Packet Channel
CQI	Channel Quality Indicator
DCH	Dedicated Channel
DL	Down Link
DPCCH	Dedicated Physical Control Channel
DPDCH	Dedicated Physical Data Channel
DSCH	Downlink Shared Channel
DSSS	Direct Sequence Spread Spectrum

DTX	Discontinuous Transmission
E-DCH	Enhanced DCH
EDGE	Enhanced Data Rates for Global Evolution
E-DPCCH	E-DCH Dedicated Physical Control Channel
E-DPDCH	E-DCH Dedicated Physical Data Channel
EGC	Equal Gain Combining
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
GCD	Greatest Common Divisor
GGSN	Gateway GPRS Support Node
GMSC	Gateway Mobile Switching Centre
GPRS	Generalized Packet Radio Services
GOB	Grid of Beams
GSM	Global System for Mobile
HAPS	High Altitude Platforms
HARQ	Hybrid Automatic Repeat Request
HLR	Home Location Register
HSCSD	High Speed Circuit Switched Data
HSDPA	High Speed Downlink Packet Access
HS-DSCH	High Speed - Downlink Shared Channel
HSUPA	High-Speed Uplink Packet Access
IMT-2000	International Mobile Telecommunications-2000
IS	Interim Standard
ITU	International Telecommunications Union
LAN	Local Area Network
LOS	Line of sight
NLOS	Non-LOS

MAI	Multiple Access Interference
Mcps	Mega Chip per Second
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
MRC	Maximal Ratio Combining
MS	Mobile Station
MSC	Mobile Service Switching Centre
MUD	Multi-User Detection
Node B	(Base Station in UMTS)
PCPCH	Physical Common Packet Channel
PCS	Personal Communications Systems
PN	Pseudo Noise
PSTN	Public Service Telephone Network
PRACH	Physical Random Access Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RACH	Random Access Channel
RF	Radio Frequency
RNC	Radio Network Controller
RNS	Radio Network Subsystem
ROT	Raise over Thermal
RRM	Radio Recourse Management
SBSA.	Switched Beam Smart Antenna
SDMA	Space Division Multiple Access
SF	Spreading Factor
SHO	Soft Handover

SfHO	Softer Handover
SFIR	Spatial Filtering for Interference Rejection
SGSN	Serving GPRS Support Node
SIMO	Single Input Multiple Output
SIR	Signal to Interference Ratio
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TFCI	Transport-Format Combination Indicator
TFCS	Transport Format Combination Set
TPC	Transmission Power Control
TTI	Transmission Time Interval
UCA	Uniform Circular Array
UE	User Equipment
UL	Uplink
ULA	Uniform Linear Array
UMTS	Universal Mobile Telecommunications System
UTRA	UMTS (Universal) Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
WCDMA	Wide Band CDMA

Chapter 1 Introduction

In this chapter an introductory analysis of the issue of capacity in WCDMA will be given at first as background information followed by motives, objectives and methodology, scope of research and main contributions.

A list of symbols used in this chapter and in the rest of the thesis is on page xii above, also a list of abbreviations is on page xv.

1.1 Technological Background

1.1.1 The cellular Concept and Bandwidth Multiplication

Before 1979, the date when first generation (1G) analogue mobile wireless communication systems were first launched the number of trials to provide some form or another of public mobile wireless communication systems was limited [1] due to the limited bandwidth available to these systems*. However, first generation mobile wireless communication systems allowed for *bandwidth multiplication*. Therefore, this date is marked as the beginning of the era of mass-mobile communications. That said though 1G systems soon failed to face the quick growing demand for its services [2].

Bandwidth multiplication in first generation systems, as well as in present technologies, is the result of the cellular concept, applied within their scope and continued to thrive afterwards. This, in fact, is the first big success towards capacity providing in mobile wireless communications [3]. In the cellular concept the communication network is made up of a number of geographical units called "cells" whereby each cell is served by a fixed transmitter/ receiver (transceiver) serving a number of users within its coverage. The cell structure allows for reliable communication using low power transmissions thereby reducing interference to others. This in turn allowed for a frequency re-use concept, whereby frequencies used in one cell can be reused at some other cells located at a re-use distance far enough for the interference to be low enough to allow reliable

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* Half duplex systems of late 1940's used a large 120KHz bandwidth for 3KHz speech reduced later in 1950's to 60KHz [1].

communication in the faraway cell. Therefore, cells in cellular systems can be grouped in clusters with a *re-use factor* (the number of cells, or *cluster size*, before the same frequencies can be safely re-used) of 3, 4, 7, 9, 12, etc[*], cells [4]. Hence, the limited bandwidth is multiplied using the re-use concept in cellular systems. The re-use distance will depend on co-channel interference limits [1]. Therefore, in effect, the interference (plus thermal noise) actually limits capacity (or capacity multiplication) in mobile wireless communications systems.

1.1.2 Capacity in First and Second Generation Systems

First generation systems used Frequency Division Multiple Access (FDMA) in which different users are granted different channels (signals are orthogonal in frequency domain and do not interfere with each other) thereby separating users in the same cell. Second-Generation (2G) mobile systems, like the Global System for Mobile (GSM), came into existence about a decade later (1990). They made use of the advances in digital technology, provided for mobility, and aimed at enhancing capacity as well. The approach to enhance capacity in such systems, like the GSM, is based on conquering another dimension of the signal in order to achieve more bandwidth multiplication [5]. This is the time domain. The channel in these systems is not only the traditional frequency band but also is defined in terms of time slots. Hence, two users can now transmit using the same frequency band but at different times. The multiple access technique is therefore called TDMA/FDMA, where TDMA stands for Time Division Multiple Access. Another 2G technique, *cdmaOne* (also called IS-95), is based on Code Division Multiple Access (CDMA) in addition to FDMA, which is the technology of present third generation systems. However, both systems were based on narrow band techniques[†] where guard bands are needed to separate channels, and time slots cannot be made smaller or otherwise signals that are separated clearly at the transmitter will not remain like this at the receiver due to the harshness of the wireless channel.

Both first and second-generation systems are aimed at voice users. It soon became apparent that a need exists to serve multimedia and data users. Second generation

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[*] These numbers can be generated using i^2+j^2+ij where i and j are positive integers.

[†] *Cdma one* relies on a wide bandwidth of 1.25MHz compared to 200KHz of GSM, but both need more than one carrier in aany case.

systems were limited on rates and data services. Hence, quick remedies were procured in the form of enhancements to these systems in order to serve these needs. GSM, for example, received a number of enhancements like the High Speed Circuit Switched Data (HSCSD), the General Packet Radio Services (GPRS), and the Enhanced Data for Global Evolution (EDGE). These enhancements act mainly on improving the link, which led to higher data rates for GSM (GSM basic rate is 9.6Kbps and reaches 130Kbps with EDGE). Description of the different 1G and 2G techniques, their enhancements, and issues of their capacities can be found in many books, e.g. [3][4] [2] [1] [6].

However, the rapid increase in the number of connections and demand for high-speed multimedia and data communication services cannot be met with these systems, even with such enhancements. This is because of the time and frequency limitations as explained. This requested that a major change be done to the multiple access system and the air interface which calls for a third generation of systems. Hence, capacity issue was a major motivation behind the introduction of the present 3G mobile communication systems such as the Wideband Code Division Multiple Access (WCDMA) [1] [5].

1.1.3 Capacity in Third Generation Systems

The requirements for 3G, which were formulated by the International Telecommunications Union (ITU) in its International Mobile Telecommunications-2000 (IMT-2000) initiative, included the capabilities to provide for high data rates and a multitude of multimedia and data services. It has been realized that a major obstacle to capacity providing using 2G systems, like GSM, is that signals are given exclusive use of narrow badwidths with much bandwidth wastes due to the need for provideng guard bands in these techniques [5]. Systems that are based on wider bands with provisioning for a flexible sharing of the bandwidth will allow for the integration of different services and provision for higher rates at the same time. In other words, removing the orthogonality (in time and frequency) barriers will result in capacity gains [5]. Therefore, most of the suggested techniques for the IMT-2000 [8] [9] [10]were based on some form of signal spreading in a wider bandwidth to allow for the common resource sharing.

1.1.3.1 The Universal Mobile Telecommunication System (UMTS)

The European choice of the Universal Mobile Telecommunication System (UMTS) was amongst the major candidates for third generation mobile technologies identified by the ITU (a background to the UMTS standard is given in [9]). WCDMA was chosen as the multiple radio access technology (air interface) for UMTS, it uses CDMA for its air interface with all the advantages of CDMA such as multiple access capability, protection against multipath interference, provision for privacy, narrow band interference rejection capability, anti-jamming capability and low probability of interception [10].

While the UMTS is more general, WCDMA and UMTS terms are used interchangeably to mean the same thing. WCDMA frequencies are in the 2000 MHz range and characterized by a wide bandwidth of 5MHz per carrier that is shared amongst all the users; i.e. all users can transmit at the same time and frequency.

In WCDMA, every signal is spread over the whole bandwidth using frequency-spreading techniques and users are separated using spreading codes. Spreading codes are invented resource and consuming them does not affect the original limited resource (the bandwidth frequencies or time slots). The bandwidth is reused by every signal in the cell and even in every other cell, as the reuse factor is now 1. This means that the bandwidth usage is multiplied manifold using these techniques. This, in addition to the statistical multiplexing and the removal of the orthogonality guard bands, forms the basis for the high capacity gains by WCDMA and other 3G systems. However, this cannot go forever, because an old new limit starts to pop up. Spreading results in power reduction that allows the coexistence of users because each user is contributing a little to the interference seen by any one of them. Hence, the quality of the links (or possibly its coverage) will deteriorate as more and more users are actually sharing the common bandwidth; or in other words, contributing to the common pollution of accumulated interference. As a result, the old link limit of interference is now literally a direct limit*. It has become also a traffic dependent limit therefore limiting the network capacity as well as the link performance. The interference, in this sense, has become the main resource to account

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* At the start, the interference is accused of being the limit in any case.

for, or in other words, the bandwidth has been encapsulated in the form of interference units.

Nevertheless, the capacity gain in WCDMA compared to 2G systems[*] is the result of the sharing of this common resource[†] between the different cells and different services and users. At the same time, all the factors that can reduce this interference will result in a capacity gain [10]. In fact, WCDMA was motivated by some of these factors like voice activity and the use of sectored antenna [12].

As a result, planning in third generation mobile communications systems like the WCDMA is about three interrelated variables; namely, capacity, coverage and QoS (Quality of Service). This is unlike heritage first and second-generation mobile communications systems in which planning is about coverage planning only. Active user capacity analysis of WCDMA is essential for different stages ranging from the initial network planning to the proper resource management of the operating network. The determination of upper bounds on the network's active-user capacity is needed to determine the traffic handling capability of the network and later in determining its performance.

In this thesis, interference analysis in WCDMA is used as the basis to arrive at a model that directly interrelates capacities for the different service classes in the cell and their coverage radii to the given QoS requirements. This provides a basis for efficient capacity sharing problem in WCDMA.

1.1.4 Capacity Enhancement in UMTS using Smart Antenna

WCDMA received recently two enhancements to its air interface; a downlink enhancement called the High Speed Downlink Packet Access (HSDPA) and an uplink enhancement called the High Speed Uplink Packet Access (HSUPA). These two enhancements aim at increasing the link rates through improved mechanisms for link control (both enhancements are described in Section 3.7.2).

However, amongst the greatest enhancements to the provisioning of capacity in WCDMA is the adoption of beamforming and smart antennas techniques. They act in

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[*] WCDMA provides six times increase in spectral efficiency over GSM generally [13]

[†] Although, the power is considered as the common resource in downlink while the interference in the uplink, the interference can be considered ultimately the limiting resource in WCDMA (Section 3.3)

the space domain* to reduce the interference and therefore boost the capacity. Smart antennas cover a wide spectrum of complex antenna-system types ([14] and Chapter 5) which is one of the obstacles for their use in mobile communications systems. However, one type of them that is simple yet beneficial enough in gaining capacity (and coverage) improvements is the *Switched Beam Smart Antenna* (SBSA), which acts directly on reducing the interference and provides for more bandwidth multiplication. An analysis to the capacity provisioning of this antenna type is also provided in this thesis.

1.1.5 Beyond 3G

CDMA is a technology that is widely open for enhancements and evolutions, which will keep itself amongst the continuous candidates for next generation mobile wireless communications systems [15]. Many incentives keep the research in CDMA/WCDMA in general and resource management a hot topic. Hence, in addition to the previously mentioned smart antennas and HSUPA/HSDPA, some of these incentives are:

i. CDMA is a candidate to other applications: adhoc networks, dense wireless LANs and power line communications [16].
ii. The "Multi-CDMA": multicarrier CDMA and multi-code CDMA in addition to multiple antenna CDMA.
iii. Possibility to increase capacity by joint decoding (multiuser detection an interference cancellation). This is described in Section 3.7.1.
iv. Possibility to increase capacity by joint assignment of powers transmitted to users in more than one cell through base stations' cooperation [17].
v. The possibility to enhance the capacity by jointly combining WCDMA with other multiple access techniques [18], e.g. joining WCDMA and TDMA results in the already standardized mode of WCDMA that is called Time Division Duplex (TDD) mode, a mode that is ideally suited for supporting asymmetric data traffic, such as web browsing [19].
vi. WCDMA proved that it would prevail as a mobile technology over other wireless technologies mainly because of its wide coverage. The new sugges-

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* Smart antennas' processing is a time-space domain processing, however, what matters is their effect in space.

tions for integration of a High Altitude Platform Station (HAPS) in WCDMA with existing terrestrial communication systems would be beneficial as several kinds of wireless services can be easily extended into remote areas [20] [21].

1.2 The Research Work

1.2.1 The Problem and Motivations

Understanding and modelling the active-user capacity and the capacity bounding in communication systems in general and in WCDMA in particular is important for use in:

1. Planning and dimensioning of mobile communications networks.
2. Resource management and capacity sharing and network optimization.
3. The integration of WCDMA in different technologies, e.g. smart antennas.

However, in WCDMA, as can be concluded from the background discussion in the previous section, capacity and capacity sharing problems are generally more complex to comprehend than in any other system, this is true for basic WCDMA or in WCDMA with any of the capacity enhancement methods, like HSDPA/HSUPA or the use of beamforming antennas. This is attributed to factors (which have been briefly discussed earlier in this chapter):

1. Capacity is interference limited (a soft limit) and not hard limited[*], with no single value for the capacity can be claimed.
2. Capacity and coverage interact with each other and with the quality requirements in the cell, which means that capacity cannot be treated in isolation from coverage. The capacity increase is accompanied by coverage shrinkage. The actual point of operation is the point of balance between capacity and coverage. This makes capacity behaviour a more complicated one. This is further complicated by the use of beamforming antennas, which tend to increase the capacity and coverage, however, their interaction is expected to be more prominent.

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[*] Coding shortage in WCDMA forms a kind of a hard limit but generally it is assumed that interference limits the capacity ahead of the coding limit (Section 3.3 discussses these limits).

iii. The integration of different services with different data rates in WCDMA further complicates the capacity sharing analysis, especially with the new links' enhancements that attempt to raise quite significantly the rates for some of the links compared to others.

Soft capacity, the limits on capacity and the capacity coverage interaction will be described in detail in the Chapter 3.

The handling of active-user capacity in WCDMA in practice and in research is situation dependent. It is different when planning for capacity and coverage than when designing techniques for the radio resource management, and can be different from one researcher to another in many cases. Generally, the following approaches exist:

a. In network dimensioning and planning,
   i. The process of (initial) dimensioning is usually based on calculating what is called the pole capacity [22] for each service separately. The pole capacity concept is based on the assumption that no power limit on the user equipment (UE) exist [23]. Therefore, link budget analysis follows to arrive at the proper coverage distance. Link budget takes into consideration the power limits on the UE, the path losses and other losses and the acceptable increase in interference (a design value based on a certain loading percentage) over the background (inevitable) thermal noise. This is repeated over all services and over the same service a number of times until arriving at a balanced operating point between the capacity of the different services, the coverage required, and the quality of service. This process is described in Section 3.6.
   ii. Active user capacity is important in evaluating the traffic handling capacity of the cell. The soft capacity limits of the WCDMA preclude the direct use of Erlang blocking formulae. Different approaches have been followed. Examples of these approaches are: in [24] simply the Erlang formula is used directly for traffic capacity estimation which tends to give a pessimistic result, in [25] the capacity was visualized in terms of basic interference units and the blocking was computed based on a modified Erlang blocking called the Knapsack model to account for the multi-service case and finally in [26] the basic capacity units were given in terms of loading percentages of each and every connection.

b. In radio resource management algorithms (RRM), mainly call admission and packet scheduling, a number of approaches is followed. Some are very basic, e.g. to assume a fixed capacity for UMTS based on, for example, the bandwidth, the pole capacity or the loading analysis, e.g. [27]. Though, in some cases, [28] [29], treatment of the multiservice case is based on certain service class capacity definition. The purpose of these cases was to demonstrate a certain parameter of the admission process (or any other RRM process) but the power limit of the UE was neglected. Hence, the coverage capacity interaction is overlooked, which may have adverse effects on some of the results obtained. The cases whereby the power limit was taken into consideration are cases in which capacity/coverage interaction can be put into direct formulae (single service case), e.g. [30], or when a multiservice case is considered, the rise over thermal and the loading analysis [31] [32] are used. In the number of cases [33] [34] where power constraints were considered, the actual interrelationship between the number of users in the different classes, coverage radii, their rates and activities, and other parameters are kept hidden. Additionally, active-user boundaries will be of a value for special conditions; for example, the case of sharing the capacity between interfering cells in the network belonging to different layers or different providers [35].

c. In systems with special enhancements, e.g. an HSDPA/HSUPA or smart antennas, the problem becomes more pressing. These enhancements will generally allow for more capacity, and capacity bounds will be more intricate in these systems. Nevertheless, understanding these bounds is necessary in cases like: the evaluation of the capacity gains attained from the use of such enhancements in certain environment with a certain degree of urbanization, the evaluation of the capacity sharing between normal users of the WCDMA and those users of the enhanced channels of HSDPA/HSUPA [36] [37], the evaluation of the option of adding extra enhanced channel to existing carrier or the addition of a new carrier to carry the extra load generated by HSPA users, etc.

From above, generally the motives for this research are:

a. In any of the cases in this subsection (i.e.[22]-[37]), the actual interaction between the different connections, the coverage radii, rates and other parameters are kept hidden which is believed to reflect negatively on the problem of resource management and capacity dimensioning in WCDMA.

b. Irrespective of the vast research on WCDMA, no single analytical model* is found that relates the capacity, coverage and QoS altogether within it whether for normal WCDMA or for WCDMA with the use of specialized antenna like the Switched Beam Smart Antenna.

1.2.2 The Objectives

The project aims to provide a solid analytical backbone to the capacity bounding limits in WCDMA networks and extend the results to certain types of smart antennas that are candidates for WCDMA. In specific, the uplink of WCDMA shall be considered, and analytic formulae for capacity and coverage bounds model shall be obtained

a. The model shall be service based and the formulae shall clearly give bounds using the number of users in the different services that can be tolerated without jeopardizing the quality of service or the coverage requirements. These bounds, which should be flexible bounds reflecting the soft capacity nature of WCDMA should take into consideration both the interference limitation and the power limitations.

b. The interference limitations should take into consideration both the interference generated from users in the same cell as well as the interferences coming from neighbouring cells, i.e. on a network level.

c. The power limitation should take into consideration the limitations imposed by the maximum transmitted power of the mobile station and the propagation environment.

d. Formulae shall be obtained taking into consideration both the basic parameters of WCDMA the environment and of the services like activity, spreading, orthogonality, path loss and quality of service requirements.

e. To show that the model is also applicable when considering some of the (non-basic) practical parameters and issues of the system and the environment such as mobility,

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* This is up to the knowledge of the researcher.

handover, the use of multi-user detection receiver, and the effect of signalling and control channels.

f. To demonstrate the usefulness of the capacity formulae and model obtained in the dimensioning and traffic planning process of UMTS networks.

The objectives for basic capacity and coverage interaction model stated above shall be re-attempted for WCDMA with the use of directional antennas of the switched beam smart antenna type. In particular to this

a. The interference limitations should take into consideration both the interference generated from users covered by the same beam, the same cell as well as the interferences coming from neighbouring cells, i.e. on a network level. Hence, a relationship must be developed that relates the interference in the sector to the interference level in the network. The effect of basic antenna parameters of gain, beamwidth and sidelobe level shall be taken into consideration.
b. Analysis shall be done for a single service at first to enable comparing the effect of varying the different antenna parameters on the active-user capacity. Comparing with the case of WCDMA with omnidirectional antennas shall be attempted. Extension to the multiservice shall be attempted also.
c. An assessment of the effect of the increased antenna system complexity; i.e. increased beams and/or reduced side lobe levels, versus capacity and coverage improvements shall be obtained using the model formulae.

1.2.3 The Approach

a. For the case of general WCDMA (with the use of conventional antennas*):
    i. A thorough investigation of the (basic) factors influencing capacity provisioning on a network level in WCDMA shall be done at first. The investigation aims to isolate the effects of each and every factor (on a service class basis) on either the power received level, the interference level or the QoS requirement of any given service class existing in the cell. A service class shall be those users with same rate requirements, same activities and QoS requirements. These investigations

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* Sometimes the term "*conventional antenna*" will be used instead of omnidirectional antenna. However, when sectored antennae are meant they will be written as is.

are given in Section 3.4 in the form of influencing factors like the services activities, rates, spreading, orthogonality of signals, thermal noise, path loss, fading, interference, codecs, antennas and many other factors.

ii. Based on the understanding of these factors, the basic equation for QoS provisioning in CDMA based systems shall be expanded to include some of these factors; the basic ones (to keep things tidier) that influence the capacity at a system level*. As some of these factors include the coverage radii and the number of users of the different service classes, a set of system equations can be found for the capacities of each service in terms of the capacities of other services and the coverage radius required for the service. Same thing can be done to coverage radii of the different services. These derivations are presented in Section 4.3 for the capacity and in Section 4.4 for the coverage.

iii. Using the same methodology above, other factors that are excluded in the basic analysis are treated later individually in order to outline their effect on the model obtained for capacity and coverage.

b. For the case of WCDMA with the use of switched beam smart antenna at the base station:

i. Generally, the same methodology for the case of conventional WCDMA applies. However, a consideration of the main factors related to the antenna system must be at first given. For this purpose, a simplified model of the antenna that considers these parameters shall be assumed. This enables quantifying their interaction with either of the received power level and interference level seen by any user in a given class. Hence, a revisit to the equation for QoS with these effects known will produce the modified model's formulae for capacity coverage interaction. This analysis is given Section 6.3.

ii. However, to gain more knowledge about the effect of such antenna systems, the analysis is given in three steps: step 1 is the analysis of the interference limit, step 2 is the inclusion of the power limit with a single service assumed, and step 3 is the inclusion of other services. Comparing the effect of the degree of com-

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* The study here is system level analysis where some factors will be hidden behind others, e.g. multipath fading can be assumed in most cases to be included in the QoS requirement. This is further pointed out in the context of the analysis.

plexity of the antenna system (starting with the conventional antenna) shall be attempted in each step.

1.3 Summary of the Main Contributions of the Thesis

A list of thesis related publications by the author is given in a subsection of this section (1.3.1 page 14). Hence, all the references in this section refer to this list using the large Latin numbers I, II, III to differentiate them from the general thesis references.

In this section, a summary of the main contributions of this research work is given. The last chapter reiterates on these contributions in more detail. The contributions in summary are:

a. For the case of general WCDMA (with the use of conventional antennas):
   i. Capacity and coverage bounding formulae were derived for WCDMA with multiservice case. The resulting formulae are class based. They take into consideration the interference on a network basis and most of the basic services, network and environment parameters. The results are in Section 4.3 for the capacity and in Section 4.4 for the coverage (Also in [VII]).
   ii. Guidelines on how these formulae (the model) can be modified to take into account some issues related to practical systems are given in Section 4.7. These issues include non-ideal power control, mobility, other link gains and losses, the use of multi-user detection receiver, and the effect of signalling and control channels.
   iii. The model is linked to ATM statistical modelling for the multiservice capacity sharing. This enabled the use of ATM results for the dimensioning of traffic (Erlang) capacity in UMTS. This is described and demonstrated in Section 4.8.3,

b. For the case of WCDMA with the use of SBSA at the base station:
   i. Results for interference analysis at the beam level were obtained (Section 6.3). Hence, the pole capacity (interference-limited capacity) of WCDMA with the use of SBSA is obtained and compared to the case of the omnidirectional antenna in Section 6.5 (Also in [I]).
   ii. Considering the limits on the UE power, capacity/ coverage formulae are obtained for the single service and multi-service cases. Using these formulae, the

improvements with SBSA, if any, of either capacity or coverage upon antenna upgrading/downgrading are studied and the conditions for attaining such improvements in the WCDMA environments are deduced. Results are in Section 6.6 and Section 6.7 (Also in [III] and [IV]).

1.3.1 Thesis Related Publications

[I] I. Aldmour, K. Al-Begain, A. Zreikat and K. Alameh, "Capacity Bounds Analysis of Switched Beam Smart Antennas in CDMA Systems," in Proceedings of the *9th International Conference on Computer Modelling and Simulation UKSIM 2006*, pp. 91-96, Oxford, UK, April, 2006.

[II] I. Aldmour and K. Al-Begain, "Adaptive Resource Allocation for Quality of Service Provisioning in 3G+ Mobile Networks in Realistic Propagation Environments," in Proceedings of the *1st Research Student Workshop*, pp 111-112, University of Glamorgan, UK, Feb. 2007.

[III] I. Aldmour and K. Al-Begain, "Uplink Capacity/Coverage Analysis of WCDMA with Switched Beam Smart Antennas," *Personal Wireless Communications*, vol. 43, no. 4, pp. 1705-1715, 2007.

[IV] I. Aldmour and K. Al-Begain, "Generalized Multi-Service Capacity/ Coverage Analysis in WCDMA with the use of Switched Beam Smart Antennas," in Proceedings of the *2nd Research Student Workshop*, pp. 26-30, University of Glamorgan, Oct., 2007.

[V] I. Aldmour and K. Al-Begain, "A New Approach for Teletraffic Capacity Sharing in WCDMA," in Proceedings of the *3rd Research Student Workshop*, pp. 2-3, University of Glamorgan, UK, Mar., 2008.

[VI] I. Aldmour and K. Al-Begain, "Degradation of Service Modelling and Investigation in WCDMA Mobile Communications," in Proceedings of the *10th*

International Conference on Computer Modelling & Simulation, UKSIM 2008, pp. 28-33, Cambridge, UK, Apr., 1-3, 2008.

[VII] I. Aldmour and K. Al-Begain, "A Simple Model for Uplink capacity in WCDMA," Submitted for publication in *IEEE Communications Letters, May, 2008.*

1.4 The Organization of the Thesis

The rest of the thesis is organized as follows:

- Chapter 2 titled "UMTS Overview" the spreading spectrum technique is described, description of the construction of UMTS networks and its channel structure. Basic concepts of UMTS like power control, soft handover, RAKE receiver and QoS classes are also presented.
- Chapter 3 titled "Capacity Provisioning in WCDMA" starts by describing the soft capacity in WCDMA followed by analyzing the limits on the uplink/downlink in WCDMA, whether being soft or hard. A detailed review is given of the factors influencing capacity provisioning in WCDMA subdivided as: signal and its processing related factors, link conditions related factors and system components related factors. The chapter concludes by discussing some of the non-traditional techniques to enhance capacity; namely, the multi-user detection and the new standardized link enhancements (High Speed Downlink/Uplink Packet Access) of the new 3GPP releases.
- Chapter 4 titled "User Capacity Analysis and Modelling in WCDMA" analyzes the active-user capacity and services' radii of coverage in a multiservice WCDMA environment and their interaction. The analysis considers the interference in the network, thermal noise, characteristics of the services, QoS requirements, and other parameters. Capacity with flexible data rates is also exploited in light of the model given. The model is later related to ATM models of statistical multiplexing, thus an approach for traffic capacity dimensioning using the model is introduced. A number of practical issues related to the model and how it can be modified to include other

parameters is included. Comparing the model and its use in dimensioning with others in research is also given.

- Chapter 5 titled "Beamforming Antennas" discusses the revolutionary methods for enhancing capacity using beamforming antennas and smart antennas in general. Both analogue and digital techniques for beamforming are discussed. The rest of the chapter is dedicated to multiple fixed beams smart antenna system (the *switched beam smart antenna or SBSA),* which is the subject of the capacity/ coverage analysis in the following chapter.
- Chapter 6 titled "User Capacity Modelling with SBSA" is devoted to the capacity/ coverage analysis of WCDMA with the use of this antenna (the SBSA) at the base station to arrive at the appropriate conditions for attaining its benefits . The analysis in this chapter is chained as follows: simplified model for the antenna, interference analysis, interference limited capacity analysis, capacity coverage of a single service and of a multiservice at the end. Results plotted and compared to WCDMA with conventional antennas and for various complexity degrees of the antenna.
- Chapter 7 titled "Conclusions and Future Work" summarizes and recapitulate the analysis and the results given in the thesis.
- Two appendices are given at the end for reference: Appendix I: OVSF and Scrambling Codes and Appendix II: Path Loss models".

Chapter 2 UMTS Overview

2.1 Background

First generation mobile wireless communication systems were first introduced in Japan in 1979 by the NTT and in Europe in 1981 by the Nordic Telecommunications company in the Scandinavian countries*. It was followed in the USA by Advanced Mobile Phone Systems (AMPS) in 1983. These systems are based on analogue techniques in the 450 or 800MHz with channels separation by 25 or 30 KHz (in AMPS).

It was soon realized that roaming could be a motive for technology growth. This, in addition to the low cost of digital integrated electronics compared to the analogue ones, has soon incited the work to arrive at a new generation of digital mobile wireless communications systems. GSM mobile communication system was meant to be the digital system for Europe. It was deployed first in 1990, and soon found a wide world adoption. GSM operates in the 900 MHz band. In addition to roaming, GSM provided more capacity for voice users. It received a number of enhancements afterwards: HSCSD, GPRS, and EDGE. The GSM suit of technologies enabled texting and data services for practical rates up to 130Kbps† [36]. In the USA, there was the IS-54 (North American TDMA Digital Cellular), introduced in 1991, with its enhancement IS136 in 1996. Also, IS-95, or what is known as *cdmaOne*, appeared in 1993. The growth of demand for data services motivated the work to arrive at systems allowing for multi-service mobile networks using fixed and variable bit rates and capable of supplying this demand [5]. The European choice of the Universal Mobile Telecommunication System (UMTS) was amongst the major candidates for third generation mobile technologies identified by the ITU. The Wideband Code Division Multiple Access, WCDMA, was chosen for the radio access technology of the UMTS [9]. The specification for UMTS is created by the Third Generation Partnership Project (3GPP) which is a joint standardization project of Europe, Japan, Korea and China. A similar evolution from *cdmaOne* was the *cdma2000*.

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* Followed by Total Access Communication Systems (TACS) in the United Kingdom in 1982.

† Theoretical rate is 384 Kbps.

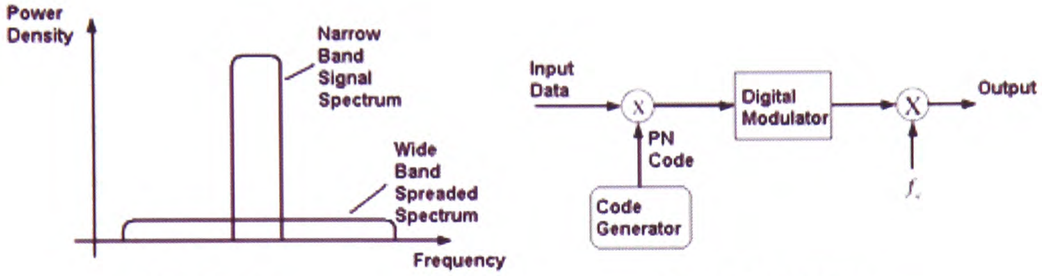
The network architecture and protocols for UMTS was based on that of second generation GSM (similarly, *cdma2000* was based on IS-95) and provided an easy path for migration [8]. Within 3GPP, the term WCDMA, refers to both UTRA-FDD (Universal Terrestrial Radio Access Frequency Division Duplex) and UTRA-TDD (Universal Terrestrial Radio Access Time Division Duplex). The first release of UMTS, Release 99, was put into implementation soon after that. A number of modifications were given by 3GPP Release 4 of 2001.

The construction of UMTS networks allows users to access both circuit-switched services and packet switched data services [10]. In UMTS, rates up to 2 Mbps can be attained in theory. Practical implementation proved that this is not feasible [36]. A maximum of 348 Kbps rates may be attained in practice. Work soon began on enhancing UMTS to allow for increased transmission rates. The first enhancement was given to the downlink direction from the base station towards the user. This is the High Speed Downlink Packet Access (HSDPA). This is Release 5 within the 3GPP standards. It was standardized in 2005. HSDPA can boost transmission rates up to 5.7 Mbps. Similarly, the uplink direction from the user toward the base station received a similar enhancement under the name High Speed Uplink Packet Access (HSUPA). This is Release 6 and it was introduced in 2006. HSUPA can boost transmission rates on the uplink up to 1.3 Mbps. Both HSUPA and HSDPA will be presented in Section 3.7.2 of the next chapter.

2.2 Spread Spectrum Systems

The narrow band techniques of the first and second generation communication systems use multiple access techniques like FDMA, and TDMA, in which each user is allocated a narrow band (and/or time slot) of the available bandwidth to the network. These techniques are based on providing orthogonality in either time, frequency or both. It has been realized, that capacity gains on the spectrum can be attained if technology migrates toward some non-orthogonal (in time or frequency) techniques like the spread spectrum techniques [38]. Therefore, most of the 3G suggested systems in order to achieve the requirements of the IMT-2000 for third generation systems were based on some kind of spreading. The gains attained using spread spectrum techniques can be attributed, amongst other factors, to the removal of the guards inherent in the previous systems [5].

There is a number of different spreading techniques [38]. In frequency based spread spectrum techniques, a narrow band signal is spread onto a wider bandwidth, therefore resulting in reduction of the power density of the signal by the ratio of the two bandwidths. This situation is illustrated using Figure 1-a. Because of this spreading, all users may transmit simultaneously on the entire available bandwidth.



(a) The Spectrum.

(b) Principles of DSSS

Figure 1: Direct Sequence Spread Spectrum.

The spread spectrum technique of the WCDMA is called Direct-Sequence Spread Spectrum (DSSS)[*]. In DSSS, each user is assigned a unique spreading code, called the *pseudo-noise* (PN) code. Its data stream is first spread out by that PN code, and then it modulates the carrier frequency. At the receiver the opposite process, a dispreading process, occurs. This necessitates the receiver being aware of the spreading code. The clock rate of the spreading code is known as the *chip rate*[†]. This principle is illustrated in Figure 1-b. The chip rate of the PN code is usually much higher than the user data rate. The ratio of the chip rate to the data rate is called the *spreading factor*. In UMTS, the spreading factor varies from 4 to 256 and the chip rate is 3.84 Mcps. Spreading factor can be varied based on one Radio Frame (also called Transmission Time Interval, or TTI) which is a the minimum processing duration for handling data coming from upper layers. One radio frame is 10 ms duration (in Standard UMTS of Release 99 and Release 4) and consists of 38,400 chips.

In addition to the gain resulting from the spreading process, spreading in WCDMA has another role in separating the users/signals on both the uplink and the downlink. The

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[*] Of all the different spreading techniques, DSSS results in less average interference (Chapter 4 in [16]).

[†] Chips are therefore basic information units and what they represent depends on the spreading (the channel).

process of separation is actually done in two stages [39]. The first stage is spreading using orthogonal spreading codes, called the *channelization codes*, while the second stage is another stage of coding using quasi-orthogonal codes called the *scrambling codes*. Both the channelization codes and the scrambling codes are explained in Appendix I. There are differences between the uplink and the downlink on how these two stages of coding are applied. This is further discussed in Section 3.4 when discussing the factors influencing capacity and coverage in WCDMA. Hence, the function of the codes (spreading codes) in WCDMA is threefold (i) to obtain a constant bit rate for transmission regardless of the data rate; (ii) to obtain spreading gain; and (iii) to accomplish channelization.

2.3 UMTS Architecture

UMTS consists of three main parts as shown in Figure 2, the Core Network, UTRAN and the User Equipment [40].

2.3.1 The Core Network

This is composed of the same components of the predecessor GPRS core network. It has two paths within it. A path for circuit switched services composed of the Mobile Switching Centre/Visitor Location Register (MSC/VLR) and the Gateway MSC (GMSC). The second path, for packet switched services, composed of the Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN). The core network includes also the Home Location Register and Authentication (HLR/AuC) a data base entity for user's profiles and authentication purposes.

2.3.2 The UTRAN: Universal Terrestrial Radio Access Network

The UTRAN is composed of multiple Radio Network Subsystems (RNS) whereby each RNS, in turn, is composed of the Radio Network Controller (RNC) and the Node B. One RNC controls more than one Node B as depicted in Figure 2. In the context of this thesis, Node B will be mainly referred to as the base station. Node B communicates with the user equipment over the U_u interface and relays data over the I_{ub} interface. Two RNC's may communicate over the I_{ur} interface. This is needed in cases of soft handover when the mobile needs to be transferred from one Node B to another belonging to different RNCs. The RNC relays circuit switched data over the backbone Iu_{cs} and packet switched data over the Iu_{ps} interface to the core network. Overall description of UTRAN (Release 4) is in the 3GPP standard [41].

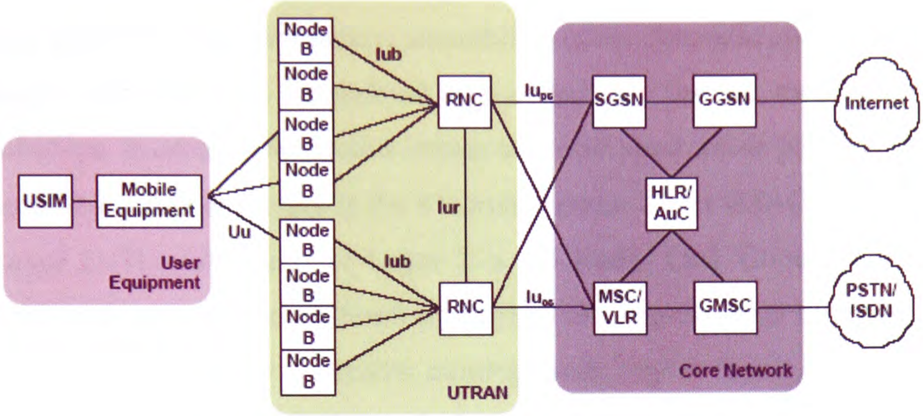

Figure 2: UMTS network architecture [40].

2.3.3 The User Equipment (UE)

This is in turn composed of the Mobile Equipment, ME, that actually communicates over the U_u interface with Node B, and the UMTS Subscriber Identity module, USIM, which holds the subscriber identity and other encrypted information.

Resource management functionalities in standard UMTS (Release 99 and Release 4) reside in the RNC of the UTRAN and in the UE. These are power control, handover control, call admission control, packet scheduling and load control. Some of these like the power control and soft handover control are standardized in UMTS and will be discussed in the coming sections of this chapter, while the other management techniques will be discussed in Section 3.5 of the next chapter when the factors influencing capacity and QoS provisioning in WCDMA are discussed. Description of radio transmission and reception by the UE and classification of UEs according to power classes can be found in 3GPP standard in [42].

2.4 UMTS Channel Structure

The protocol structure for any wireless communication system can be divided into layers with each layer providing services to the layer above it. The physical layer (Layer 1) is at the bottom of the protocol hierarchy. Layer 1 provides the physical channels that are defined by a specific carrier frequency, scrambling code, channelization code and time start and stop*. Time durations are defined by start and stop instants measured in integer multiples of chips. In other words, radio frames and time slots define physical channels.

On top of the Physical Layers is the Medium Access Layer (MAC). MAC is a sub-layer of Layer 2. The other part of Layer 2 is the Radio Link Control Layer (RLC). Transport channels are channels offered by Layer 1 on request from the MAC layer to carry the data and control bits streams coming from higher layers, i.e a process of mapping the transport channels to Layer 1 channels. Transport channels define how and with what characteristics data is transferred over the air interface (shared by users or dedicated to a single user). The bits passed to Layer 1 in transport blocks of a multiple of one radio frame (1, 2, 4, or 8 radio frames) called the Transmission Time Interval (TTI). A number of bit processing operations are done on these blocks of data at the physical layer (*bit rate processing*) before spreading and other *chip rate processing* operations. *Bit rate processing* operations are like adding redundancy bits for error detection and correction, interleaving, multiplexing, rate matching and segmentation (to distribute the bits onto the different radio frames properly).

A comprehensive description of the processing in RLC Layer and the Physical Layer's *chip rate processing* and *bit rate processing* operations is given in [43]. A brief description of some of the transport and physical channels in UMTS and their mapping in the UL and the DL is given below. The complete list of Physical channels and mapping of transport channels onto physical channels in FDD for Release 4 is described in 3GPP specifications [44]. It is worth mentioning that some physical channels and signals for synchronization and common pilots don't have a corresponding transport channels [44].

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* and a certain phase (0 or π/2) on the uplink.

2.4.1 Transport Channels

A general classification of transport channels is into two groups:

- Dedicated Channel (DCH) on the downlink or uplink: These are the actual channels carrying the data coming from higher layers. They use inherent addressing of UE. The DCH is transmitted over the entire cell or over only a part of the cell using for example beam-forming antennas.
- Common channels, using explicit addressing of UE if addressing is needed. These are the channels needed for broadcasting on the downlink, the Broadcast Channel (BCH), paging on the downlink, the Paging Channel (PCH) and for random access on the uplink, the Random Access Channel (RACH).

On the downlink, in Release 99, a common transport channel shared by several UEs, the Downlink Shared Channel (DSCH), was also defined. This channel was not implemented in practice. Similarly, on the uplink, the Common Packet Channel (CPCH) is an uplink common transport channel that was not implemented as well. These two channels were removed from standards later. More powerful channels; the High Speed Downlink Shared Channel (HS-DSCH) for packet access on the downlink (in HSDPA), and the Enhanced-Dedicated Channel (E-DCH) on the uplink (in HSUPA), were introduced in Releases 5 and 6 respectively, and they are receiving a wide interest. Section 3.7.2 describes these two enhancements.

2.4.2 Physical Channels

2.4.2.1 Uplink physical Channels

On the uplink, there are two common physical channels, the Physical Random Access Channel (PRACH) that is used to carry the RACH and the Physical Common Packet Channel (PCPCH) is used to carry the CPCH. Both RACH and CPCH are transport channels. There are also two types of uplink dedicated physical channels: the uplink Dedicated Physical Data Channel (uplink DPDCH) and the uplink Dedicated Physical Control Channel (uplink DPCCH).

The DPDCH and the DPCCH are I/Q code multiplexed within each radio frame. The uplink DPDCH is used to carry the DCH transport channel data. There may be zero, one, or several uplink DPDCHs on each radio link. The uplink DPCCH is used to carry control information. The control information consists of known pilot bits to support channel estimation for coherent detection, transmission power-control (TPC), commands, feedback information (FBI), and an optional transport-format combination indicator (TFCI). The transport-format combination indicator informs the receiver about the instantaneous transport format combination of the transport channels mapped onto the simultaneously transmitted uplink DPDCH radio frame. There is one and only one uplink DPCCH on each radio link.

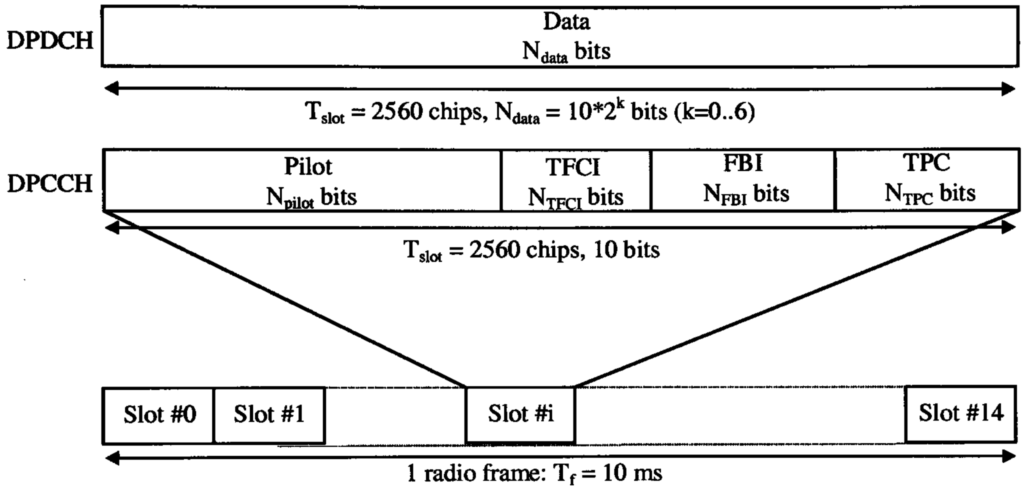

Figure 3: Frame structure for uplink DPDCH/DPCCH [44].

Figure 3 shows the frame structure of the uplink dedicated physical channels. Each radio frame of length 10 ms is split into 15 slots; the slot is a duration, which consists of fields containing bits. The length of a slot corresponds to 2560 chips, corresponding to one power-control period (power control is described in Section 2.5).

The parameter k in Figure 3 determines the number of bits per uplink DPDCH slot. It is related to the *spreading factor* (SF) of the DPDCH as SF = 256/2. The DPDCH spreading factor may range from 256 down to 4. The spreading factor of the uplink DPCCH is always equal to 256, i.e. there are 10 bits per uplink DPCCH slot.

2.4.2.2 Downlink Physical Channels

There is only one type of downlink dedicated physical channel, the Downlink Dedicated Physical Channel (downlink DPCH). Within one downlink DPCH, dedicated data generated at Layer 2 and above, i.e. the dedicated transport channel, is transmitted in time-multiplex with control information generated at Layer 1 (known pilot bits, TPC commands, and an optional TFCI). The downlink DPCH can thus be seen as a time multiplex of a downlink DPDCH and a downlink DPCCH in contrary to I/Q multiplex on the uplink.

Figure 4 shows the frame structure of the downlink DPCH. Each frame of length 10 ms is split into 15 slots, each of length $T_{slot} = 2560$ chips, corresponding to one power-control period.

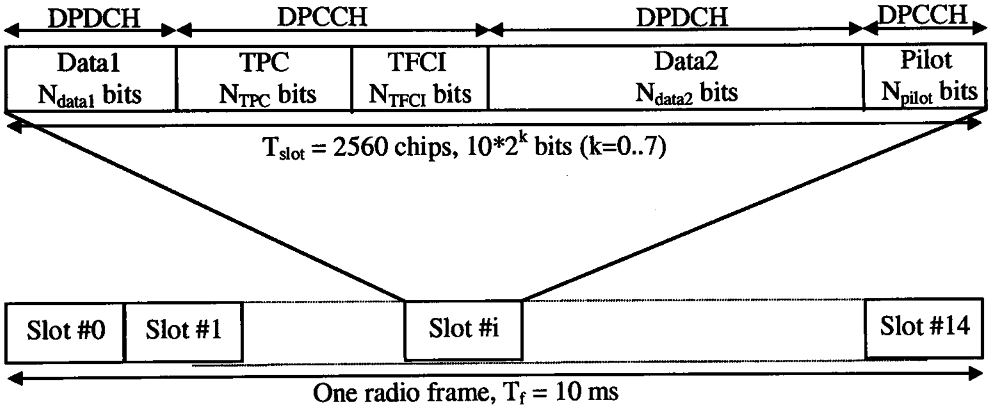

Figure 4: Frame structure for downlink DPCH [44].

The parameter k in Figure 4 determines the total number of bits per downlink DPCH slot. It is related to the spreading factor of the physical channel as SF = 512/2. The spreading factor may thus range from 512 down to 4.

2.5 Power Control

Power control was also used in 2G systems like GSM [45]. In such systems, power control is mainly used to protect QoS of the user himself[*]. However, in UMTS, where the interface is CDMA based, it plays a much bigger role especially on the uplink due to the near-far effect whereby a nearby user may generate excessive interference compared

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[*] Of course, power control is essential to second-generation IS-95 (*cdmaOne*) same as in WCDMA.

to the others faraway from the base station. Power control is needed to make sure that every user is generating just enough power for the QoS level that he requires while at the same time protecting the QoS levels of all other users.

Initially the UE, when attempting to connect to the network, receives information about the used and allowed upper and lower power level limits in the cell. Furthermore, the UE evaluates the path loss to Node B based on downlink pilot signal and decides on a proper power level based on these evaluations. This is the *open-loop power control.*

Additionally, there are two *closed-loop power control* algorithms, one is the *inner loop*, and the other one is the *outer loop*. The inner loop power control up/down signals are generated at a high rate of 1500 Hz and are updated every slot period through the TPC field (as depicted earlier to this in Figure 3). The purpose of the outer loop power control is to set the Signal to Interference Ratio (SIR) target for the link. SIR target is adjusted according to changes in propagation conditions (multipath profile) and quality of the connection. In doing so, the SIR for each block is converted to block error probability. Each block is then classified as erroneous or not, which gives the block error rate (BLER) estimates. The BLER estimates are used in order to decide if the SIR target should be increased or decreased. The outer loop algorithm runs at a much lower rate than the inner loop. Power control in UMTS is described in 3GPP specification [46].

Transmission power control schemes deal with variations in received power level due to the multitude of factors causing signal reflection, refraction, etc, in the communication channel, which multiply manifold when users are on the move (a discussion of the propagation and fading factors is given in Section 3.4.2 of the next chapter). These are the less predictable and yet very relative aspects of signal propagation [47]. Therefore, accurate power control is essential in CDMA not only in order to mitigate the near-far effect problem, but also, as a link adaptation technique to enable provision of different QoS levels for different streams by assigning different power levels and thus may be also called *power modulation* [47].

In the new enhancements to UMTS, the HSDPA and HSUPA, power control is removed from the downlink enhancement, the HSDPA (only for the new shared channel, but is still used with coexisting traditional channels). In HSDPA, link adaptation is performed by adapting the modulation technique or the coding (channel coding) in what is referred to Adaptive Modulation and Coding (AMC). However, in the uplink, power control is indispensible due to the near far effect, and is therefore kept for the uplink enhancement, the HSUPA. The new enhancements are introduced in Section 3.7.2 of the next chapter.

2.6 Handover Control

Handover in UMTS is mainly a soft handover (SHO) type. This means that a user close to the cell boundary might be connected simultaneously to two or more base stations. Depending on the links' conditions (SIR ratio), this UE will determine on a set of active base stations. In the uplink, the mobile station signal is received by the two (or more) base stations, combined in one of them (the serving base station in which the UE was originally registered). On the downlink, the mobile terminal receives the signals from the different base stations in the active set and combines them to recover the signal. The combination in either case is done using maximal ratio combining. Although the handover process may be originated by either the UE or the base station, the final decision for handover is made by the serving RNC (the RNC to which the UE will be attached by the end). The necessary measurements of the SIR for handover purposes are done using pilot signals. The I_{ur} interface, depicted in Figure 2, is used to communicate handover information when handover is to be done between two Node Bs belonging to two different RNCs connected via an I_{ur} interface.

The handover may occur between two overlapping sectors of the same Node B and it is called in this case Softer Handover (SfHO). In general, the rescannable acceptable percentage of the connections in SHO is about 20-30% [48] while it is 5-15% of the connections in SfHO [48].

Soft handover advantages the capacity in the cell, especially on the uplink. This is because the interference caused by users in soft handover is reduced due to diversity reception by more than one base station with no added cost on the mobile station (MS) itself; i.e. almost no extra power required. Typical value for soft handover gain used in the uplink link budget is 2-3 dB [48].

However, the situation on the downlink is a bit different. On the downlink, the two or more base stations involved have to allocate a fraction of the power that could have been used by other users to the MS in soft handover resulting in a decrease of the capacity by this fraction. This shall, to some extent, wipe out the gains resulting from soft handover diversity. This somehow explains why in the new enhancements to UMTS (Section 3.7.2), the HSDPA and HSUPA, soft handover is kept for the uplink enhanced channel while removed from the downlink shared channel.

2.7 RAKE Receiver

In a multipath channel, the original signal reflects from obstacles such as buildings and mountains, and the receiver receives several copies of the signal with different delays. In principle, other copies of the signal itself can be seen as interference therefore will be suppressed by the processing gain like other signals. However, a further benefit is obtained if the multipath signals are combined using RAKE receiver. Not all multipath signals can be resolved using the RAKE receiver; they must be separated by more than one chip from each other.

RAKE receiver [10] consists of a bank of correlates, each receiving a multipath signal. After dispreading by correlates, the signals are combined using, for example, maximal ratio combining. Because the received multipath signals are fading independently, a diversity gain (called micro diversity in contrast to macro diversity of the soft handover combining) is attained resulting in improved performance.

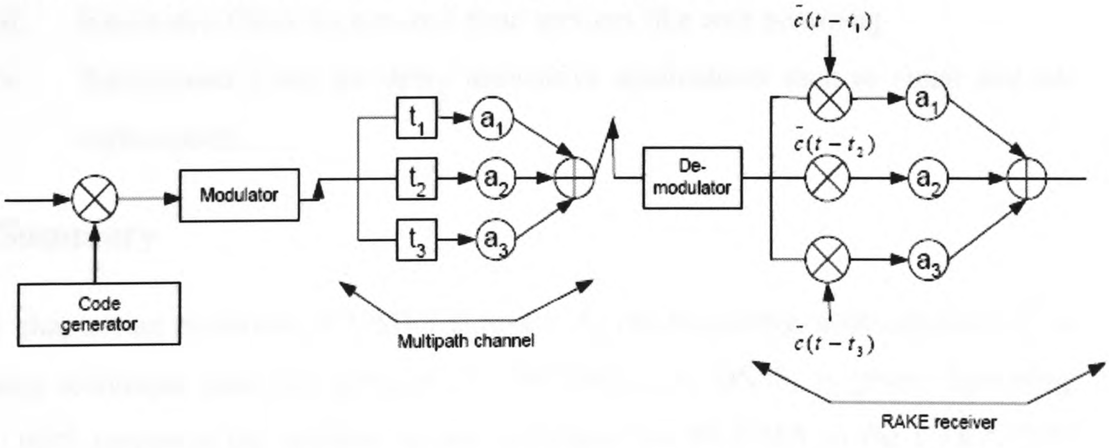

Figure 5: Principle of RAKE receiver [10].

Figure 5 describes the principle of RAKE receiver with three fingers. There are three multipath components with different delays t_1, t_2, t_3, and attenuation factors a_1 a_2 a_3, each corresponding to different propagation paths. The RAKE receiver has a receiver finger for each multipath component. In each finger, the received signal is correlated by a spreading code, which is time-aligned with the delay of the multipath signals. After dispreading, the signals are weighted and combined. Combination can be done using Maximal Ratio Combining (MRC) or Equal Gain Combining, (EGC) [10].

2.8 UMTS Service Classes

Second generation wireless systems enabled voice traffic for commercial use. Since then the increase in customer's needs and demands paved the way for the development of third generation wireless systems, aimed at multimedia traffic requiring higher data rates. This also opened the door for a wide range of applications to fit in the aimed data rates. That is why it has been realized that it is necessary to categories traffic into different classes of varying QoS requirements. In W-CDMA/UMTS the QoS classes have been divided into the following four classes. These are

i. *Conversational Class*, that is characterised by low delay requirements but tolerate high bit error rates. Examples are delay sensitive applications like voice, video and VoIP (Voice over IP).

ii. *Streaming Class* that tolerates higher delays in applications like streaming video and music.

iii. *Interactive Class* for non-real time services like web browsing.

iv. *Background Class* for delay insensitive applications such as email and advertisements.

2.9 Summary

In this chapter, an overview of UMTS is given. At the beginning, a description of the spreading technique used for spreading in WCDMA, the DSSS, is given. Spreading using DSSS serves as the multiple access technique for WCDMA in the UTRA-FDD mode (the mode of concern in this study). Spreading is done by correlating the narrow band signal with a unique higher rate spreading code called PN code. Spreading results in spreading gain given by the ratio of the fixed chip rate of 3.84 Mcps of UMTS to the bit rate.

UMTS consists of three main parts: the core network, the UTRAN and the UE. In the core network the main users' databases exist, the switching of signals between the different mobile users and the interconnection with the public telephony network (the PSTN) and the internet occur. The UTRAN consists of Node B (the base station) which actually communicates with MEs over the wireless channel and the RNC. One RNC controls a number of Node Bs. The UE is composed of the ME and the USIM.

Physical channels are defined by a specific carrier frequency, scrambling code, channelization code and time start and stop. Transport channels are mapped to physical channels within the physical layer channels.

In UMTS, power control plays an important role especially on the uplink. Power control is done through an open loop that is important for initial settings, an outer (slow) closed loop that makes fine adjustments to the target levels and an inner fast loop that actually adjusts the power level in every slot.

Handover in UMTS is mainly soft handover whereby one user can be actively connected to two or more base stations at the same time. The receiver in UMTS can be a RAKE receiver type in which copies of the signal due to multipath reception can be combined constructively to enhance signal strength. In UMTS standards, four QoS classes that differ in their tolerance for delays and errors are defined: the conversational, streaming, interactive and background Classes.

Chapter 3 Capacity Provisioning in WCDMA Based Systems

3.1 Introduction

Capacity was the major drive behind all 3G mobile communications including WCDMA, which provides a kind of soft capacity that will be explained first. A system with soft capacity will have soft limits. The limits on capacity in WCDMA, whether soft or hard, either on the uplink or on the downlink are discussed afterwards.

A comprehensive review of the factors influencing capacity provisioning in WCDMA on either link is then presented. Those factors are classified into three categories. The first category includes those related to the signal and its processing, e.g. spreading and data rates. The second category includes those factors related to the link conditions, e.g. fading, interference and noise. Finally, the third category includes those related to the system components, e.g. antenna and receiver.

Call admission, scheduling, load control, etc, are functions of the radio resource management algorithms that aim to optimise capacity use and will be discussed afterwards. Next, the process of capacity/coverage planning and optimization in WCDMA is briefly discussed with a concentration on loading analysis and the rise over thermal techniques in this process.

Finally, a brief description is given to two of the non-traditional techniques used to gain capacity: the multi-user detection and the enhanced uplink/ downlink new standards. Beamforming and smart antenna techniques are described in a later chapter.

3.2 The Concept of Soft Capacity in WCDMA

The WCDMA communication system is an interference limited system with frequency reuse factor as low as 1[*]. It is not limited by hardware or frequencies which make the concept of capacity sharing the most distinguished characteristic of WCDMA.

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[*] Although some scholars like to describe WCDMA as having a reuse factor of less than 1 because of the soft capacity described in this subsection.

Capacity sharing, or in ATM terms, *statistical multiplexing* [49] is usually referred to in WCDMA as *soft capacity*. Soft capacity in UMTS is usually described as the increase in channels that are available in the cell when less interference is coming from neighbouring cells [50] [24].

Also soft capacity is used to describe the sharing of capacities between different users and services which results in the overall increase of traffic tolerated in WCDMA [51]. Hence , soft capacity in this sense is sometimes referred to as *multi-user diversity* [20]. Recent updates to WCDMA are aimed at utilizing this concept to the full by introducing enhanced shared channels on the downlink in HSDPA or enhanced dedicated channels on the uplink in HSUPA. The improved mechanisms in these enhancements allow a single user, or more than one user, to use these channels in a quick manner in response to fast changes in the propagation conditions. This results in an increase of soft capacity gains resulting from the *multi-user diversity*.

3.3 Limits on Capacity/ Coverage

In 3G WCDMA, Capacity / Coverage can be limited on both the uplink and the downlink. In the case of the uplink, two limits apply, the first is a limit on capacity when the aggregate interference from all sources reaches a certain threshold, and the second is a limit on coverage when the UE reaches its maximum power emission. These two limits apply as follows:

- The increase of interference in the uplink due to the admission of a new call may result in the exceeding of the interference threshold at the forefront of the base station receiver. The interference threshold is based on certain QoS requirements, capacity and coverage requirements. Hence, it can be said that the capacity is *interference limited on the uplink*. The main interference ingredients in this case are the signals belonging to other users in the same cell and signals belonging to other users in neighbouring cells in addition to the inevitable thermal noise component*.

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* Components of the same signal due to multi-path propagation are not considered interference because they are combined in the receiver to even better signal power.

- Coverage of users is *power limited on the uplink* due to the limited power of the user equipment devices; as it might be too far from the base station and it has to emit more power in order that its received power exceeds the aggregated interference and noise by a certain threshold enough to establish a reliable connection.

In the case of the downlink, two limits also apply. The first limit is the limit on capacity when the aggregate power needed to be transmitted by the base station to all users reaches a certain threshold. The second limit is the limit on coverage when the UE travels far away from the base station and thus needs more power than the allotted power to overcome the increased interference from neighbouring base stations. These two limits apply as follows:

- Power requirements of the new user may require exceeding the maximum allowed power to be emitted by the base station in the downlink. The cell capacity is said to be *power limited in the downlink.*
- The main interference ingredients on the downlink are the contribution from signals of other users from the same base station* in addition to downlink signals from neighbouring stations (not to forget thermal noise). In addition to that, as the user travels away from his original base station, its received power decreases and the interference from neighbouring base stations increases, resulting in a gradual decrease in the link reliability and the UE will therefore request more power. A limit will be reached whereby the link is degraded to a level where no more increase in power to this user will result in that this user being out of coverage, therefore, this limit is also referred to as *coverage limit on the downlink.*

All these can be described as soft limits, however, the downlink is characterised by an additional limit, a hard limit, due to the limited number of orthogonal codes used on the downlink to separate users especially when integrating services of different rates.

From the above discussion, it is evident that, two resources on the downlink limit the capacity, namely, the power and the code. While on the uplink it is the interference. However, the interference may be still be regarded as the general limit as the maximum power limits of transmitters are set to limit the interference as well.

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* they will contribute to the interference although they were transmitted orthogonal to each other, this is explained later in this chapter

In the analysis given in the coming chapters, only active-user capacity on the uplink is analysed and therefore the limits on the uplink will be only of concern.

3.4 Factors Influencing Capacity/Coverage in WCDMA

As said before, WCDMA was designed for capacity increase by the use of a wide bandwidth of 5MHz and the selection of spread spectrum as the multiple access technique. Spread spectrum is a technique for efficient use of the spectrum by allowing additional (spread spectrum) users to share the same band as other existing users thereby having a re-use factor of 1. This means that users in neighbouring cells will be using the same frequencies used in the cell. Hence, the network coverage and system capacity will be linked as every user, anywhere, can in principle, limit the interference seen by the other users. Having interference limited capacity means that any factor that results in interference reduction will result in capacity increase [10]. In fact WCDMA was motivated by some of these factors like voice activity and the use of sectored antenna [12].

The factors that affect interference (or improve the signal relative to the interference) can be divided into those related to the signal and its processing, those related to the link conditions, and those related to the transceiver and other system design parameters. These factors are discussed in the following subsections.

3.4.1 The Factors Related to the Signal and its Processing

Those include the activity of the signal, the signal rate and its spreading factor and spreading codes design and associated orthogonality and the code allocation strategies. Hard limits imposed by the code design are also introduced.

3.4.1.1 Activity Factor

Signals such as voice are composed of successive on and off (silence) periods. WCDMA makes use of this to reduce interference by incorporating a voice monitoring and activity detecting circuitry at the transmitter to suppress transmission during the off periods.

The on-off periods are random processes; i.e. the on period (or the off) is a random variable. For a Poisson assumption, it is shown [52] that the average number of users that are simultaneously on is also a Poisson random variable with reduced traffic load by the same percentage. For traffic of A Erlang, the number of connected users, N, in the cell will be given by the distribution $P(N = n) = e^{-A}\frac{A^n}{n!}$. Let us suppose that once a mobile call is connected to the network the mobile user is ON (active) with probability υ and OFF with probability 1- υ.

Let M be the number of mobiles in a cell that are active at any single instant of time. The probability that this number be equal to m giving that N=n users are connected shall be [52]

$$\begin{aligned} P(M=m) &= \sum_{n=0}^{\infty} | P(M=m \mid N=n).P(N=n) \\ &= \sum_{n=m}^{\infty} \frac{n!}{m!(n-m)!} \upsilon^m (1-\upsilon)^{n-m} e^{-A} \frac{A^n}{n!} \\ &= e^{-\upsilon A} \frac{(\upsilon A)^m}{m!} \end{aligned} \qquad (3.1)$$

In the previous equation it is assumed that the probability of m active given n users follows a Bernoulli distribution. In the capacity and interference analysis given in the next chapters, voice activity can therefore by treated in a simple multiplicative format as inspired by (3.1).

In addition to the application type, the activity factor depends on the technology (the vocoder and channel coding types) [22]. For voice signals, usually a factor of 0.58 to 0.67, typically 0.64, is assumed [22]. For video telephony a 100% activity is used all the time because the video codec continuously adapt the quality (mainly the picture quality) to the available bandwidth [22]. A table of activity factors on the uplink (UL) and on the downlink (DL) for data and packet switched services (as part of a complete traffic profile) based on practical results (range from 7%-80%) is given by Table 3.17 in [22].

3.4.1.2 Signal Rate and Spreading

WCDMA is a spread spectrum communication system which means that as the signal is spread more in frequency, the less its power spectral density will be and therefore the less interference it causes to others providing more room for more users. In general, capacity is proportional to spreading; the more spreading the more users can be added. In [12], the capacity of a WCDMA cell was approximated (under some assumptions) to be equal to the spreading factor. Spreading factors range in WCDMA is from 4 to 256 (spreading gain of 6-24dB).

WCDMA supports Real-Time (RT) and Non-Real Time services (NRT). Voice and video telephony are examples of real time services while web-browsing and messaging are examples of NRT services. RT calls are usually characterized by fixed rates. Nevertheless in WCDMA multi-rate real time services are available that are characterised by having some elasticity in their rates. This concept was used earlier in second generation networks to adapt voice signals data rates in what is called Adaptive Multi-Rate (AMR) coding. AMR will be discussed later in this section.

NRT services are more flexible down to zero rate but their performance is characterized by the end to end delay or the so called Sojourn times [53] [54].

3.4.1.3 Orthogonality and Spreading Codes Design

Separating users/signals in WCDMA on both the uplink and the downlink is done using a two stage coding. In the first coding stage a set of orthogonal codes, called the *channelization codes* (they are also called OVSF codes for orthogonal variable spreading factor codes) are used, followed by a second stage of coding using a long *scrambling codes* called the Gold codes, Appendix I describes the two stage coding process.

The roles of first stage; the orthogonal codes, varies between the uplink and the downlink. On the downlink its role is to separate different users in the cell/sector, while on the uplink its role is to separate data and control channels of the same user equipment. Similarly, scrambling codes have different roles on the downlink compared to the uplink. On the downlink, different cells/sectors are granted different scrambling codes while on the uplink different users are separated using different scrambling codes.

Orthogonal codes provide perfect separation. However, they suffer from two major drawbacks. The first problem with orthogonal codes is that they exhibit poor out of phase autocorrelation (ACL) and cross-correlation (CCL) properties. ACL leads to self interference which is the interference from multipath copies of the signal itself. CCL results in increased multiple access interference (MAI). The second problem with orthogonal codes is that they have a limited set of codes, therefore they may not be able to serve the needs of all users/signals in the cell while at the same time be reused in all neighbouring cells. For these two reasons, on the uplink, Gold codes of 24 initialization bits long is used [48] giving rise to 16,777,232 chips code length with only 38,400 chips needed to scramble a radio frame (10ms at 3.84 Mcps). This totally solved the problem of the scarcity of codes in the cell for all users/signals on the uplink.

On the downlink a total of 2^{18}-1=292,143 Gold codes can be generated [48], only 8192 of them will be used. They provide cell/sector identification. Additionally, Gold codes enjoy low CCL properties.

Because transmission on the uplink is asynchronous, transmission orthogonality is not kept between different users and all users will contribute to multiple access interference seen by any given user. While on the downlink, transmission can be made synchronous, and therefore orthogonality can be kept and MAI can be ideally zero. However, in reality, due to multi-path propagation, the received signals are not perfectly orthogonal anymore and thus they cause intra-cell interference. The orthogonality factor, O, is used to account for this on the downlink. The value O=0 is usually used to account for full orthogonality and the value of 1 is used to express the completely non-orthogonal case. The loss of orthogonality is manifested when the propagation delay between two impulses arriving at the receiver is less than the chip period, T_c. Consequently, the RAKE receiver cannot resolve the paths and the fading that results, which causes interference at the detector output. The delay corresponds to a path length difference of $\Delta d \leq L$. In the case of WCDMA, T_c =260.4 ns and, therefore, L=78 m.

In network dimensioning stages an orthogonality factor O=0.5 is usually assumed. As the study given in the next chapters concentrate on the uplink, the orthogonality factor will not be explored any more throughout (besides when commenting on how a model for the downlink, as well, can be obtained in further research).

3.4.2 The Factors Related to the Link Conditions

Knowledge of radio propagation characteristics is a prerequisite for the design of radio communication systems [10]. Mobile radio channel is a time varying fading channel. The signal on its way from the transmitter to the receiver may be reflected, diffracted and scattered due to the presence of various objects and obstacles like buildings, trees, etc, in the environment. In addition, the different paths will result in different attenuations. Thus actually the received signal is a multitude of signal copies arriving at the receiver at different instants of time with different amplitudes and phases. This phenomenon is called *multipath fading*. The different signal components will therefore combine at the receiver either constructively or destructively in a completely random fashion producing a time varying signal. Fading can be *small scall fading* in the order of half a wavelength due to multipath propagation (multipath fading) or medium scale fading in the order of tens or hundreds of wavelengths due to obstructions called *shadow fading*. Additionally, signals are attenuated more with distance raised to a power constant ranging from 3-5, typically 4, called the propagation constant, C_p. The attenuation with distance is called the *path loss*. In addition to these fading phenomenas, the wireless channel is impaired by multiple access interference and the non-evitable thermal noise. These will be discussed below starting with thermal noise.

3.4.2.1 Thermal Noise Level

Thermal noise is attributed to two sources, first the terrestrial thermal noise and the contribution from the transceiver electronics. The terrestrial thermal noise density in dBm/Hz is given by B_cT_e, where B_c is Boltzman Constant=$1.38\text{x}10^{-23}$ Jouls/Kelvin, T_e is the equivalent temperature in $^{\circ}K$ (typically -174 dBm/Hz). Thermal noise is calculated for 4.096 MHz band by assuming 5-dB system noise figure is -103 dBm [55] (on the uplink).

Thermal noise level is used as a reference for interference computations in the cell. The rise over this reference level (called *rise over thermal*) is related to the cell loading. This is further discussed in 3.6 when talking about capacity planning in WCDMA.

3.4.2.2 Path Loss

The signal power as it travels from the base station antenna to the receiver antenna suffers attenuation loss, called the *path loss*, L_p. Therefore, the available transmission power, P_S, at the transmitter, L_p at a distance d, and the received power, P_r (assuming accurate power control), are interrelated as follows:

$$L_p(d) = \frac{P_s}{P_r} \tag{3.2}$$

In path loss models, the order of decline of the signal power as it travels is proportional, by a factor, K_p, to the distance raised to a power exponent, called the *propagation constant*, C_p (or the *path loss exponent*), or $L_p(d) = K_p \cdot d^{C_p}$.

The parameters K_p and C_p depend on the environment (degree of urbanization), the heights of the antennas at both the base station and the receiver and the frequency of operation. The propagation constant is of the order of 3-5. In free space, this exponent is 2, corresponding to a 20 dB/decade power decline with distance.

Many models were devised to predict the path loss. Appendix II describes two important models [56] (in addition to free space model) that are used in mobile wireless environments. These are the COST 231-Hata for macro-cellular environments with variations for the different urbanization levels, and COST 231-Welfish-Ikagami semi empirical model for micro-cellular environments. Figure 6 shows Variation of propagation constant with the variation of the antenna height of the base station using the COST 231-Hata model.

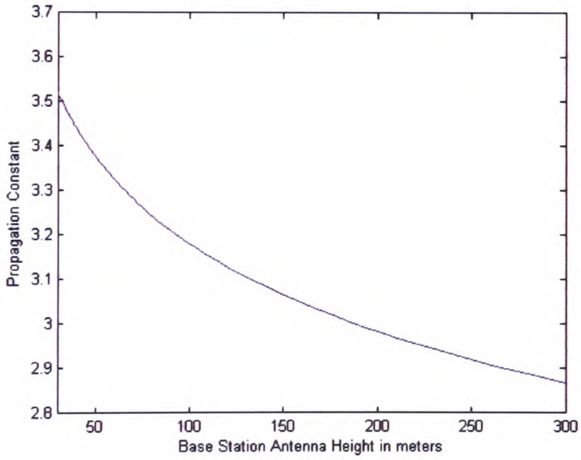

Figure 6: Variation of the propagation constant with the variation of the BS antenna height.

3.4.2.3 Shadow Fading

The path loss, L_p, over a distance d, computed using the path loss models in the previous subsection will give rise to an average received power called the *area average*. However, terrain variations and shadowing objects will result in the path loss variation around the area average. This is called *shadow fading* [1] or sometimes called *medium scale fading*.

Therefore in obstructed environments the path loss at a particular location is modeled as log-normally distributed (normal in decibels) about the mean distance path loss and is expressed as [12]

$$L_p(d) = K_p \cdot 10^{\zeta/10} \cdot d^{C_p} \tag{3.3}$$

where K_P and C_p are the parameters of the path loss model. The term $s = 10^{\zeta/10}$ represents the shadow-fading component where ζ is a Gaussian random variable with zero-mean and standard deviation σ, which ranges from 6-12 dB for urban environments, typically 8. The received power is now a random variable z with lognormal density given by

$$f_z(z) = \frac{1}{\sigma' z \sqrt{2\pi}} e^{-(\ln z - \mu)^2 / 2\sigma'^2} \tag{3.4}$$

where P_s is the transmitted power, $\mu = \ln(P_s / K_P) - C_p \ln(d)$ and $\sigma' = \sigma \ln(10)/10$.

On the uplink, accurate closed-loop power control is needed to ensure that for any link the received signal is of a certain level above the interference. However, due to shadow fading described herein, inaccuracies in the closed-loop power control process are expected. Therefore, the received signal quality cannot be kept at the minimum required level at all times and may fall below it, which is called *outage*. The outage probability is a reliability measure defined as the QoS loss probability (say 1 percent per-user maximum), when the received interference exceeds the tolerance level [57] [20].

Of course, shadow fading is a statistical phenomena and to ensure that the UE is not in outage with a certain confidence , the minimum required quality level will have to be increased by a certain multiplier, Γ, that is a function of the outage probability, P_{out}, requirement and the shadow fading parameter σ [58]. Γ is called *power-control-correction factor* (*outage factor*). The value of Γ is given by

$$\Gamma = 10^{\left(\frac{\sigma'^2}{20} - \frac{Q^{-1}(\varphi)\sigma'}{\ln(10)} \right)} \tag{3.5}$$

where φ is the reliability ($\varphi = 1\text{-}P_{\text{out}}$) and

$$Q(x)=\int_{x}^{\infty}\frac{1}{\sqrt{2\pi}}e^{-t^2/2}dt.$$

Inaccuracies in power control mechanisms due to shadow fading can result in inaccuracies in estimating the capacity in power controlled links unless the parameters of the shadow fading is taken into consideration.

To combat the effect of shadow fading an accurate power control mechanism must be in operation, which is not an easy task. The new enhancement to Node B like HSDPA and HSUPA aimed, amongst other aims, at reducing the effect of shadow fading through mechanisms like HARQ, small TTI and fast scheduling, HSPA is considered in Section 3.7.2. The use of diversity antennas is another method of combating shadow fading (as well as multipath fading). Section 3.7 discusses how capacity is improved using diversity and the new standards.

3.4.2.4 Multipath fading

Multipath fading is the result of mobility and is characterised by heavy fluctuations in the received signal over a distance of half a wavelength (7.5 cm for 2000MHz carrier). Multipath fading is modelled using *Rician* distribution when a line of sight path (or at least one path that is distinctively strong) exists between the transmitter and the receiver. When no line of sight path exists, the *Rayleigh* distribution is usually used to characterise the fading.

In WCDMA the RAKE receiver is used to combine constructively discernable signal copies from different paths after adjusting their phases and magnitudes. Variations in power requirements due to multipath fading are mainly taken into consideration by the inner loop of the power control algorithm, which runs at a high rate (Section 2.5). Nevertheless, at higher speeds, the inner loop fails to cope with the fast variations and the outer-loop will have to increase its target E_b/N_o to account for this. This is further discussed in Section 4.7.2 when considering mobility.

3.4.2.5 Multiple Access Interference (MAI)

As described when orthogonality was discussed earlier in this chapter, on the uplink, all other signals in the same cell contribute to the interference seen by any user in the cell while on the downlink only a non-orthogonal interference part is contributed by other signals, which were originally transmitted orthogonal to each other. In both cases, another contributor to MAI will be the interference coming from neighbouring cells. This is a non-orthogonal interference in either case.

It is common in literature to assume that users controlled by other cell base stations introduce multiple cell interference power into a given base station whose average is a fraction f of the multiple access interference, seen at the base station, that is due to in-cell users [59] [60]. This is usually made based on the assumption of uniform loading in all cells. Hence, f, represents the relative other-cell *interference factor.* The value of the interference ratio, as given in [12], lies between 0.5 and 0.6 for path loss exponent of 4 and log-normal shadowing standard deviation $\sigma=8$. In [60] f was given to be 0.45 to 0.91 for $\sigma=4$ to 12, with 0.55 for $\sigma=8$. In network planning and dimensioning a value that will reflect a certain condition in the network shall be assumed [61]. Typically, 0.55 is used.

However, it is different, when (real time) resource management in a multi-cell UMTS scenario is the issue under consideration. In such a case, the cell and neighbouring cell loading status and the ratio between external and internal interference f matters, and a (real time) value should be known in order to achieve the minimum transmitted power criterion with accuracy. Measurement based method can be used to estimate f in real time. In this method, the ratio f can be estimated based on local measurements without the need of interchange of information between different cells. This includes measuring the total broadband interference together with the individual power levels of the users and their instants of transmissions that are available to the base station [48]. In this method, the effect of thermal noise and leakage interference from other bands and sources will be included [48]. The estimation ratio f is induced from the ratio measured in the previous frame [58]. A second method to estimate f instantaneously is through information interchange about loading conditions between RNCs in states before current state where a decision for admission is to be taken [48] for example. Although in [59] an estimation technique to reduce overhead is suggested.

MAI seen on either the uplink or the downlink will also include leakage interference from users of other (adjacent) carriers due to non-perfect filtering and separation. Limits are imposed by 3GPP standards [62] on base stations' power output, power output dynamic range, out of band emissions and other spurious emissions to minimise these interferences. Interferences from these sources will not be modelled in the analysis given in the coming chapters. Additionaly, the co-existence of narrow band microwave systems may corrupt the CDMA signal's spectrum in a narrow frequency band without inflicting significant interference [38].

3.4.3 Factors Related to Transceiver, Antenna Architecture and other parameters

In the previous chapter, the RAKE receiver architecture was described. The use of this receiver is not mandatory in the standards. However, it provides diversity gain against multipath fading therefore providing better receiver sensitivity. Additionally, the number of fingers will influence its performance, however, as number of fingers is increased, combining losses starts to appear [10]. Generally, the construction of the transceiver will include other parts that may influence its sensitivity.

The capability to compress data, e.g. speech compression codecs, through source coding techniques is used to protect the link by adapting the codec to channel conditions. This results in providing capacity by degrading to lower rates. The use of higher channel coding (Turbo codes) compensates for the decrease in their processing gain [22].

Diversity and sectored antennas are traditionally used in mobile wireless communications including 3G to enhance capacity. Diversity antennas act by improving the fading conditions in the cell while sectored antennas act through reducing MAI. Some of these factors will be considered in the following subsections (RAKE receiver was discussed in Section 2.7).

Later a more revolutionary techniques, on the transceiver side (Multi-User Detection, Section 3.7.1), and on the antenna side (beamforming and smart antennas, Chapter 5) will be described.

3.4.3.1 Coding

Adaptive Multi Rate (AMR) is an audio data compression scheme optimized for speech coding. AMR is adopted as the standard speech codec by 3GPP [63] and is now widely used in GSM and UMTS. It uses link adaptation to select from one of eight different bit rates based on link conditions. The AMR codec uses 8 source codecs with bit-rates of 12.2, 10.2, 7.95, 7.40, 6.70, 5.90, 5.15 and 4.75 Kbit/s.

AMR utilizes Discontinuous Transmission (DTX) with Voice Activity Detection (VAD) and Comfort Noise Generation (CNG) circuitry to reduce bandwidth usage during silence periods. This effect was discussed when considering the activity factor in Section 3.4.1.1.

The use of higher channel coding (Turbo codes) for higher rates 64Kbps circuit/packet switched services and 128/384Kbps packet switched data compared to voice users (using convolutional coding) is used to allow the use of lower E_b/N_o for the higher rates services to compensate for the decrease in their processing gain [22]. This reduction is about 3.8 dB on the average (Table 2.3 in [22]).

3.4.3.2 Sectored Antennas

Sectorized antenna systems subdivide the cellular area into sectors that are covered using directional antennas looking out from the same base station location. Sectorization increases cell capacity. Each sector is served by one antenna and one transceiver, hence forming one cell from capacity point of view that is serving the users within its coverage. The capacity is therefore increased by the factor of the number of sectors. Many factors will contribute to the reduction of capacity with sectorization below this theoretical limit, especially with increased number of sectors. Amongst these factors is that the antenna pattern is shaped by the metallic properties of the antenna causing increased overlap between the sectors. Furthermore, increasing the number of sectors increases the handoffs that the mobile experiences while moving across the cell [64]. Therefore, the reasonable number of sectors in WCDMA is typically from 1 to 6 [61] [65].

There are issues related to the interaction of base station antenna and system's capacity and coverage, e.g. antenna beam tilting and shaping of the elevation pattern are used to attempt control of cell contours [66].

3.4.3.3 Diversity Antennas

Diversity is used on the uplink by incorporating two (or more) antenna elements at the base station in the reception system. The antennas must be physically separated to create space diversity. Diversity is used to improve reception by counteracting the negative effects of multipath.

Combining results in an improvement in the effective strength of the received signal at the base station (diversity gain). Usually combining is done by making the system alternatively connect to the element with the higher signal strength received. This is *switched diversity*. Alternatively, the phase error in the two multipath signals is corrected and the signals are then combined using, for example, the *maximal ratio combining*. This is *diversity combining*.

3.4.3.4 Code Allocation

Providing high data rate links in WCDMA is possible in one of two different ways. In the first one, the one usually adopted, is the use of single code with lower spreading factor. The second method is to use one or more codes; i.e. more than one data channel of the same user. In the second method, all codes shall have the same length, same spreading factor and are orthogonal to each other.

Spreading codes are branches of the code tree (code tree is explained in Appendix I), the lower the data rate the longer the branch is. Two codes in different levels are orthogonal to each other if one of the code words is not the mother (root) code of the other. This will lead to the restriction that the station cannot simultaneously use two codes, where one code is the mother of the other [67]. Therefore, a high data rate user will result in chopping a large number of the codes for the lower data rates.

As a result, code blocking on the downlink may occur due to the extensive use of high data rates. Therefore, the hard limit due to coding may limit the capacity before the start of the soft limit. In addition to that, the random use of spreading codes for the low data rates may result in code tree fragmentation. Code Allocation strategies aim at minimising code tree fragmentation, preserving the maximum number of high rate codes, and enhancing the statistical multiplexing and spectral efficiency of UTRA-FDD access.

3.4.3.5 Signaling

As can be noticed from the discussion of the channel structure in UMTS in Section 2.4, the traffic, or user data, is not the only element that requires radio interface capacity in UMTS. A lot of signalling information, e.g. pilots and other control signals and some common control channels destined to all users, must be communicated on either the uplink or the downlink for proper functionality of the network. In practical systems, on the downlink [68], a fraction of the total transmission power is devoted to the signalling overhead. While on the uplink, the interference contribution of the signalling must be evaluated.

3.5 Radio Resource Management (RRM) Tools

As previously discussed in this chapter (Section 3.3), the interference; or more specifically, the interference on the uplink and the base station's power on the downlink are the two main resource units in WCDMA. These are to be consumed in units of connections and packet grants of different services at different rates, durations, etc. The aims of resource management techniques in the network are to ensure that these resources are consumed in the best efficient way; i.e. maximizing capacity, while at the same time satisfying / maximizing certain goals of quality for these connections individually and/ or combined. This is in addition to their role in protecting the available capacity (e.g. by proper code strategies to protect against hard limiting due to code shortage as described in Section 3.4.3.4).

Therefore, understanding the way capacity is consumed in the network and the influence of the different ways in which capacity can be shared on the QoS metrics in the network will help to improve either one. This is an attribute of all of the resource management techniques in UTRA, in particular, call admission, scheduling, load and congestion control and power control.

Additionally, the actual capacity in the system, payload, in any case will be less than what the interference or power limits impose. This is due to the need of signalling and control information interchange on the air interface as described earlier in Section 3.4.3.5. These signals are necessary for the correct functioning of RRM schemes, inherent, and are irreducible in most of the cases (e.g. power and handover control signals).

3.5.1 Call Admission Control

The main task of the Call Admission Control (CAC) is to estimate whether a new call can have access to the system without sacrificing the requirements of existing calls. Thus, the admission control algorithm should predict the load of the cell if the new call is admitted. If the air interface load is allowed to increase excessively, the coverage area of the cell is reduced below planned values and the quality of service cannot be guaranteed. The availability of transmission resources is also verified by admission control. Based on these results, the RNC either grants or rejects access.

The Admission Control algorithm is executed whenever a bearer is set up or modified. The effective load increase by admitting another bearer is estimated for both the uplink and downlink. The bearer can only be admitted if the uplink and downlink admission control admit it, otherwise it is rejected. Admission control can be interference based [50], capacity Based [57], resources based [28], handover priority based [69], QoS class priority based [70], and adaptive QoS based admission control [71].

Call admission control and scheduling enable QoS provisioning despite the unpredictable traffic characteristics.

3.5.2 Handover Control

Soft handover mechanism in UMTS and the associated gain acquired by the link due to the mobile being in soft handover are discussed in the previous chapter (Section 2.6). Handover management and admission control are much interrelated, reducing the dropping rate for handover calls will generally result in increasing blocking rates of new calls originated in the cell itself. Handover management shall monitor handover rates to prevent excessive use of handover that may result in reducing the capacity on the downlink (extra code and power required from the base station), hence, reservation techniques that are based on say mobility may be used in order to reduce dropping probability of soft handover calls. Handover can also be used to distribute the load evenly amongst cells or carriers* when the cell becomes congested for one reason or another.

3.5.3 Packet Scheduling

Packet scheduling is used to properly allocate the available resources (power/interference and code) in a timely manner between the packet data users (bursty traffic and delay tolerant) of interactive and background services. It decides on the transport channel while attempting to guarantee the QoS requirements for real time services (service classes in UMTS are discussed in Section 2.8 in the previous chapter). Scheduling aims at maximizing throughput. However, fairness provision to packet users is an objective as well. Of course, the network loading must not be exceeded in all cases. Scheduling algorithms varies on these goals. Round Robin scheduling provides fairness while C/I scheduling maximizes link throughput on the account of fairness [53].

Packet scheduling algorithms have gained more interest with the introduction of the new enhanced channels on the uplink and on the downlink (HSDPA/HSUPA) discussed later in this chapter. The reduction of the transmission time interval in such enhancements to 2 msec (10 msec in standard UMTS) means that scheduling can respond more quickly to the variations in the link conditions providing for more throughput maximization and fairness provisioning. Additionally, scheduling (with these enhancements) has gain more dimensions, e.g. selecting between channel encoding using QPSK or 16 QAM modulations in the downlink enhancement of HSDPA, and selecting between 2ms and standard 10 msec TTI in the uplink enhancement of HSUPA.

3.5.4 Load Congestion

Admission control and packet scheduling are at the forefront of ensuring that the system works below its limits. However, due to the evolution of system dynamics (mobility aspects, increase in interference, etc.) the system may reach a congestion status in which the QoS guarantees are at risk. Load control mechanisms are devised to face such situations.

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* In the later one, handover between carriers is a hard handover in which the UE has to be detached from the first carrier before being attached to the new carrier.

Detection of load congestion involves monitoring of SIR targets for each individual connection as well as the *Load Factor* and/or the *Rise over Thermal* values on the uplink and the downlink (Section 3.6.1 discusses these parameters). Strategies to face such a situation range from dropping some low priority connections, degrading elastic connections, delaying packets, and handing some connections to other cells or carriers.

3.6 Planning for Capacity and Coverage in WCDMA

The process of planning for capacity and coverage in WCDMA consist of a number of stages, starting with requirement and strategy for coverage, quality and capacity per service, followed by a coverage planning and site selection process. In the last stage of coverage planning and site selection, capacity requirements of traffic distribution, service distribution, and allowed blocking parameters will interact and a number of refinements have to be done, this is called dimensioning. Interaction with RRM parameters of handover, loading, etc, is done at early stages of planning with refinements for network optimisation at later stages of network operation and maintenance. This process of network planning and optimisation is depicted using the block diagram in Figure 7 . Details of the radio network planning process can be found in [48] [72] [61].

3.6.1 Rise over Thermal and Loading Analysis

Of interest to this study out of the above planning process are two concepts that are of immediate relevance to capacity and coverage dimensioning: the loading and interference margin described herein and the link budget described in the next subsection. The *interference margin* is the maximum value by which the total noise and interference level in the cell is allowed to rise over the level of thermal noise power. The actual rise value is called the *rise-over-thermal* (ROT), with thermal noise power is used as the reference.

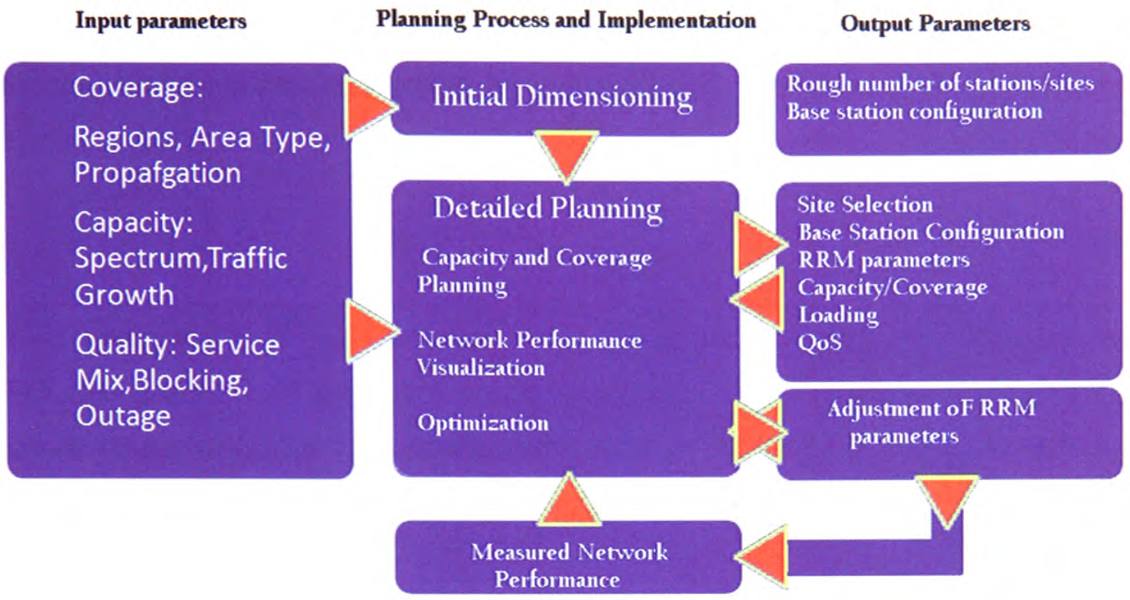

Figure 7: Radio network planning process (Chapter 8 in [41]).

The interference margin is accounted for in link budget calculations when determining the maximum cell coverage. An increase of noise rise above the planned interference margin means that some users will be in coverage outage. The ROT is therefore used as a measure of cell loading. Uplink cell loading η_{UL} is related to ROT as*

$$ROT = \frac{I_t}{N_t} = \frac{1}{1-\eta_{UL}} \tag{3.6}$$

For N users in the cell with the k^{th} user running at a rate R_k, with activity υ_k, and a minimum acceptable QoS ratio of $(E_b/N_o)_k$, the *load factor* on the uplink [61] η_{UL} is given by

$$\eta_{UL} = (1+f).\sum_{k=1}^{N} \frac{1}{1+\dfrac{W}{\upsilon_k.R_k.\left(E_b/N_o\right)_k}}. \tag{3.7}$$

The relation takes into account the loading from neighbouring cells through the interference ratio f. Having a 100% loading in the cell means the interference level has become infinite and the number of users in the cell has reached its pole capacity. The pole

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* The relation is usually given in dBs as: $ROT\,(dB) = -10\log(1-\eta_{UL})$.

capacity, N_{pole}, for the cell when all users are of service type q, requesting a rate R_q, with activity υ_q, and a minimum acceptable QoS ratio of $(E_b/N_o)_q$, is given by (Equation 3.5 in [22])

$$N_{pole_q} = \frac{1}{1+f} \frac{W}{R_q \upsilon_q \left({}^{E_b}\!/_{N_o} \right)_q} \tag{3.8}$$

Similar treatment can be given to the downlink. However, since this study focuses on the uplink, the downlink relations will not be given herein. The derivation of the above relations for the uplink and the corresponding relations for the downlink can be found in [48] [72].

3.6.2 Link Budget

The objective of the link budget analysis in any communication system is to determine the maximum path loss and the corresponding distance that the UE can be at away from the base station and still maintain a target quality for a given UE maximum transmission power*. This typically depends on many factors, amongst these are: the gains of the antennas of both of the UE and the base station, the noise figures, the penetration and cable losses and the required signal to noise ratio.

However, for UMTS, the link budget has one extra requirement; it must also include the noise rise due to captured subscribers. The value of the noise rise is not always equal to the noise rise calculated from the loading equation, and this necessitate that the UL analysis be done in an iterative way that continues as we tune between the capacity and coverage analyses [25].

A detailed description of link budget analysis and tables for such losses and gains can be found in [48] [72].

3.7 Non Traditional Methods of Increasing Capacity in WCDMA

The direct approach to increase capacity is to increase the bandwidth by using more than one carrier in the network. This is usually done to serve the high capacity needs of spots like airports and bus stations by forming micro and pico cells that use additional carriers,

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* The maximum transmission power is standardized by 3GPP according to the UE class, typically 125mW for voice and 250 mW for data [42].

but the idea can be applied in general to increase capacity. This is an effective approach as doubling the carriers more than doubles the capacity due to trunking gain. However, the bandwidth is the most valuable resource and it is usually much more economical to gain capacity by increasing the efficiency of using this resource.

Another traditional approach that is used with all mobile wireless generations is the partitioning of cells into smaller cells to achieve a power of two capacity-multiplications. This is an efficient technique as well; however, the increased cost precludes the extensive use of this technique [73].

Most of the traditional and non-traditional techniques to improve the bandwidth utilization rely on interference mitigation and/or link improvement. Therefore, cell partitioning, sectorization and diversity antennas are amongst the traditional techniques (described earlier in this chapter). Multi-user detection and the use of smart antennas are amongst the non-traditional techniques. Link improvement is in the core of the recent enhancements to WCDMA, namely, HSDPA for the downlink and HSUPA for the uplink.

3.7.1 Multi-User Detection (MUD)

This technique is one of the most promising interference reduction methods [74]. Multi user detection assumes the knowledge of all users' signatures and estimates of all users' channel impulse responses in order to improve the detection of each individual user. The employment of this algorithm is more feasible for the uplink because all mobiles transmit to the base station and the base station has to detect all the users' signals anyway [75]. The functional diagram of a receiver based on joint detection is shown in Figure 8.

The major drawback of joint detection lies in the receivers' greater complexity. This complexity increases exponentially with the increase in the number of users to be demodulated simultaneously. This subject is the area of a wide research to arrive at suboptimum receivers of reasonable complexity. A comprehensive analysis of MUD receiver's architecture is given in [10].

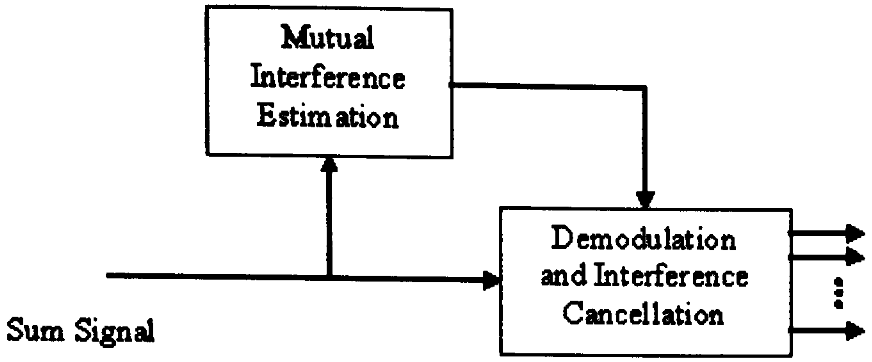

Figure 8: Block diagram for interference and joint detection receiver [74]..

3.7.2 Recent Enhancements to UMTS

WCDMA is widely open for enhancements that will keep it a technology for the future [15]. Two major enhancements to UMTS have been recently put into implementation. The first is a downlink enhancement called the High Speed Downlink Packet Access, (HSDPA) in 2005, while the second, an uplink enhancement, is the High Speed Uplink Packet Access (HSUPA) in 2006. They are, respectively, Release 5 and Release 6 within the 3GPP specifications.

The combined HSDPA/HSUPA is usually referred to as HSPA. HSPA is expected to be the mainstream technology for mobile broadband in the near future especially with the rising growth in packet data traffic compared to voice traffic [76].

In both HSUPA and HSDPA, new transport channels are introduced. These channels aim to enhance the link throughput as well as the total cell capacity. In both techniques, the link throughput is enhanced based on the following principles

i. Moving some of the RRM functionalities from the RNC to Node B. This means that the user data rate can be adjusted to match the instantaneous radio channel conditions due to the reduced delays. Which in turn made possible to reduce the TTI to 2 ms and at the same time enabled the introduction of a set of link enhancements techniques whereby applying them results in an overall reduction of the burden on the network's overall capacity of running the link at high rates.

ii. The enhancement shall be given to the users who are in favourable positions to communicate at high speeds. Though scheduling techniques to provide fair treatment, while at the same time trying to provide overall throughput are the subject of a wide research, e.g. on the downlink [77]. [78]. and [79]. [80]. on the uplink.

iii. The increased link rates can be implemented using higher spreading and/or the use of multi-code per user/service, which is a feature available to normal UMTS as well, but was not utilized.

A number of changes and alterations to the mechanisms related to the enhanced channels have to be done in UMTS. Some of the enhancements that were applied at first to the premier downlink channel of HSDPA (2005) are repeated for HSUPA (2006) with a number of some other differences.

HSPA is progressively adopted by mobile operators with an expected fast growth in the number of subscribers [76]. Amongst the basis for the expected fast growth is that HSPA will form the most cost effective way to provide high-speed mobile broadband access to both rural communities and the developing world. HSPA shall incite new services utilizing the enhanced broadband coverage, mobility and availability in work, health, environment, etc. As the analysis in this thesis focuses on the uplink, description that is more detailed will be given to the second enhancement, HSUPA, while HSDPA will be briefly described first.

3.7.2.1 HSDPA

HSDPA aims at higher downlink user's peak data rates of the order of 10 Mbps together with higher quality of service and improved spectral efficiency. Compared to the Release 99 architecture, HSDPA introduces a High Speed DSCH (HS-DSCH) that can be given to one user (at high rate) or shared between multiple users. To enable this, the following enhancements to the link were adopted:

- A short 2-ms TTI,
- The use of Adaptive Modulation and Coding (AMC), whereby adaptation is based on channel conditions that are measured and reported frequently by the UE to Node B through the *Channel Quality Indicator* (CQI) [81].
- Multi-code transmission,
- Fast physical layer (L1) hybrid ARQ (HARQ),

- The packet scheduler is moved from the radio network controller (RNC) to the Node-B where it has an easy access to air interface measurements. This facilitates advanced packet scheduling techniques, meaning that the user data rate can be adjusted to match the instantaneous radio channel conditions.

3.7.2.2 HSUPA

The preparations by 3GPP for the standardization of an uplink enhanced dedicated channel of HSUPA started as early as 2003 [82]. In HSUPA, an enhanced uplink dedicated channel called the Enhanced DCH (E-DCH) is standardized [83] to carry packet data at rates up to 5.76 Mbps (in theory) with practical rates in the order of 1.3 Mbps. The enhanced channel enhances speeds in a similar way to the downlink enhancement of Release 5. It flexibly enables simultaneous voice and data connections.

The main enhancement to UMTS lies in the addition of RRM functionality to Node-B that performs fast scheduling, power control and ARQ. The transmission time interval in HSUPA is reduced to 2ms like in HSDPA but the normal 10ms TTI of UMTS is kept as well to account for long delays in processing requests from users close to cell edge. In HSUPA, power control is retained (in contrary to HSDPA), but it is now faster because the mechanism of power control is moved to Node B. Having power control enforced on the new channel does not necessitate to adaptively controlling the channel (the use of AMC) like in HSDPA. The E-DCH can be in soft handover like normal DCH.

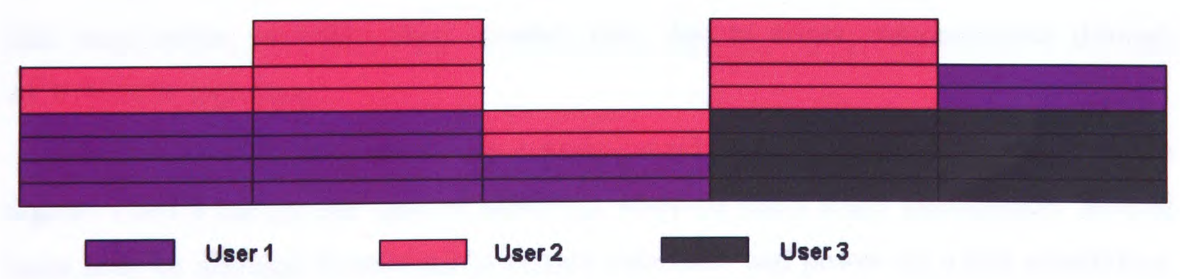

Figure 9: Several UE transmitts simultaneously in HSUPA.

The HSUPA imposed a number of additions/ changes to the network structure and channel structure in UMTS described previously in this chapter. Network structure changes are mainly software and hardware changes in Node B to encompass a new RRM functionality that handles the E-DCH fast scheduling, ARQ and other procedures for the enhanced channel. Similar to the normal dedicated channels in UMTS, DCH, which are mapped onto the physical channels, DPCH, the E-DCH transport channel is mapped onto the newly introduced uplink E-DCH Dedicated Physical Data Channel (E-DPDCH), and will require a control channel of its own, the E-DCH Dedicated Physical Control Channel (E-DPCCH).

Table 1: Data Rates with code combination.

Number of Codes	Data Rates (Kbps)
One Code with SF 4	960
Two Codes with SF 4	1920
Two Code with SF 2	3840
Two Code with SF 4 and Two Code with SF 2	5760

In HSUPA the UE sends a Transmission Request to the Node B requesting resources. Node B responds to the UE with a Grant Assignment, allocating uplink band to the UE (rates and timing). The UE transmits data using an appropriate transport format based on the grant allocation and its own favourites. The rates that the user may vary from one TTI to another TTI as illustrated in Figure 9. Variable rates are obtained using variable spreading factor and code combination for higher data rates. Retransmission of the same data may occur, probably using another rate, due to errors communicated through ACK/NACK signalling.

In effect, HSUPA is a set of high-speed channels that are received at Node B like in normal UMTS (unlike the case of HSDPA). Multiple users share interference. Several users may be allowed to transmit at certain data rates and power on a fast scheduling. The fast scheduling operation in HSUPA addresses the trade-off between several users wanting to transmit at high data rate all the time and the need to satisfy all requested grants while maximizing resource utilization and preventing overloading.

3.7.3 The Use of Smart Antennas

The use of smart antennas is another revolutionary technique to increase capacity. It will not be described here as Chapter 5 is devoted to them.

3.8 Summary

Soft capacity concept is a key attribute of WCDMA allowing for capacity sharing between cells, users and services. Both the uplink and the downlink have soft limits on their capacity. The uplink is limited by the accumulated interference from other users in the cell and in other cells and by the maximum power of the user equipment. The downlink is limited by the base station's power and the interference from other base stations and other users in the cell. Additionaly, the downlink can be hard limited due to code shortage.

Capacity provisioning in WCDMA is influenced by factors related to the signal and its processing like the activity, signal rate and its spreading, orthogonality and spreading codes design. In addition, capacity provisioning is affected by the usually non-controllable link conditions like the thermal noise level, path loss, slow fading (shadow fading), multipath fading and multiple access interference. Other factors (controllable) are related to transceiver and antenna architecture like the use of the RAKE receiver and adaptive multi-rate codecs, the use of sectored and diversity antennas, code allocation and signalling strategies.

Capacity optimization requires the effective use of a proper radio resource management tools like the call admission, handover control, packet scheduling, and load congestion. In the uplink, noise rise level (over the thermal noise reference) is used as a measure of cell loading. A 100% cell loading corresponds to infinite noise rise. Link budget in UMTS differs from link budget in other communication systems by the consideration of the rise over thermal limit.

Multi-user detection, MUD, is a special receiver design in which an attempt to cancel the interference based on the knowledge of the codes of other users. It is usually a complex technique to enhance capacity.

Two major enhancements to UMTS have recently been put into implementation. The first is a downlink enhancement called the High Speed Downlink Packet Access, HSDPA (2005) aiming at data rates of the order of 10Mbps, while the second, an uplink enhancement, is the High Speed Uplink Packet Access, HSUPA (2006) aiming at data rates of the order of 6 Mbps. They are, respectively, Release 5 and Release 6 within the 3GPP specifications. In both techniques, the link throughput is enhanced based on reducing delays in response to channel fluctuations by moving basic RRM functionalities down from the RNC to Node B, reducing the transmission time interval, and the introduction of a set of high-speed link enhancements techniques.

Chapter 4 User Capacity Analysis and Modelling in WCDMA

4.1 Introduction

Planning in third generation mobile communications systems like the WCDMA is about three interrelated variables; namely, capacity, coverage and QoS. This is unlike heritage first and second-generation mobile communications systems in which planning is about coverage planning only. The planning for capacity and coverage as well as resource managements in WCDMA has mainly been dependent on interference loading analysis; e.g. [48] [72], whereas the actual interrelationships between the rates of the different services and capacities remain obscure. For example, a network with two main services can have a 60% loading regardless of whether these were of one service or of the other or any combination of them. Additionally, the 100% of one service has not the same throughput as the 100% of the other service because of the different parameters (different E_b/N_o and different activities). This gives rise to more losses, which necessitate that the higher rate service to contend with a less throughput (a cell that can accept 200 from 15Kbps service alone has to accept less than 100 from a 30 Kbps service).

In this chapter, a revisit to the basic equation for interference analysis in WCDMA reveals that it is possible to interrelate capacities for the different service classes and their coverage radii thereby providing a basis for efficient capacity sharing problem in WCDMA.

The results of the analysis in this chapter show that uplink cell capacity in terms of the number of users of any single service class can be partitioned, in theory, into three parts. The first is the upper interference limit, which represents the upper capacity bound for this service that is independent from distance and propagation conditions. The second one, which is distance/propagation dependent, is the reduction in the number of connections of this service due to limited uplink power of the mobile units. The combination of the first two parts represents the capacity of the service, *class capacity*, when no users of other services exist. The third and final part is the reduction in the number of users of this service due to the existence of other users of other services. The net capacity is obtained by subtracting the reductions, both the second and third parts from the upper interference limit, i.e. the first part.

Similarly, coverage analysis is also partitioned into three parts. The first part, called the intrinsic coverage, represents the maximum coverage for a single user in the network that is only limited by thermal noise and the propagation conditions. The second part accounts for the shrinkage in coverage due to the presence of other users of the service. Similarly, the combination of the first two parts represents the coverage of the service, *class coverage*, when no users of other services exist. The third and final part accounts for further shrinkage in coverage due to the presence of users of other service classes. The net coverage is also obtained by a simple combination of the three parts.

The chapter starts with some assumptions about the network and the system followed by the capacity analysis and the coverage analysis. Based on the formulae obtained capacity / coverage interaction is analysed together with examples. Capacity with flexible data rates is also exploited in light of the model given. In addition, the model is later related to ATM models of statistical multiplexing and therefore a dimensioning approach for traffic capacity using the model is introduced. A number of practical issues related to the model and how it can be modified to include other parameters is included. Comparing the model and its use in dimensioning with others in research is also given.

4.2 Analysis Assumptions

The system considered will be assumed to be of the simple WCDMA type. Antennas at both ends are assumed to be of an omnidirectional antenna at both ends and no recourse to MUD, diversity and sectorization antennas, beamforming and smart antennas and other techniques is assumed. A brief discussion will be given later in this chapter on how some of these parameters can be included in the model obtained for capacity and coverage in the pursue analysis, while beamforming antennas are treated later in coming chapters.

Additionally, let us assume that there are one or more *service classes* of users in the cell whereby users of the same service class are basically requiring the same data rate, the same QoS (expressed by their E_b/N_o requirement) and of the same activity. Let also the number of active connections in the cell of any service class q be N_q connections. The ***user capacity*** shall be the maximum number of connections of any one class that can be safely accepted in the cell concurrently without jeopardizing the QoS and coverage requirements of the service class given or of any other class. This means that the ***user capacity*** when more than one class is involved will be the set of all points in a Q dimension space (Q being the number of classes) on the edge of operation (beyond which no guarantee for QoS or coverage radii). The *user capacity* will be referred to occasionally in this thesis as the *active-user capacity* to differentiate it from the traffic (Erlang) capacity, which stands for the average number of users (active or non-active) that can be served with a certain blocking rate while requesting the service with a certain traffic per user [60]. Additionaly, the active user is the one connected (a call or a long stream of data) though their might be discontinuities in the call/ stream of data due to the activity pattern of the kind of signal communicated. The discontinuities are accounted for using the activity factor described in the previous function. Therefore, the active-user capacity is call level (connected calls or sessions) capacity.

Furthermore, the users are assumed to be uniformly distributed in the cell. Also, a constant value will be assumed for the *interference ratio, f,* of the total other interference coming from surrounding cells, I_{ot}, to the same beam interference, I_{sc}, expressed as $f = I_{ot} / I_{sc}$ (Section 3.4.2.5 discusses this ratio in detail). Thereafter, the total interference, I_t, seen by any user, including thermal noise power, N_t, can be written as

$$I_t = N_t + (1+f)I_{sc} \tag{4.1}$$

It is also assumed that accurate power control is enforced. Hence, the power received from any user at the front end of the receiver in the base station is controlled to a value P_r required for satisfying a minimum signal quality level. This minimum quality level is expressed as the Signal to Interference ratio (SIR) before dispreading, or E_b/N_o (bit-energy to noise density) ratio after dispreading*. SIR is the ratio between the re-

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* Alternatively, terms of SINR (Signal to Interference and Noise ratio) and E_b/I_t (Energy per bit to total interference density) are recently replacing these terms to imply the inclusion of interference other than thermal noise. However, the traditional terms will be kept throughout this study.

ceived signal strength of the connection from mobile to the base station and the sum of all signals received at the base station and thermal noise.

The SIR target for a radio link depends on three factors. If R is the data rate of the carried service, W is the UMTS specific chip rate of 3.84Mcps, and E_b/N_o is the required ratio between signal bit energy and interference spectral density (including noise spectral density), then

$$\frac{S}{I}=\frac{R}{W}\frac{E_b}{N_0}. \tag{4.2}$$

The E_b/N_o ratio is a figure of merit for the digital demodulator, its value depends on the implementation (quality of the receiver), error correcting codes used, channel impairment such as multipath fading, and, of course, the error rate requirements [38] [12]. In CDMA, the sum of the interference from other users and along multiple propagation paths can be approximated as being additive Gaussian noise therefore a monotonic relationship can be found between the Bit Error Rate (BER) and E_b/N_o. Values of E_b/N_o are typically obtained from the results of radio link simulations, e.g. Table 2.9 in [84] and Table 2.3 in [22].

If the case of non-perfect power control is to be taken into account, a modifying factor Γ, Γ is independent of service class [58], can be used where Γ is a function of the given outage probability and standard deviation of shadow fading as given by (3.5) in the previous chapter (Section 3.4.2.3). Section 4.7.1 in this chapter shows how this parameter can be included in the resulting equations. Service activity of a service is also considered using its activity factor υ.

As detailed in the previous chapter, the propagation phenomena models may be subdivided, based on the rate of variation with respect to the wavelength, into: path loss that are related to variations over large distances, medium scale models, or the shadow fading models, and the sub wavelength models or the small scale fading resulting from multipath. In capacity analysis, multipath fading models are not usually modelled. In general, the use of techniques such as interleaving, diversity reception and the use of the RAKE receiver, greatly mitigate multipath fading. At any rate, it is reasonable to assume that the effects of the multipath fading are encapsulated in the requirements of the system [52]. Thereafter what remains after excluding multipath fading are the distance-driven path loss models and the shadow fading.

4.3 Capacity Analysis

Analysis is done using two service classes at first, then, a generalization to the Q service case will be made. Let P_1 and P_2 be the received signal strengths for service class 1 and 2 at the threshold of satisfying a certain QoS (certain energy per bit to noise power spectral density, E_b / N_0) for each class (scaled by Γ). Using (4.1) to obtain the total interference and noise power received at Node B. Plugging the power and interference values in (4.2) for a user of service class 1, while remembering to subtract the interference contribution from the user itself given by υP_1 , the following equality holds:

$$\Gamma\left(\frac{E_b}{N_0}\right)_1 = \frac{W}{R_1} \frac{P_1}{N_t + (1+f)I_{sc} - \upsilon_1 P_1}. \tag{4.3}$$

where

W: is the Chip Rate for WCDMA (3.84 Mcps),

R_1: is the bearer data rate for service class 1,

P_1: is the required received power in order to satisfy the QoS requirement defined by this equation,

N_t : is the thermal noise power,

f: is the ratio of interference from other cells to the interference in the same cell (I_{sc}),

υ_1: is the activity factor for service 1, and

Γ: is a modifying factor to E_b/N_0 ratio to account for inaccurate power control.

Power control errors and shadowing effect will not be considered at this stage. Therefore, instead of E_b/N_o ratio, a modified ratio, γ_1, will be used; i.e. $\gamma_1 = \Gamma.(E_b/N_o)_1$.

$$\gamma_1 = \frac{W}{R_1} \frac{P_1}{N_t + (1+f)I_{sc} - \upsilon_1 P_1}. \tag{4.4}$$

The equality in the previous two equations is the result of power control mechanism on the uplink, which necessitate that any user transmit just enough power to satisfy the link quality requirement as described when power control was discussed in Section 2.5.

For the case of two services only, with N_1 and N_2 connections, the same cell interference, I_{sc}, can be computed as:

$$I_{sc} = \upsilon_1 P_1 N_1 + \upsilon_2 P_2 N_2 . \tag{4.5}$$

In the previous equation, it was assumed that the average number of users of any of the two services that are simultaneously on with average activities υ_1 and υ_2 would be on the average reduced by the same percentage. In other words, voice activity effect enters the formulation (for interference) in a simple multiplicative manner, giving rise to a loading effect of $\upsilon_1 N_1$ and $\upsilon_2 N_2$ of the two services respectively. This has been discussed in Section 3.4.1.1 of the previous chapter.

Using (4.4) and (4.5) we may find the maximum number of users of service 1, N_1, given N_2, beyond which QoS is not satisfied as

$$N_{\max_1} = \frac{WF}{\upsilon_1 R_1 \gamma_1} + F - \frac{N_t F}{\upsilon_1 P_1} - \frac{\upsilon_2 P_2}{\upsilon_1 P_1} N_2, \text{ where } F = \frac{1}{1+f} \quad . \tag{4.6}$$

Similarly, for service class 2 we may find the maximum number of users of this service, N_2, given N_1, to be

$$N_{\max_2} = \frac{WF}{\upsilon_2 R_2 \gamma_2} + F - \frac{N_t F}{\upsilon_2 P_2} - \frac{\upsilon_1 P_1}{\upsilon_2 P_2} N_1 . \tag{4.7}$$

Repeating for three services, both (4.6) and (4.7) will have an extra term similar to the last part of each of them but with the subscripts in the numerator replaced by 3 (i.e. the term $-(\upsilon_3 P_3 / \upsilon_1 P_1) N_3$ to (4.6) and the term $-(\upsilon_3 P_3 / \upsilon_2 P_2) N_3$ to (4.7)). Service 3 formula can be obtained similarly. Hence, in general, the maximum number of users of any service q, N_{max}, beyond which QoS is not satisfied for an arbitrary number of services, Q, can be written as the combination of three parts as

$$N_{\max_q} = N_{upper_q} - N_{power_q} - N_{others_q}, \qquad q = 1, 2, \ldots, Q \tag{4.8}$$

The first term on the right side in (4.8), N_{upper}, for any service q, represents the upper limit on number of users of the service q, with no other users of other services, limited only by interference. N_{upper} is given by

$$N_{upper_q} = \frac{WF}{\upsilon_q R_q \gamma_q} + F \tag{4.9}$$

The upper throughput of service q is therefore given by

$$T_{upper_q} = N_{upper_q} \upsilon_q R_q = \frac{W}{\upsilon_q \gamma_q} + \upsilon_q R_q F . \tag{4.10}$$

The interference limited capacity, N_{upper}, using (4.9) is a typical value usually used as a measure of capacity and called the *pole capacity* (Section 3.6.1), which is used to represent the 100% loading (Section 3.6.1) or the *soft capacity* limit [48]. However, in most of the cases, the value F given at the end of (4.9) (or $\upsilon_q R_q F$ at the end of (4.10)) is neglected [22]. The F will be removed from (4.9) if the effect of the interference increase due to the user itself is not considered from the initial derivation (the value $\upsilon_l P_l$ in the denominator in (4.4) is neglected). While this approximation is valid for low data rates voice users, the effect cannot be neglected when it comes to high rates. This was found necessary with recent re-consideration of the pole capacity in light of the new HSUPA uplink enhancement by mobile companies [23].

The limit given by (4.9) is attained assuming that there is no limit on the received power of users of this service (P_q, power received, can be infinite). As power is finite reduction in capacity occurs to service q due to power limitation on the uplink caused by path, distance and the limited power on the uplink for users of this service. It is worth to note that the value $F = 1/(1 + f)$ is the reduction in the tolerated cell interference in a multi cell network. Accordingly, the capacity is reduced by F. Hence, the second term, N_{power}, in (4.8), for service q, is the reduction in capacity due to finite received P_q power, i.e. power limitation. Examining (4.6) and (4.7) it can be found that N_{power} is given by

$$N_{power_q} = \frac{FN_t}{\upsilon_q P_q}. \tag{4.11}$$

The furthest mobile station from the base station suffers the maximum path loss and thus it determines the received power level at the base station. The furthest any mobile can reach is determined by the maximum power output P_{Smax} of the mobile. Generally, the path loss, L, between the transmitter and the receiver can be written as $L_p(d) = K_p \cdot d^{C_p}$, where d is the distance, K_p is a multiplying factor that is dependent on antenna heights, frequency and other parameters and C_p is the propagation constant of the environment (more details given in Section 3.4.2.2 and Appendix II). In addition, other parameters on the link like antennas gains, body loss, penetration losses and macro and micro diversity may be considered by inclusion in this parameter as well. Section 4.7.3 in this chapter gives more details on the inclusion of such parameters.

Thereafter, the value of N_{power} in (4.8) for maximum reduction in capacity for service q may be written in terms of the maximum power output P_{Smax} of the mobile units, maximum distance for class q, d_q, and the path loss parameters K_p and C_P. In the following equation N_{power} is written as being proportional to the maximum distance for this service (raised to the propagation constant)

$$N_{power_q} = \alpha_q d_q^{C_p} \text{ ,where } \alpha_q = K_p \frac{N_t F}{\upsilon_q P_{Smax}}. \tag{4.12}$$

The power-limited reduction given by the previous equation is usually accounted for using the link budget analysis (Section 3.6.2) which attempts to arrive at the path loss and coverage distance for the service by considering a certain finite ROT value. In this case, one user, typically the furthest, will be limiting the coverage for the service. Using this equation, however, results in value of the reduction of the maximum capacity due to having at least one user, out of all the users, at a distance d_q from the base station, thereby defining the coverage.

Define N_{class} to be the class capacity of service q when no users of other services exist. Therefore, N_{class} will be given by the combination of the first two parts in (4.8) and can be found using (4.9) and (4.11), or

$$N_{class_q} = N_{upper_q} - N_{power_q}. \tag{4.13}$$

The *class capacity* given in the previous equation defines a capacity value for a set of users of the same parameters (class) when no other users of other classes exist. Hence, it has a more practical meaning than the relatively non-practical *pole capacity*. Some researchers used this to study the coverage/capacity interaction in UMTS for a single service [85] and as a basis for admission [86].

However, when others using other services exist in the cell, there will be a class capacity for each service class that corresponds to the required cell coverage; i.e. one value of distance used in obtaining the class capacity.

Examining the last term (or terms if more than two services) in (4.6) and (4.7) reveals that they represent the extra reduction (while preserving the coverage) due to others in other services. This is the third term in (4.8), N_{others} (others to service q) representing the reduction in maximum capacity of service q due to the presence of users of other services, $\hat{q}$ ($q,\hat{q}$=1,2 ...Q, ,$\hat{q}\neq q$). Thereafter, the maximum capacity, N_{max}, given in (4.8) for any service q can be re-written as

$$N_{max_q} = N_{class_q} - N_{others_q} \tag{4.14}$$

In WCDMA powers, data rates and QoS of two different classes i and j are interrelated by $P_i/P_j=\gamma_i R_i/\gamma_j.R_j$ [87]. Thereafter, N_{others} in the general case can be written as

$$N_{others_q} = \sum_{\substack{\hat{q}=1 \\ \hat{q}\neq q}}^{Q} \alpha_{q\hat{q}} N_{\hat{q}} \quad \text{, where } \alpha_{q\hat{q}} = \frac{\upsilon_{\hat{q}} \gamma_{\hat{q}} R_{\hat{q}}}{\upsilon_q \gamma_q R_q}. \tag{4.15}$$

One interesting feature of Eq. (4.15) is that the reduction effect of one service class on any other class is propagation and power independent and only depends on the relative interference effect of the two services given by their relative rates, relative QoS requirements and relative activities.

As traffic fluctuates, a slack may result in the number of connections at any instance of time of one or more of the services. This slack may be given to any one, or more, of the services that accept flexible rating. Let ξ_q be the up-rating increase ratio for service q, the values of ξ_q of all services must satisfy the following set of inequalities

$$\xi_q \leq \frac{N_{upper_q} - \sum_{\substack{\hat{q}=1 \\ \hat{q}\neq q}}^{Q} \xi_{\hat{q}} \alpha_{q\hat{q}} N'_{\hat{q}}}{N'_q + N_{power_q}}, q = 1 \ldots Q \tag{4.16}$$

N'_q is the new number of connections of service q, and $\xi_{\hat{q}}$ be the already granted up-rating increase ratio for service $\hat{q}$, if any.

4.4 Coverage Analysis

Conversely, we may obtain the maximum coverage that is attained by the mobile unit transmitting at maximum power $P_{S\max}$ for a certain limit on capacity N_1, N_2,..., N_Q. Similar to the capacity case, we start with the two services case. Using (4.4), (4.5) and the propagation parameters K_p and C_p, the maximum coverage distances, d_{max}, for service class 1 and 2 are obtained for a given N_1 and N_2 capacity

$$d_{max_1}^{C_p} = \left(\frac{WF}{R_1\gamma_1} + \upsilon_1\right)\frac{P_{Smax}}{K_pFN_t} - \frac{\upsilon_1 P_{Smax}}{K_pFN_t}N_1 - \frac{\upsilon_2\gamma_2R_2P_{Smax}}{\gamma_1R_1K_pFN_t}N_2.$$

$$d_{max_2}^{C_p} = \left(\frac{WF}{R_2\gamma_2} + \upsilon_2\right)\frac{P_{Smax}}{K_pN_t} - \frac{\upsilon_2 P_{Smax}}{K_pFN_t}N_2 - \frac{\upsilon_1\gamma_1R_1P_{Smax}}{\gamma_2R_2K_pFN_t}N_1.$$

Extending to three or more services, we may write the maximum coverage distance, d_{max}, for any user of any service class q in multi-service environment of Q classes as

$$d_{max_q}^{C_p} = d_{intr_q}^{C_p} - d_{same_q}^{C_p} - d_{others_q}^{C_p} \quad , q = 1, \ldots, \mathrm{Q}. \tag{4.17}$$

All terms in the previous equation are raised to the power of the path loss exponent C_p. The first term on the right side in (4.17) is given by (4.18) below. Notice that d_{intr}, as given by (4.18) is only limited by thermal noise. It is therefore called the *intrinsic distance*, d_{intr}, for the service

$$d_{intr_q}^{C_p} = \left(\frac{WF}{R_q\gamma_q} + \upsilon_q\right)\frac{P_{Smax}}{K_pN_tF}. \tag{4.18}$$

The value for d_{intr} in the previous equation is the maximum any mobile station (MS) can attain if it is alone. The second term in (4.17), d_{same}, is the decrease in distance (all raised to the power of the path loss exponent C_p) for service q due to interference from users of the same service and can be written as proportional to the number of users of this service

$$d_{same_q}^{C_p} = \beta_q N_q, \text{ where } \beta_q = \frac{\upsilon_q P_{Smax}}{K_pFN_t} \tag{4.19}$$

The distance of service q if no other users of other services exist, *class coverage*, d_{class}, can be obtained using

$$d_{class_q}^{C_p} = d_{intr_q}^{C_p} - d_{same_q}^{C_p} = d_{intr_q}^{C_p} - \beta_q N_q \tag{4.20}$$

The third term on the right side in (4.17) , d_{others} is the reduction in maximum distance (again raised to C_P power) for service q due to users of other service classes, $\hat{q}$ and is given by

$$d^{C_P}_{others_q} = \sum_{\substack{\hat{q}=1 \\ \hat{q}\neq q}}^{Q} \beta_{q\hat{q}} N_{\hat{q}}, \text{ where } \beta_{q\hat{q}} = \frac{\upsilon_{\hat{q}} R_{\hat{q}} \gamma_{\hat{q}}}{R_q \gamma_q} \frac{P_{Smax}}{K_p F N_t} \tag{4.21}$$

The maximum coverage for any service q (after taking the reduction effects of other services) may be written as

$$d^{C_p}_{max_q} = d^{C_p}_{class_q} - d^{C_p}_{others_q} = d^{C_p}_{class_q} - \sum_{\substack{\hat{q}=1 \\ \hat{q}\neq q}}^{Q} \beta_{q\hat{q}} N_{\hat{q}} \tag{4.22}$$

4.5 Capacity / Coverage Interaction

Based on the previous analysis/model for capacity and coverage we may visualize the process of coverage/capacity interaction as follows:

a. Having a single user in a cell, the coverage (an intrinsic coverage) is given by (4.18). This user can therefore communicate at the intrinsic distance $d=d_{intr}$ (or $d_{same}= d_{others}= 0$), for that service class, limited only by thermal noise level and governed by the maximum power that its battery allows P_{Smax}, combined the gain of the antenna at the base station and the mobile and other parameters of the link. Of course, its coverage will depend on the data rate and the QoS requirement of the service. This is the maximum distance any user of the service can attain, in theory.

b. If others, of the same service type, are now in the cell and in other cells, F ,by definition, will be less than 1, a reduction in distance (raised to C_p power) proportional to the number of users of this service is given by (4.19).We may also write the reduction in terms of intrinsic distance, as

$$d^{C_p}_{same_q} \cong \beta'_q N_q d^{C_p}_{intr_q}, \text{ where } \beta'_q = \frac{\nu_q R_q \gamma_q}{WF}$$

c. If others, of other service types, are also in the cell and in other cells, the reduction in distance (raised to C_p power) due to a certain other service is proportional to the number of users in that service with a proportionality factor that depends on the services data rate as given in (4.21). This reduction can be re-written as well in terms of the intrinsic distance as

$$d_{others_n}^{C_p} = \sum_{\substack{\hat{q}=1 \\ \hat{q}\neq q}}^{Q} \beta'_{q\hat{q}} N_{\hat{q}} d_{intr_q}^{C_p}, \text{ where } \beta'_{q\hat{q}} = \frac{\upsilon_{\hat{q}} R_{\hat{q}} \gamma_{\hat{q}}}{WF}$$

Thus, d_{max} for service q can be approximated as:

$$d_{\max_q}^{C_p} \cong (1 - \beta'_q N_q - \sum_{\substack{\hat{q}=1 \\ \hat{q}\neq q}}^{Q} \beta'_{q\hat{q}} N_{\hat{q}}) d_{intr_q}^{C_p}$$

However, when $\hat{q} = q$, $\beta'_{q\hat{q}}$ converges to $\beta'_{\hat{q}}$, and thus we may write the last equation as

$$d_{\max_q}^{C_p} \cong (1 - \sum_{\hat{q}=1}^{Q} \beta'_{q\hat{q}} N_{\hat{q}}) d_{intr_q}^{C_p} \qquad (4.23)$$

d. Having more and more users of any service in the cell, more and more shrinkage in coverage occurs for the coverage of this service. In the limit as the number approaches the upper interference limit N_{upper} (4.9) the coverage approaches 0.

e. Of course, the capacity in the previous clause is for (theoretically) zero coverage (or for users who do not have a limit on their power output). Designing for a certain coverage r, which is the typical situation (together with limited power output of the mobile unit $P_{S\max}$) the capacity will be reduced by an amount N_{power} given by (4.12) proportional to the coverage radius r (raised to C_p power). Also, the following approximation applies to N_{power}:

$$N_{power_q} \cong \alpha'_q r_q^{C_p} N_{upper_q}, \text{ where } \alpha'_q = \frac{K_p R_q \gamma_q N_t}{W P_{S\max}}$$

The value N_{class} given in (4.13) can be re-written as

$$N_{class_q} = (1 - \alpha_q r_q^{C_p}) N_{upper_q}$$

f. The effect of other users of other services on the capacity of any service q is given by (4.15). Note that the effect of any other service, $\hat{q}$, depends on the number of users of that service, $N_{\hat{q}}$, the relative weights of voice activity factors $\nu_{\hat{q}}/\nu_q$, and the relative weights of the data rates $R_{\hat{q}} / R_q$.

4.6 Discussion / Numerical Examples

In the cell planning, it is usually requested that all services have the same maximum coverage distance; i.e. cell radius. Therefore, the cell radius will be used for the distance in the capacity equations. Let the environment be a suburban environment with path loss model given by the COST 231-Hata model (Appendix II), the path loss L_p in dB is given by

$$L_p = 46.3 + 33.9\log f_c - 13.82\log h_b - a(h_m) + (44.9 - 6.55\log h_b)\log d,$$

where $a(h_m) = (1.1\cdot\log f_c - 0.7)h_m$-$(1.56\cdot\log f_c - 0.8)$, h_b is the height of the base station, h_m the height of the mobile station, f_c is the frequency in MHz and d is the distance in Km. Let h_b=60m (typical for macro cells), h_m=1.5m (typical height of a mobile handset), f_c=2000MHz. Computing the path loss parameters using the previous equation gives: K_p=133.5dB and C_p=3.33. Also let f=0.55 (Section 3.4.2.5), hence F will be 0.645 (by computation), N_f=-102.7dBm (Section 3.4.2.1) and W=3.84Mcps. Assume that we have 2 services with rate, activity and E_b/N_o parameters of (15Kbps, 0.67, 3dB) and (30Kbps, 1, 3dB) assumed respectively. Assume also that a coverage radius of 1.5 Km is required and the maximum transmitted power shall not exceed P_{Smax}=250mW (Class II UE). Using these in the capacity equations given in this chapter results in that the values of N_{upper}, N_{power}, and N_{class} are 123.2, 18.2, 105.0 for service 1 and 41.3, 12.2 and 29.1 for service 2 respectively. In addition, the coefficients, α_{12} and α_{21} are 3.0 and 0.33 respectively. Thus, capacity equations can be written as

$$N_{\max_1} = 105.0 - 3.0 * N_2 \tag{4.24}$$

$$N_{\max_2} = 29.1 - 0.33 * N_1 \tag{4.25}$$

Figure 10 shows the admissible region formed by the two bounding lines (solid lines) given by (4.24) and (4.25). It is clear that the admissible region is limited by the inner region bounded by the line for N_2, Equation (4.25). Of course, the boundaries must be a staircase and not a solid continues line, however, they are drawn as solid lines for simplicity.

Assume that both services accept multi-rates or non-real time traffic and can accept their bandwidth to be increased. Then any slack in the operating point that may occur due to traffic fluctuations can be utilized to the advantage of the service itself, or the other one, as given by (4.16). Assuming a hard limit on the number of connections is applied and operating point (39,16) on the boundary line is selected. Using Erlang-B (lossy) formula (for indication purposes only) a traffic of (31.5, 10.5) Erlang may be served at a 3% blocking rate for both services. This results in an average slack of (7.5, 5.5). We may calculate (a combined) cell loading as the ratio of the total cell throughput as 31.5*15+10.5*30=787.5 Kbps to the boundary operating point throughput of 39x15+16x30=1065 Kbps, or 74%.

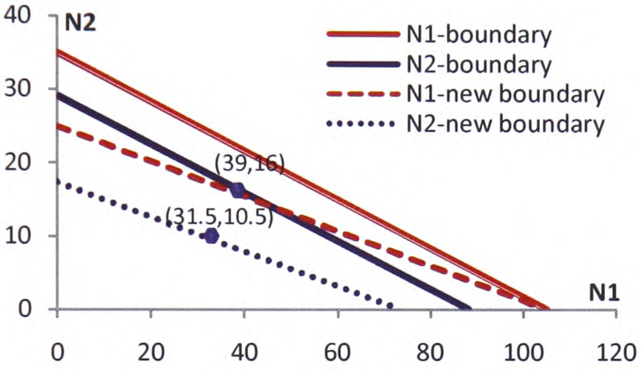

Figure 10: Boundaries for capacity.

This slack when granted to the service that is non-limiting to the operating point, service 1, results in possible rate increase factor ξ_1=1.8 and overall throughput increase by 8%. However, when granted to service 2, the limiting service, it results in possible rate increase factor ξ_2=1.8 and an overall throughput decrease by 16%. The new boundaries after the last case are shown (dotted lines) in Figure 10. This technique can be used when managing voice data with AMR used (Section 3.4.3.1) when mixed with other service of higher data rate.

4.7 Issues Related to Practical Systems

The model adopted (formulae for capacity and coverage) was simplified by assuming deterministic channel model (accurate power control assumed), overlooking other channel gains and losses (for simplicity of analysis), assuming all users are connected to one base station, and no recursion to complex techniques like the MUD ...etc. These factors are discussed below to show how the model may be altered to reflect these parameters.

4.7.1 Including Shadow Fading

In the previous analysis, the shadow fading was assumed to be included in the modified E_b/N_0 that is increased to by a factor Γ, called the *outage factor*, to account for shadowing loss (Section 3.4.2.3). With shadowing loss being class independent, we see that its effect will reflect in the model, for capacity, by a decrease in the upper capacity N_{upper}, see (4.9), and for coverage by a decrease in the intrinsic coverage, d_{intr}, see (4.18), by a factor of approximately $1/\Gamma$, giving

$$N_{upper_q} = \frac{WF}{\upsilon_q R_q \Gamma \gamma_q} + F$$

$$d_{intr_q}^{c_p} = \left(\frac{W}{R_q \Gamma \gamma_q} + \upsilon_q \right) \frac{P_{smax}}{K_p N_t}$$

Correspondingly, class capacity N_{class} and class coverage d_{class} will decrease by the same amount in N_{intr} and N_{upper}. The boundaries resulting from the modified boundary will give a tighter admissible area. In the two classes' bounding model given by the example in Section 4.6 the new boundary is a line that is parallel to the original boundary line given for the initial E_b/N_0 value (the slope is defined by the mutual parameters, $\alpha_{q\hat{q}}$, that are not altered by shadowing).

However, different service classes might differ in their tolerance to errors that may result from, say, being in outage. As an example, voice class connections require a guaranteed data rate but they may tolerate large error percentages while a tighter limit must be imposed on outage percentage for data class connections requesting a low error percentage. The result of this differentiated treatment is that the factor Γ for one class will be different to that for the other class. Therefore, in addition to class capacity (and coverage) being modified as explained above, the mutual effect of one connection of one class on any other class will be also modified by a factor proportional to their relative outage factors, Γ_1 / Γ_2, i.e. the factor $\alpha_{q\hat{q}}$ in (4.15) for capacity and the factor $\beta_{q\hat{q}}$ in (4.21) will become

$$\alpha_{q\hat{q}} = \frac{v_{\hat{q}} \gamma_{\hat{q}} \Gamma_{\hat{q}} R_{\hat{q}}}{v_q \gamma_q \Gamma R_q}$$

$$\beta_{q\hat{q}} = \frac{v_{\hat{q}} R_{\hat{q}} \Gamma_{\hat{q}} \gamma_{\hat{q}}}{R_q \Gamma \gamma_q} \frac{P_{s\max}}{K_p F N_t}.$$

4.7.2 Including Mobility

Mobility is included in the model using the selected E_b/N_o value. At higher speeds the fast power control inner loop (Section 2.5 describes power control loops in UMTS) cannot cope with the fast variation in the channel resulting in higher error rates. To maintain the same BLER at the receiver, the outer power control loop will compensate the power control imperfection by maintaining a higher target E_b/N_o [72]. Tables that give the target E_b/N_o ratio at different speeds are available. Table 2 shows typical values for the uplink 64Kbps data.

Table 2: Uplink E_b/N_o targets at various speeds

for1 % BLER target and 64Kbps data (Source: Table 4.3 in [72]).

UE Speed (Km/h)	Target E_b/N_o uplink (dB)	
	Average	Standard Deviation
3	3.75	1.0
20	3.75	1.1
50	3.7	1.46
120	4.1	1.86

In the analysis, the maximum E_b/N_o target value can be used. Of course, this may result in under dimensioning, as not all users are moving at high speeds. A more contemplating approach is to have more granularity in the definition of the service class by having the same service with different speeds expected to be subdivided into more than one (speed) class, e.g. pedestrians and low speeds, medium speeds and high speeds, each having a corresponding E_b/N_o. Hence planning for the number of high-speed users (and their coverage radii) can be accomplished accordingly using the model given herein.

Handover is the result of mobility. Calls in soft handover enjoy an extra diversity gain due to soft handover. Therefore, users of the same service that are in soft handover can be put in a class of their own with a less QoS (smaller E_b/N_o) requirement due to macro-diversity.

4.7.3 Including of other Link Gains and Losses

It is clearly seen that not all parameters mentioned in Section 3.4, like diversity gain, antennas gains, penetration losses, etc, are considered in the model so far. However, as these parameters apply to all service classes with equal effect, they may be ignored to simplify utilization of the model in designing and optimizing resource management strategies, for example, the admission strategies. Nevertheless, the inclusion of these can simply be done by modifying the propagation-multiplying factor K_p by their values (simple multiplication or addition when Decibel values, dBs, are used). In the forthcoming chapters these factors will be assumed normalized to 1.

Exception to this is the case of Switched Beam Smart Antenna that is considered in Chapter 6. Another similar exception is the case of the use of sectorization (Section 3.4.3.2). Usually, a parameter called sectorization gain, ς, is used [61] to reflect the decrease in capacity due to reduced interference. Example, a three sector base station will have $\varsigma = 2.4$ [12] (2.55 used in [22]). This factor may enter in the previous model for the upper capacity using an interference ratio of value $\varsigma.f$ in the same way it is used to affect the loading equations [61]. However, the antenna has other parameters like its gain and side lobe levels that will affect the capacity coverage interaction, which is considered in the model given in this chapter. As the sectors' antennas resemble from interference point of view the Switched Beam smart Antenna analyzed in Chapter 6 then the same treatment may be applied to sectored antenna as well.

4.7.4 Including of Multi-User Detection Effect in the Model

As previously described in 3.7.1, MUD is suggested as a technique to reduce interference especially at the uplink and thus further enhance capacity. Ideally, MUD can be used, in theory, to eliminate (totally) the interference from sources within the same cell, I_{sc}. Of course, practical suboptimum techniques were suggested, though still remain complex enough for the actual implementation. Nevertheless, for any given MUD technique, a parameter ψ that characterizes its suppression capability [50] can be assigned to it. Therefore, the total interference I_t seen by any user given by (4.1) can be rewritten as $I_t = N_t + (1-\psi+f)I_{sc}$. Of course, this will alter all the subsequent capacity and coverage relations in a similar way to the effect of the variation of the intercellular interference ratio f, i.e. f shall be replaced by f-ψ. MUD will not be considered any more in the analysis as it is out of the scope of this study.

4.7.5 Including Signalling and Control Channels

Traditionally, a fixed assignment of power (DL) or noise contribution (UL) is used to account for their presence as mentioned in Section 3.4.3.3 earlier in this chapter. To include them in the model herein, the same approach may be applied; i.e. the class capacity can be reduced by a fixed amount to account for their presence as a lump sum. However, another approach may lead to a better evaluation of their influence especially for real time resource management technique.

Every user on the uplink, as explained when discussing the channel architecture in UMTS in Section 2.4, will have at least one traffic channel, DPDCH, and one control channel, DPCCH, operating at a high spreading (low rate). These channels are separated on the uplink using orthogonal spreading codes. For simplicity purposes, it can be assumed that complete orthogonality between the traffic channel and the control channel of the same user is kept. Then the control channels may be treated as a class by itself having its own rate and activity. They cannot be a limiting class in any case as their number cannot be greater than the user traffic channels* and they run at low rates. Other signalling and common channels may be treated similarly†.

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* Assuming orthogonality kept then their number will be 1 less than the corresponding users (for the case of 1 traffic channel per user).

† except for those signaling that are not power limited.

4.8 Dimensioning

4.8.1 Erlang Formula

In an environment whereby each service q is served using a number of servers N_q The blocking rate Bk_q for any service class q, $q=1...Q$, with its users offering a lossy traffic of A_q Erlang, is calculated using Erlang B formula

$$Bk_q = \frac{A_q^{N_q}}{N_q! \sum_{n=0}^{N_q} \frac{A_q^n}{n!}}. \tag{4.26}$$

Erlang formula was used for a long time for the dimensioning of fixed telephone networks and served as well for the dimensioning of mobile communications systems of 1G and 2G systems that are characterized by a hard limit on their system capacities, e.g. frequencies in analogue 1G systems and frequencies and time slots in GSM. For systems that blocked calls may wait, the measure of grade of service shall be the probability that the call is blocked and the delay is more than a certain maximum. In this case, another formula called Erlang C formula is used. Any reference on traffic engineering discusses these formulae.

However, for systems with soft capacity that are characterized by sharing the capacity between different services modified approaches has to be adopted*. Some of them (will be discussed later) are based on relating the soft capacity in WCDMA somehow to the ATM statistical multiplexing results.

Similarly, in this thesis, the model given can utilize these ATM results. It has a number of advantages over the other approaches, which will be discussed later. In the next subsection a quick review of some of the results from ATM research will be given. The established relationship of these results with the model in this study will be described later with examples.

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* Erlang Formula is still useful in UMTS for the code dimensioning (channels), the dimensioning of resources at the MSC and RNC and interfaces [22].

4.8.2 Dimensioning in ATM

The information in this section is mainly from [49] [88]. Consider a system (or a link) with capacity of $\hat{C}$ Mbps shared among Q different services as depicted in Figure 11. The basic unit for capacity, $\Delta\hat{C}$, is taken as the greatest common divisor of the different rates requirements, i.e. $\Delta\hat{C}=\mathrm{GCD}\{\hat{C}_1,\ldots,\hat{C}_Q\}$. Hence, the maximum number of available units $C=\lfloor \hat{C}/\Delta\hat{C} \rfloor$. Each service q demands c_q resource units in terms of $\Delta\hat{C}$ units for one request given by $c_q=\lfloor \hat{C}_q/\Delta\hat{C} \rfloor$. Blocking for service q takes place when there are not at least c_q resource units to serve a request. The user arrival processes are Q Poisson processes with mean rate of arrival λ_q (interarrival time = $1/\lambda_q$) and the service time has exponential distribution with mean $1/\mu_q$. Then the traffic offered per service is $A_q=\lambda_q/\mu_q$.

For such a configuration, a product form solution for the determination of the blocking probabilities of the different services in the multiplexer exists. Let the system state be given by the number of accepted calls from each class $(n_1,n_2,\ldots,n_Q)$, where $n_q=1,\ldots,\lfloor C/c_q \rfloor$. The set S of allowable states is determined by

$$S=\left\{(n_1,n_2,\ldots,n_Q)\middle|\sum_{q=1}^{Q} n_q c_q \le C\right\} \tag{4.27}$$

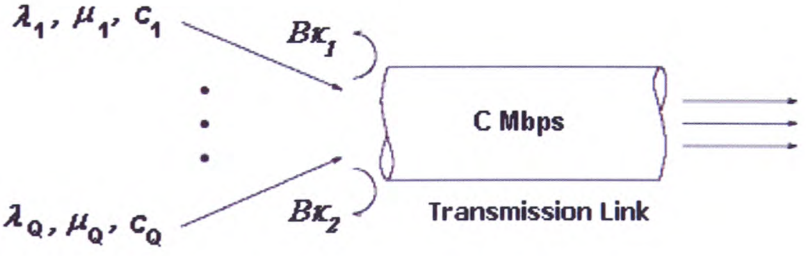

Figure 11: Basic link model with complete sharing [49].

A multidimensional Markov chain is associated to this system and shall be of a dimension as the number of services. Figure 12 shows an example of the state-space for a 10 Mbps transmission link ($\hat{C}$ =10 Mbps) serving two traffic classes with bit rate requirements of $\hat{C}_1$= 2 and $\hat{C}_2$= 4 Mbps, arrival rates λ_1 and λ_2 and service rates μ_1 and μ_2

respectively. In this case the rate requirement of class 1 will be used as the basic bandwidth unit for capacity; i.e. $\Delta\hat{C}$ =2 (resulted from $\Delta\hat{C}$ =GCD{2,4}). Hence, the maximum number of available units $C==\lfloor 10/2 \rfloor =5$ and the resource requirements for the two classes shall be $c_1 =\lfloor 2/2 \rfloor =1$ and $c_2 =\lfloor 4/2 \rfloor =2$.

A subset S_q of S is the set of all blocking states for service q, that is, when there are not at least c_q resources units allowable. Let Bk_q be the blocking rate for service q. Hence, Bk_q is given by

$$Bk_q = P(S_q) = P\left\{(n_1, n_2, \ldots, n_Q) \middle| C - c_q < \sum_{q=1}^{Q} n_q c_q \leq C \right\} \tag{4.28}$$

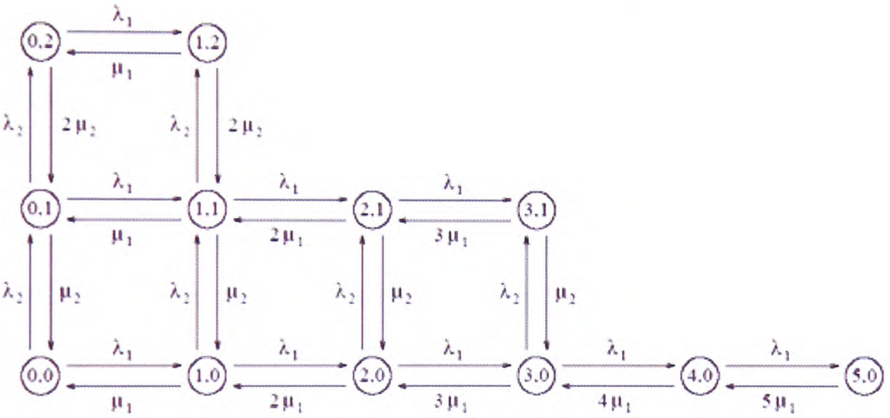

Figure 12: State space example [49]

For the example in Figure 12 three blocking states can be identified for the service 1 while five states are for the second service. Therefore the blocking probabilities for the two classes are

$$Bk_1 = P(1,2) + P(3,1) + P(5,0)$$
$$Bk_2 = P(0,2) + P(1,2) + P(2,1) + P(3,1) + P(4,0) + P(5,0)$$

To evaluate the blocking rates given by (4.28) using the product form solution [49], first, the un-normalized probabilities of any valid state is given by the product form

$$\tilde{P}(n_1, n_2, \ldots, n_Q) = \prod_{i=1}^{N} \frac{(\lambda_i / \mu_i)^{n_i}}{n_i} \tag{4.29}$$

The summation of the un-normalized probabilities over all possible states of gives *G(S)*

$$G(S)=\sum_{(n_1,n_2,\ldots,n_Q)\in S}\tilde{P}(n_1,n_2,\ldots,n_Q) \tag{4.30}$$

Similarly, $G(S_q)$ is given by the summation over all blocking states for service q, that is

$$G(S_q)=\sum_{(n_1,n_2,\ldots,n_Q)\in S_q}\tilde{P}(n_1,n_2,\ldots,n_Q) \tag{4.31}$$

Blocking for service q is given by $G(S_q)/G(S)$.

A recursive (exact) algorithm for finding the blocking probabilities in addition to a number of approximate solutions with comparisons of their accuracies and complexities can be found in [49] [88].

4.8.3 Using the Model as a Dimensioning Tool

Examining (4.14) and (4.15) reveals that they can be re-written in the format of (4.27) through normalizing the mutual coefficients by the smallest value α_{qm} of them to get $c_1=\alpha_{q1}/\alpha_{qm}$, $c_2=\alpha_{qm}/\alpha_{qm}$, ... $c_q=1/\alpha_{qm}$,... $c_Q=\alpha_{qQ}/\alpha_{qm}$, and $C=N_{service_q}/\alpha_{qm}$. This means that the maximum capacity is given in units of the resource requirements of the least harmful interfering service represented by the reduction in capacity due to one connection of that service; i.e its mutual parameter α_{qm}. This is usually for the class with least rate, however, other factors of activity and QoS may influence that. The maximum capacity therefore is the number of users that that class that can be accommodated for the coverage radius given.

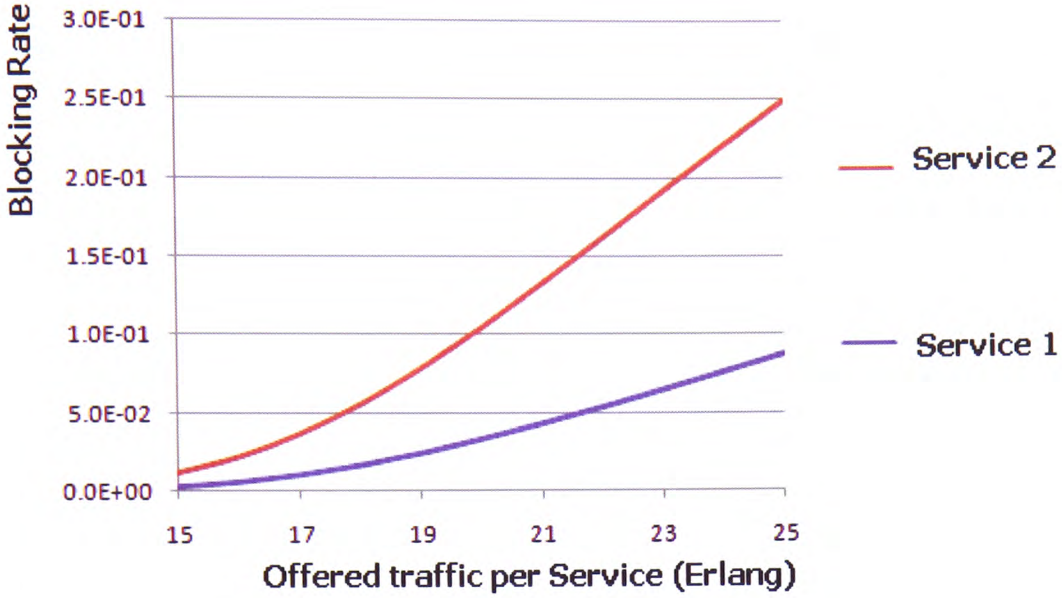

Figure 13: Blocking rates variation for system with two services against increased traffic.

Applying this to the example in Section 4.6, by normalization using the coefficient of N_1 of the limiting boundary equation given by (4.25), the values of c_1=1, c_2 =3.0 and C=87.3 (in units of service 1) and a traffic of (31.5, 10.5) Erlang as before. The blocking probabilities in this case shall be (obtained using the recursive algorithm described in the previous subsection) are Bk_1=0.41% and Bk_2=1.4% compared to the 3% each obtained by the hard blocking assumption and the use of regular Erlang formula, which is an expected result. Figure 13 shows the blocking probabilities variation for these two services in the example with increased traffic of equal value for both services.

In this figure, it is clear that the higher data rate service suffers a higher blocking probability when offered traffic is the same for both services for obvious reasons. The problem worsens more with increased difference between the two services. Reservation techniques are suggested to reform or equalize the blocking probabilities [49] [88]. These can be studied in light of the given model. More suggestions for further research based on the coupling between the capacity/coverage model and ATM theory is given in the last chapter.

4.9 Model Comparisons

In deriving the model for capacity and coverage in this chapter an assumption of homogenous cellular structure was assumed. While this might influence the accuracy of the model, this is a typical assumption in industry and research, especially for the dimensioning process [25] [26][51]. The major approximation is obtained by considering a flat and homogeneous landscape. That is to say, the target area is divided into different morphology classes, or clutter types (urbanization degree, standard deviation for shadowing, penetration loss, etc), which are considered separately on the assumption that each clutter forms an exclusive homogeneous area. This assumption results in identical sites per clutter, which may be considered "prototype" sites in the planning process [25].

The modelling of the user capacity in this chapter is *class-based* model. Class based models for UMTS are used by others also for either the dimensioning or the RRM algorithms [28] [25] [26] [29] [51]. This is in spite of that class based modelling entitles some approximations in a variable environment like the wireless channel of UMTS. There are two main sources of variability; one is that the interference seen by any one user can be different from any other in the same class. The good news is that this variability characterises the downlink only while in the uplink modelling it is valid to assume that the interference is the same for all. For the downlink, the interference seen by the different users will depend on their locations while for the uplink it is the furthest one, or in other words the designed coverage, that actually determines this level. For the downlink case the average interference computed for a user halfway between the base station and the cell edge is usually used, e. [24] [89].

The second source of variability is that the different users in the same class might face different shadowing and fading conditions requesting in that the external power loop to adjust the target QoS on a user level. However, the assumption of ideal power control (or a power control with corrected E_b/N_o), the E_b/N_o for any service class may be regarded a constant [25]. In addition, the assumption of homogeneity made in the previous clause helps augments more this assumption.

As explained within the context of the derivation in this chapter, the obtained interference limited capacity, N_{upper}, complies with the recent findings by the telecommunications industry [22]. It was found in [22] that approximating this pole capacity by neglecting the interference effect of the last admitted user (neglecting the value F from the *pole capacity* or v_qR_qF from the pole throughput) is a valid approximation for low rate services only [23] and must be considered when higher rates are there.

The model provides a snapshot of the capacity and coverage interaction at the boundary of operation of satisfying different target QoS requirements and target coverage radius for the different services. The model is demonstrated as a dimensioning tool. Of course it does not constitute a complete dimensioning/planning tool, however, dimensioning usually start by the initial selection/estimation of loading and number of connections to satisfy the traffic requirements imposed by the busy hour [72].

In [24] simply the Erlang capacity was used to estimate traffic capacity gains from soft handover. In [25] the capacity was visualized in terms of basic interference units and the blocking was computed based on a modified Erlang blocking called the Knapsack model to account for the multi-service case. In [26] the basic capacity units were given in terms of loading percentage of each connection. The last two approaches of [26] [29] make use of the results from ATM with defined maximum bandwidth and apply to UMTS. A maximum capacity is sought somehow and a basic unit for resource sharing was defined; in [25] the basic unit is an interference unit while the maximum is the noise rise limit, in [26] the basic unit is the GCD* of loading percentages of all call streams.

One close approach to the one in this study, i.e. to use the number of connections, is given in [29] whereby the capacity is visualized as the aggregate capacity in units of voice users with ratio depending on voice activities and rates ratio. The aim in that work is to analyse the soft capacity gain when interference sharing between cells is considered. In here, the interference ratio is considered in the capacity bounds and therefore soft capacity is accounted for. Additionally, the influence of QoS(s) ratio is also taken into consideration while it is not taken in [29] with no attempt made to link the capacity and coverage and simply a certain maximum capacity was assumed.

Generally, the initial dimensioning for capacity coverage using the previous model shows that this approach provides the following advantages over the other approaches

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* GDC is the greatest Common Divisor.

i. Multiservice dimensioning in one step compared to the single service dimensioning process based on iteration between capacity and coverage [61] [25] by relating the problem of capacity and coverage planning and the dimensioning process together.

ii. The direct use of number of connections instead of loading percentages [26], interference units (rise over thermal) [25] or else . This is a more meaningful and useful.

4.10 Concluding Remarks

In this chapter, a different approach to the capacity/ coverage issue in WCDMA on the uplink is laid out. Comparing to traditional approaches, namely, the loading analysis, the analysis gives a way to transfer the problem of loading analysis from pure interference analysis (whereby the interrelationships between different service classes, rates and coverage radii are kept hidden) to a direct one whereby these interrelationships are apparent.

The result of this chapter is a model for capacity on the uplink whereby for any single service the allotted capacity is partitioned into three parts. The first is the upper interference limit, which represents the upper capacity bound for this service that is independent from distance and propagation conditions. The second one, which is distance/propagation dependent, is the reduction in the number of connections of this service due to limited uplink power of the mobile units. The third and final part is the reduction in the number of users of this service due to the existence of other users of other services. The net capacity is obtained by subtracting the reductions, second and third parts from the upper interference limit, i.e. the first part. One interesting feature of Eq. (4.15) is that the reduction effect of the capacity of one service class on any other class is shown to be propagation and power independent. It depends only on the relative interference effect of the two services given by their relative rates, relative QoS requirements and relative activities.

Similarly, coverage is also partitioned into three parts. The first part, called the intrinsic coverage, which represents the maximum coverage for a single user in the network that is only limited by thermal noise and the propagation conditions. The second part accounts for the shrinkage in coverage, for this service, due to the presence of other similar users. The third and final part accounts for further shrinkage in coverage due to the presence of other users of other service types. The net coverage is also obtained by a simple combination of the three parts.

This model is unique; it interrelates the coverage, capacity, rates and other system parameters. Also, it can be used in making decisions, whether in planning phase or in operational stages for admission decisions because we have explicit numbers of connections of the different services, though interrelated. In network planning, assumptions can be made about all the parameters in the equations, like interference ratio and activity, while in resource managements, e.g. call admission, information about these parameters can be obtained instantaneously from within the running system just previous to admission decision.

It is also shown that shadowing losses (Section 4.7.1) and other link parameters, losses and gains (Section 4.7.34.8) and many other practical issues (mobility, MUD,etc) can be included in the model. Additionally, the model is demonstrated to be used as an initial dimensioning tool (Section 4.8).

Code Division Multiple Access (CDMA) is designed to optimize spectrum utilization by allowing all users to share the common allotted frequency band .However, the continuous growth in demand for more services, higher throughputs and more connections calls for new approaches to provide higher capacities. The default omnidirectional transmission method spreads the electromagnetic energy of the signal over large regions of space. The intended mobile station actually receives a very small portion of the transmitted energy accompanied by much interference from all other sources. Thus, one of the promising frontiers to enhance capacity in mobile communications systems is the adoption of antennas that have directional properties whereby the antenna is capable of concentrating energy in the direction of the intended other part of the communication link, whilst simultaneously suppressing energy levels in all other directions. This is especially beneficial to CDMA systems in which interference generated by other users in the cell and in neighbouring cells limits the system capacity [90]. In the first of the following two chapters a brief revision of beamforming and smart antennas' types, processing, etc, is given, while the second chapter analyze the capacity gains from using one type of smart antennas called the *switched beam smart antenna* in WCDMA.

Chapter 5 Beamforming Antennas

5.1 Introduction

The cellular concept is one of the early methods of spatially exploiting the wireless channel for the advantage of the capacity in mobile wireless communications systems. The use of diversity antennas in which two or more antennas are physically separated to receive from or transmit over more than one path is another form of spatial exploitation. The use of sectorisation to further exploit the spatial domain is common to second and third generation systems as well. Both diversity and sectored antennas concepts were discussed in Chapter 3.

Before the era of mobile wireless communications, other techniques existed for spatial exploitation called the *beamforming* techniques. Beamforming techniques are alternatively referred to as *spatial filtering* techniques. In beamforming, a beam is steered in a way to block the reception of radio signals coming from specified directions, while a filter in the time domain combines energy over time. The beamformer combines energy over its aperture therefore obtaining a certain antenna gain in a given direction while having attenuation in other directions.

Beamforming techniques at that time were analogue beamforming techniques, e.g. Butler matrix, and were used in applications like the Radar. Alternatively, beamforming can be attained digitally using an array of antennas (or alternatively *antenna elements* to emphasise that it is a one antenna system) with digital processing performed on the different signals transmitted (received) on the different antennas before (after) being converted to (from) analogue modulation form suitable for transmission over the wireless channel. Analogue beamforming using Butler matrix is discussed in Section 5.2 while digital arrays are presented in Section 5.3.

Beamforming antennas come under the broad title of smart antennas. A smart antenna system is any kind of antenna capable of changing its radiation pattern, by any means, in response to angular amplitude changes in the signal(s). Under this definition, a large class of antennas exist ranging from fixed and adaptive beamforming antennas, phased arrays, diversity array antennas: Single Input Multiple Output (SIMO) and Multi Input Single Output (MISO), and the Multi Input Multi Output Antenna (MIMO) systems. In this work, multiple beamforming antennas of the fixed type are only considered.

Beamforming was initially introduced with coverage improvement in mind [73] [91]. However, in systems like UMTS where the MAI limits the system capacity they can provide capacity improvement as well. Their effect of increasing capacity is the result of combining both their interference reduction capabilities together with a new dimension for bandwidth multiplication* by re-using the bandwidth a number of times in the same cell.

Beamforming, especially of the fixed beams type, are the easiest to integrate in the environment of mobile wireless communications systems and yet they can provide many benefits to these systems. Recommendations for measurements and signalling within UMTS for the support of beamforming enhancements are given by 3GPP [92]. The potential benefits of using beamforming in UMTS are discussed in Section 5.5.

5.2 Analogue Beamforming

The use of beamforming antennas dates back to the 50's with their applications to radar and antijam systems [93]. Beamforming antennas were therefore called *scanning* antennas. One of the most famous of these is the Butler Matrix beamformer [94]. Other analogue techniques that are less attractive for the mobile wireless communications systems exist, e.g. the lens based beamformers like the Rotman lens [95].

Generally, analogue beamforming techniques have the advantage of lower processing delays and reduced computational overhead, numerical stability as they do not require intense signal processing and beam selection can be based on radio frequency (RF) analogue signal processing and simple control logic (especially for the fixed multiple beams type considered in here) [96]. In addition, analogue beamformers does not require that their RF amplifiers to be calibrated like the digital ones.

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* The term *bandwidth multiplication* is used in this thesis to denote the frequency re-use in general.

5.2.1 The Butler Matrix

The Butler matrix [94] is an analogue devise that consists of power splitters and fixed phase shifters in the form of hybrids. Figure 14 shows the construction of a 4-port Butler matrix and the hybrid used in the construction of the matrix. The system is easily expanded to support eight beams by repeating this pattern for a further four ports [97], and so on for higher order matrices.

Butler matrices produce a number of orthogonal beams of the sin x/x pattern. Figure 15 depicts the radiation pattern for an 8-port Butler matrix beamformer. The *cusping loss* is shown in the figure, which is the reduction of the power for a signal close to the beam edge, a problem associated with such beamformers.

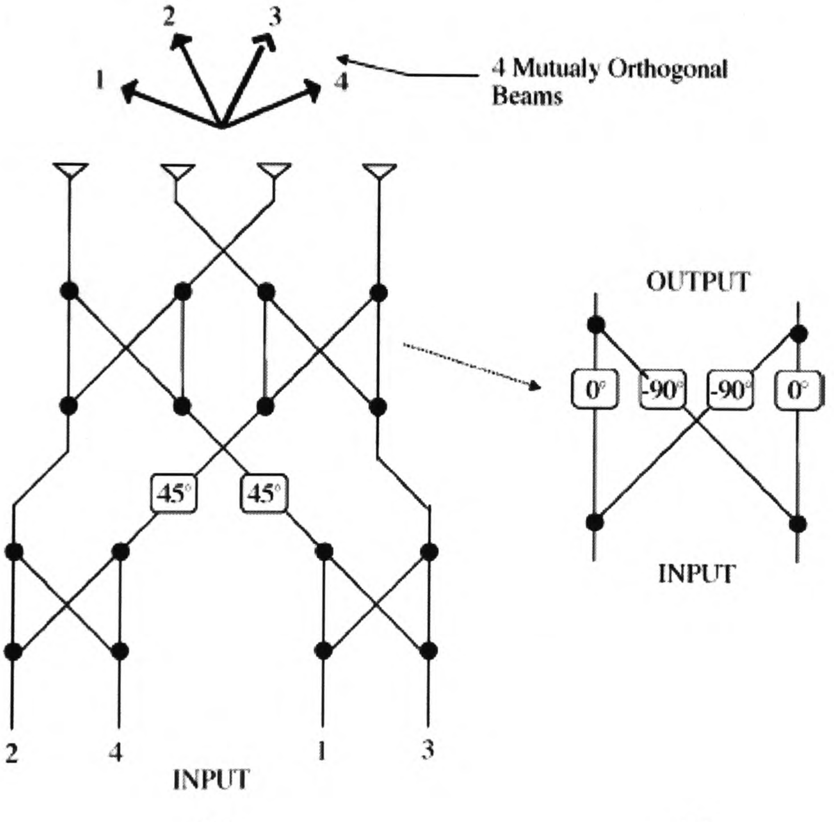

Figure 14: (a) 4 port Butler Matrix. (b) The hybrid used [89].

The Butler matrix continues to receive interest even in this era of digital processing. Examples on recent research on the design and use of the Butler matrix are many. In [98] a simplified procedure for designing Butler matrices is introduced for 128 ports and more. In [99] a modified Butler matrix with a higher side lobe level suppression to -15 dB is implemented, to -20 dB in [100], and with a broadside [101]. Wideband Butler matrices designs for use in switched beam antenna systems are given in [102].

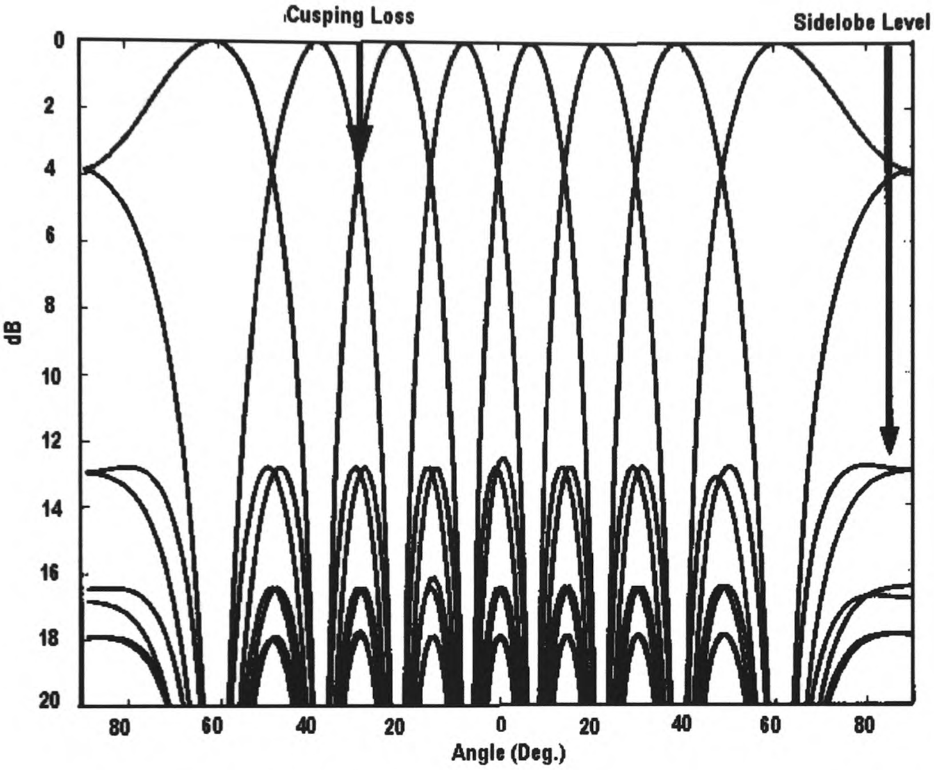

Figure 15: Radiation pattern for eight-port Butler matrix [96].

5.3 Digital Beamforming

5.3.1 Basic principle

Figure 16 depicts a two-element *Delay-and-Sum* beamformer. The two elements are separated by a certain distance. Assume that a plane wave arriving from direction θ induces voltage $s(t)$ on the first element. As the wave arrives at the second element T seconds later, depending on the separation distance and angle of arrival, the induced voltage on the second element will be a delayed version of the one on the first element, or $s(t\text{-T})$. If the processing for the signal induced at Element 1 delayed it by time T, as well, this signal will become also $s(t\text{-T})$. With no further delay is provided at Element 2, both voltage wave forms will be the same. The output of the processor is the sum of the two signals $s(t-T)$. A scaling of each waveform by 0.5 makes the gain in direction θ equal to unity. In every other direction, it is expected the gain is less than 1 (because the delay T corresponds to difference in time of arrival at the two elements of a signal projected with angle θ).

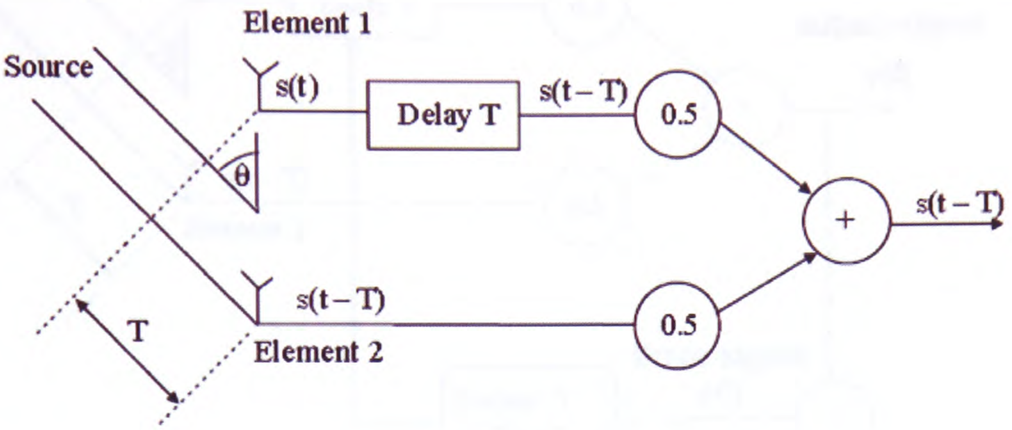

Figure 16: Two element *Delay and Sum* Beamformer [103].

5.3.2 Beamforming with Pilots

The basic goal of a beamforming antenna is to maximize the output SIR when not only having the desired wave but also with the arrival of interfering signal(s). In an environment where multiple waves are arriving, the antenna's response is the superposition of each wave. The primary objective is to extract the desired one from amongst the mingled received signals. Two situations exist [104]

i. **Trained Criteria:** When the arrival directions of the waves are unknown to the receiver: To distinguish the desired signal from interference, a training code contained within the desired signal's wireless packet frame is used. To estimate the difference between the received signal and the training code, the Minimum Mean Square Error (MMSE) criterion is used to optimize the multiplying weights. This is depicted in Figure 17 in which the error signal obtained by the MMSE criterion is used to optimize the delay in the first branch.

ii. **Blind Criteria:** A more formidable challenge arises in maximizing the SIR when the transmitted signal includes no training code or when the signal waveform direction is unknown to the receiver. The objective of blind beamformers is to extract the desired one from amongst the mingled received signals without having any information about the transmission beforehand.

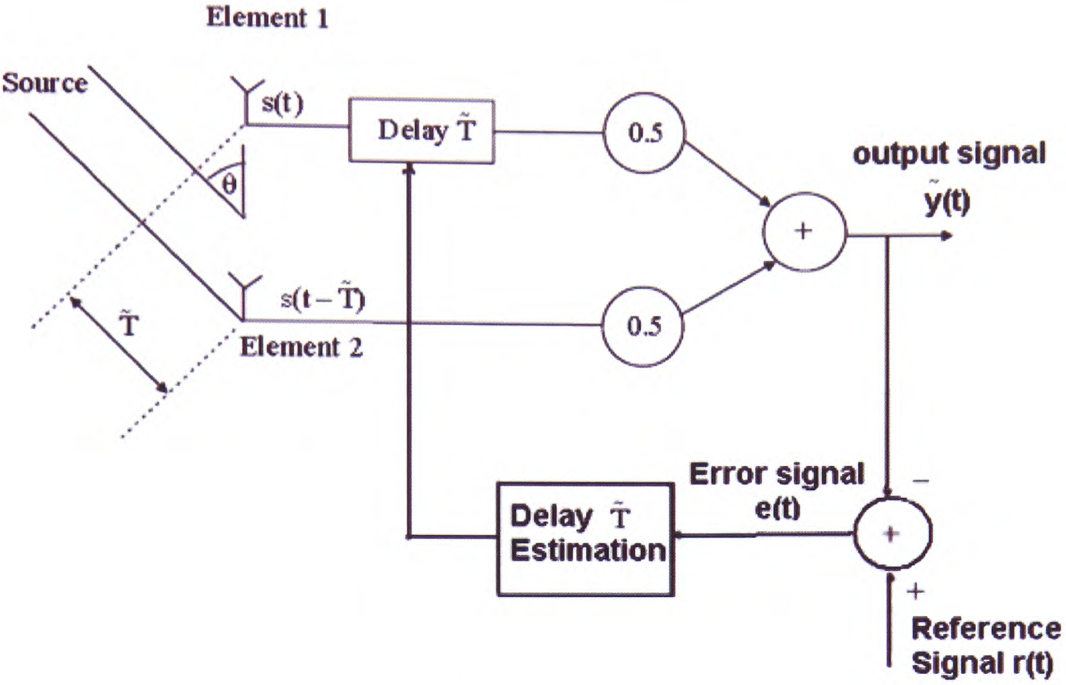

Figure 17: Least Mean Square Algorithm [103][104].

5.3.3 The General Beamforming Array

Generally, for an L element antenna array, each of the signals arriving at the different antenna array elements are multiplied by complex weighing factors (a magnitude and a phase) as shown in Figure 18, then the output of the processor can be written as [103]

$$y(t) = \sum_{l=1}^{L} w_l^* . x_l(t) \tag{5.1}$$

where **w** is the weight vector $\mathbf{w} = [w_1, w_{2,\dots,} . w_L]^T$, and **x(t)** is the signal vector $\mathbf{x(t)} = [x_1(t), x_2(t), \dots, x_L(t)]^T$. The * denotes the complex conjugate and the ^{T} stands for transposition.

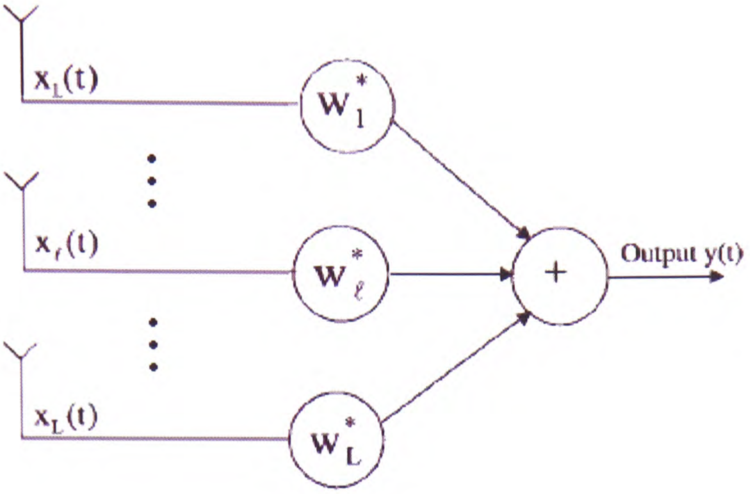

Figure 18: Antenna Array System [103].

The output *y(t)* can therefore be written as the inner product of $\mathbf{w}^{\mathrm{H}}$ and **x(t)** (where $^{\mathrm{H}}$ is for complex conjugate transpose)

$$y(t) = \mathbf{w}^{\mathrm{H}}.\mathbf{x(t)} \tag{5.2}$$

Let the received signal vector **x(t)** be the sum of three components, the wanted signal vector, $\mathbf{x}_s\mathbf{(t)}$, the interfering signal $\mathbf{x}_I\mathbf{(t)}$ vector and thermal noise **n(t)**, or $\mathbf{x(t)} = \mathbf{x}_s\mathbf{(t)} + \mathbf{x}_I\mathbf{(t)} + \mathbf{n(t)}$. Assuming the three components are zero mean stationary processes, the mean output power $P = |y(t)|^2 = E\left[y(t)y^*(t)\right]$, where E denotes the expectation operator, can be easily shown [103] to be the sum of three components P_s, P_I and P_n given by

$$\begin{aligned} P_s &= \mathbf{w}^{\mathrm{H}} R_S \mathbf{w}, \text{ where } R_s = E\left[\mathbf{x}_s\mathbf{(t)}\mathbf{x}_S^{\mathrm{H}}\mathbf{(t)}\right] \\ P_I &= \mathbf{w}^{\mathrm{H}} R_I \mathbf{w}, \text{ where } R_I = E\left[\mathbf{x}_I\mathbf{(t)}\mathbf{x}_I^{\mathrm{H}}\mathbf{(t)}\right] \\ P_s &= \mathbf{w}^{\mathrm{H}} R_n \mathbf{w}, \text{ where } R_n = E\left[\mathbf{n(t)}\mathbf{n}^{\mathrm{H}}\mathbf{(t)}\right] \end{aligned} \tag{5.3}$$

Elements of the matrices $\mathbf{R}_s$, $\mathbf{R}_I$ and $\mathbf{R}_n$ denote the correlation between various elements, For example, $R_{S_{ij}}$ denotes the correlation between the i^{th} and the j^{th} element of the array $\mathbf{R}_s$. Hence, the signal to interference ratio $SIR = P_S / P_N$, where $P_N=P_I+P_n$, at the output of the array system may be written as

$$SIR = \frac{\mathbf{w}^{\mathbf{H}} R_S \mathbf{w}}{\mathbf{w}^{\mathbf{H}} R_N \mathbf{w}}, \text{ where } R_N = R_n + R_I \quad (5.4)$$

It can be deduced from the last equation that the weights of the array system determine its performance. The selection process of these weights depends on the application and leads to various types of beamforming schemes.

5.3.4 Beamforming Methods

In the simple adaptive beamformer of Figure 17 a pilot signal was used to adjust the delay by continuously comparing with the output. In a general adaptive system, all the information available to the processor, including the present received signal vector is used in optimising the magnitudes and the phases of the weights, as depicted in Figure 19. This is done so that the main beam tracks the desired user and places nulls (or side lobes) in the direction of interferers.

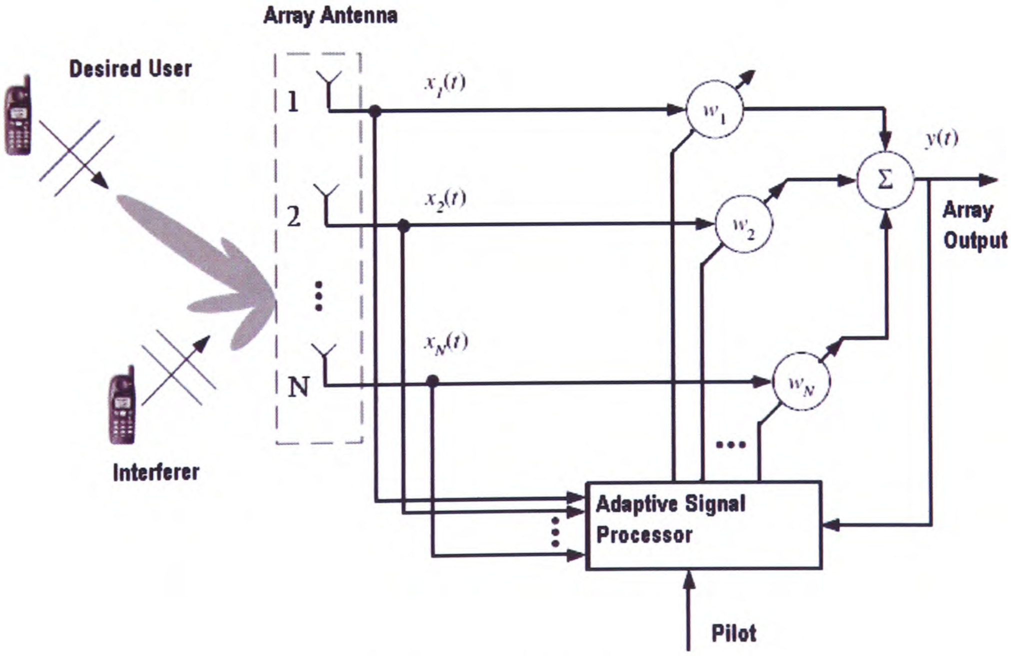

Figure 19: General adaptive beamforming [104].

Some beamforming methods are briefly described below [103]:

i. *Conventional Beamforming*: aims at maximizing the gain in the direction of the desired signal.

ii. *Nulling Beamformer*: cancels the interfering signals by providing nulls in the directions of the interferers. This requires that information about the directions of the desired signal and the interferers be available.

iii. *Optimal Beamforme*: in which nulls are also provided, however, it is the direction of the desired signal that is only needed. Optimization requires a reference signal (or the desired signal direction be known) in order to estimate the optimum weights of beamformer.

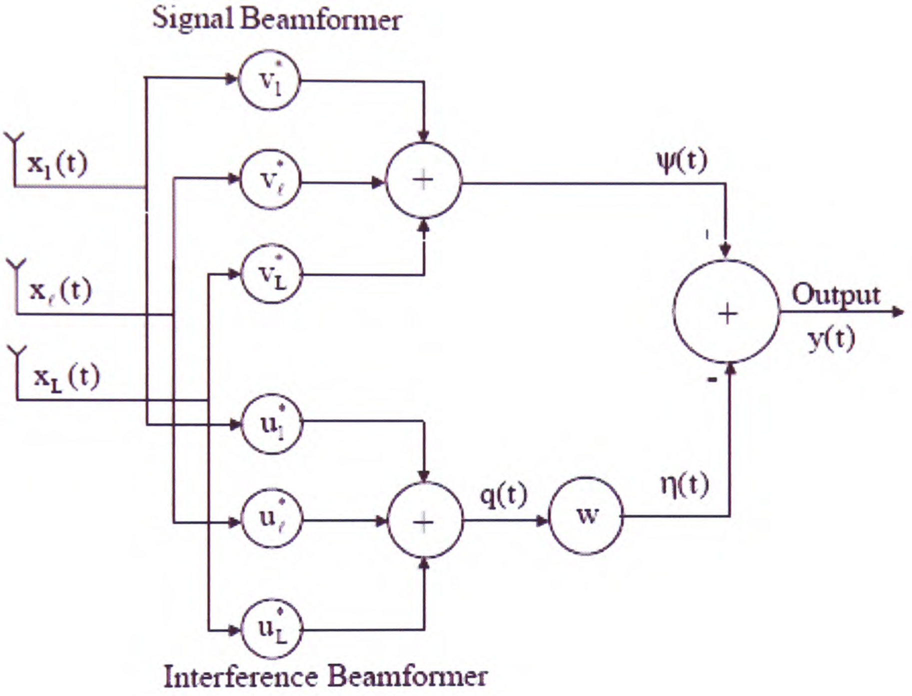

Figure 20: Post Interference Canceller [103].

iv. General Beam Space Array, in which interference cancellation is effected by subtracting the outputs from two different array processors, one maximizes the signal and the other produces a null in the signal direction, thus the difference results in interference cancellation. An example of this category of is the *Post Interference beamformer canceller* (PIC) depicted in Figure 20. In this figure the **V** array is optimized to maximize the wanted signal in its output $\psi(t)$, while the **U** array produces an output $\eta(t)$ that is effectively the interfering signal (adjusted by the weight multiplier w) with the wanted signal cancelled. Subtracting the two outputs effectively cancels the interfering signal. Of course, an adaptive processor (not shown) is needed to adjust the weights in the two arrays. If the adaptive algorithm is based on MMSE (Minimum Mean Square Error), the array system is called *Multi-user MMSE*, therefore combining the idea of MUD (Section 3.7.1) and beamforming.

5.3.5 Multiple Beam Antennas

In mobile wireless applications, there are many users (wanted signals) and they cause interference to each other at the same time. Therefore, in order to utilize beamforming, multiple beams must be generated at the same time using more than one set of array weights generating more than one beam. Each beam shall be directed at one user (or a group of users) while at the same time nulling or at least suppressing the signals from others. An N port Butler matrix will generate N beams. In digital beamforming the beamforming network must be repeated N times. This is depicted in Figure 21.

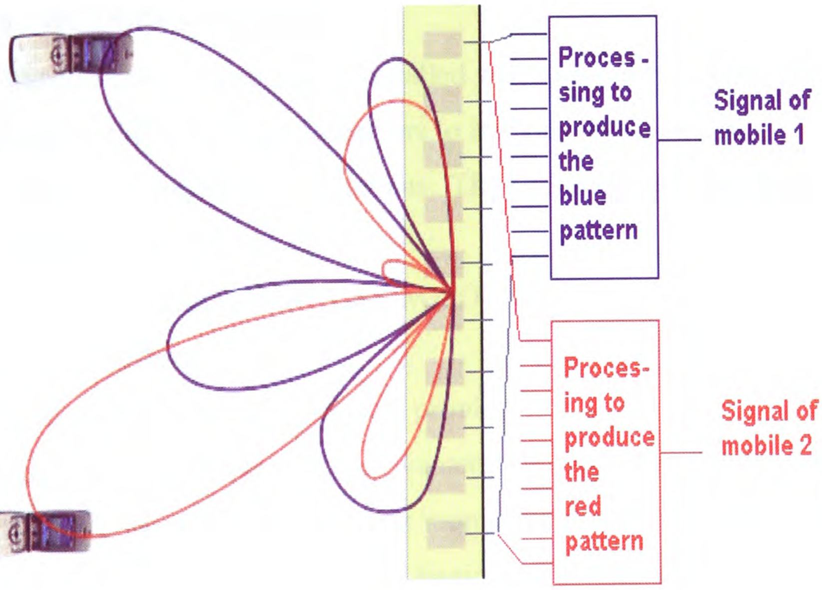

Figure 21: Multiple Beam Antennas.

5.3.6 Array Types

The array antenna mainly is either a Uniform Linear Array (ULA) or a Uniform Circular Array (UCA) of antenna elements. The individual antenna elements are usually identical, with omnidirectional patterns in the azimuth plane.

5.4 Smart Antennas

Beamforming antenna comes under the broad title of *smart antenna.* A smart antenna system is any kind of antenna capable of changing its radiation pattern, by any means, in response to angular amplitude changes in the signal(s). Under this definition, a large class of antennas exists:

i. Fixed multiple beam antennas: these antennas form a number of beams in predefined directions in space, each beam of which is focused on a group of users. This is usually combined with a selection capability to select the beam that provides the best signal quality. These antennas are also called Switched Beam Smart Antenna (SBSA). This study focuses on the analysis of such antennas in the WCDMA environment.

ii. Phased arrays: these are also called *tracking arrays.* They act by adjusting the phase of the weighing multipliers to track a certain source.

iii. Adaptive beamforming antennas: They provide the capability of tracking and nulling the interferers.

iv. Diversity antennas (SIMO and MISO)

v. MIMO systems.

Generally, all smart antennas types, can provide

i. Gain in the direction of the wanted signal(s) therefore resulting in increased coverage, reduced power output requirement and increased battery life. The gain factor was a major drive at the beginning for the use of beamforming antennae arrays in systems operating in the 2GHz band (e.g. PCS-1900, eand UMTS) [73] to increase the sensitivity of reception and increase the coverage to account for the reduction resulting from the doubling of the operating frequency (from GSM-900).

ii. Suppressing (or nulling when possible) of the interferers, therefore improving signal quality. This can improve capacity in TDMA/FDMA systems like GSM*. However, capacity improvements in interference-limited systems, like WCDMA, are expected to be much larger. The capability to reduce the interference is called *spatial filtering for interference reduction* (SFIR).

iii. *Space Division Multiple Access* (SDMA), which is the spectrum re-use or bandwidth multiplication in the angle domain (the beams).

iv. Diversity gain when multiple antennas are used to send the same data on the different elements.

v. The MIMO systems provide linear increase of throughput proportional to the number of elements.

More on the benefits that smart antennas may provide to the mobile wireless systems can be found in, for examples, [105] [64] [106], and on their possible configurations when used in mobile communications can be found in, e.g. [108] [109] [110]. More on the smart antenna system architecture, the RF components of filters and down/up converters and other hardware variations can be found in [111]. A comprehensive state of the state of the art study of smart antennas from aspects of receiver and transmitter design, channel, technology and integration into networks, systems can be found in [112]. More on adaptive beamforming techniques is in [96] [113]. Transceivers design in smart antennas in [114].

The Integration of smart antennas in the mobile wireless environment faces a number of challenges regarding complexity, cost and applicability. The switched beam antenna system is one of the simplest; however, it can be beneficial enough. In the next section, this type of antenna is reviewed in more detail. An analysis, similar to the analysis given in Chapter 4, of the performance of WCDMA networks regarding capacity and coverage with the use of this antenna system at Node B is given in the next chapter.

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*Limited deployments of smart antennae in GSM only exist because the cost outweighs the benefits.

5.5 The Switched Beam Smart Antenna (SBSA)

The Butler matrix introduced in Section 5.2.1 , as well as the digital techniques for beamforming *, can both be used to produce several highly directive, fixed, pre-defined beams in space to cover the whole cell (or a whole sector) in an omnidirectional like coverage. The beam pattern resulting from digital techniques is called Grid of Beams (GOB) and an arbitrary number of beams can be formed using such techniques [96]. This beamforming network is usually followed by a switching mechanism. The role of the switching mechanism is to choose the setting that gives the best performance, usually in terms of received power. In its simplest (and most common) form, the switching mechanism is a selection one. In such a case, the system detects the signal strength and chooses one beam, from a set of several beams that gives the maximum received power. This configuration is shown in Figure 22.

Because of the higher directivity compared to a conventional antenna, a directional gain is acquired by the signals received from the intended direction while the signals arriving at other directions are suppressed by the value of the gain in the sidelobe directions.

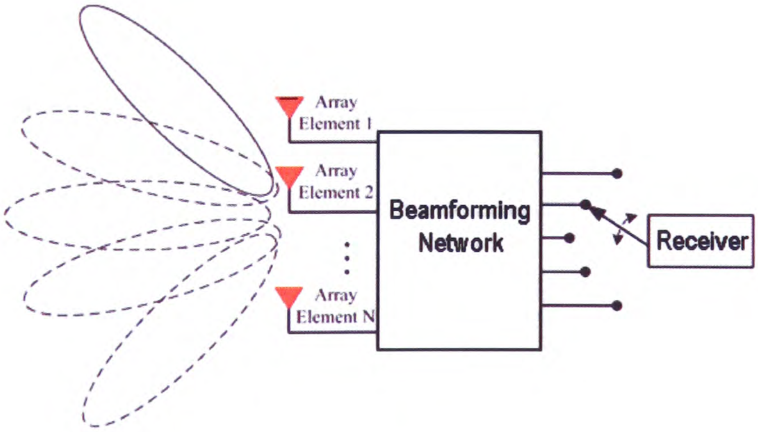

Figure 22: Functional Block Diagram of a Switched Beam Smart Antenna [96].

Such an antenna will be easier to implement in existing cell structures than the more sophisticated adaptive arrays. Such antennas are considered by many, e.g. [116] [117] to be a robust and cost-effective method of increasing capacity in cellular networks. In a

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* Digital techniques do not require the beams to be orthogonal, enabling the beam cusp to be adjusted [96].

CDMA system there are many users using the same channel, hence forming beams toward all users not to mention nulls towards all the interferers will become computationally very complex and even not feasible with the limited degree of freedom (the number of elements), Simulation studies conducted in [118] showed that thses systems can have a performance that is comparable to adaptive systems in a CDMA environment and the switched beam antenna array outperforms the tracking beam antenna array when the desired signal is not sufficiently stronger than the interferer. A switched beam antenna can be thought of as an extension of the conventional sector antenna in that it divides a sector into several micro-sectors. Several advantages of switched multiple beams over traditional sectored antenna can be pointed as

i. Beam pattern of sectored antenna is characterised by the metallic shape and properties of the antenna itself producing antenna pattern overlap [64] while beamforming can be made more directive using the techniques mentioned.
ii. As a result, sectoring is only practical up to six sectors per cell [65], typically three, while with beamforming order can be made higher.
iii. In beamforming, the signal is received using all of the antenna elements at the same time while in sectoring the signal is received using one antenna at a time.
iv. This last one means that the reception using beamforming is done by one system, or in traffic terminology, one trunk, regardless of the number of beams. While a cell with 3 sectors will form 3 trunks. This results in a trunking efficiency (or trunking gain) of the beamforming antenna [115] [107].

In addition to the above, beamforming may be made more complicated to attain some more advantages as follows

i. Windowing techniques may be applied to enhance suppression in the sidelobe level more.
ii. A combining functionality may be added to the switching mechanism to combine constructively multipath signals arriving through different angles in environments characterised with wide large spreading angle. Better performance is demonstrated in [116] whereby maximum-ratio combining (MRC) is used to combine signals from all of the available paths in the beams and the beam re-

ceiving the most power in the uplink can be used to transmit to the desired mobile on the downlink. In any case, adjacent sectors employing different scrambling codes can be detected as softer handover (SfHO) giving some diversity gain [89].

iii. A number of suggestions were made to ad some adaptivity to the fixed beam systems for enhancing their performance. Therefore, handling situations like hot spots, radio resource management algorithms can be used to slowly vary the beam arrangement over time to adjust for long term variations [119]. In [120] a smart antenna technique based on rotation and resizing of the available sectors is suggested.

The SBSA, as said above, is deemed the simplest of the smart antenna systems (considered more complex than conventional sectorization). Simplifications will be combined with deficiencies as follows

i. As more than one user is received within a beam, an intended user with its signal toward the beam edge will receive less gain than the interfering signal towards the centre [121]. This reduces the signal level compared to other interferes. Of course in WCDMA environments the wanted signal (differentiated by its code) will receive an extra boost due to the processing gain. This in addition to other enhancing techniques (like angular combining) will help alleviate this.

ii. Low performance in rich multipath environments characterised by a wide spreading angle, however, the use of angular combining to gain angular diversity will help alleviate this. Angular combining is not considered in this thesis.

Additionally, one of the incentives for the use of beamforming in general, and the switched beam techniques, in particular, will be the introduction of enhanced links using HSDPA or HSUPA on the uplink. These, can make use of beamforming to attain higher coverage for high data rates or to improve the opportunity for any single user to be scheduled for higher rates by, for example, devoting one full beam to this user. The deployments of such technologies aim at suburban and rural environments to provide broadband coverage at low cost compared to fixed broadband , which makes the issue of angular spread less pressing.

5.6 Summary

In this chapter, the revolutionary methods for enhancing capacity using beamforming antennas and smart antennas in general are discussed. Both analogue and digital techniques for beamforming are discussed. One of the most famous of the analogue beamformers is the Butler Matrix beamformer, which received recent interest because of its potential for use in mobile wireless communications. The use of digital beamforming allows for a wide range of adaptive beamforming techniques to track users, suppress and null interference interactively. Pilots are needed to support this. However, blind algorithms do exist. Beamforming lies under the bigger title of smart antennas that also include other techniques like the MIMO systems.

The complexity and cost associated with adaptive beamforming techniques based on tracking a single user preclude them from being easily integrated into the environment of the mobile wireless communications systems. One technique that is simple, however, can be beneficial enough, is the Switched Beam Smart Antenna system. It consists of a beamforming network of the Butler type or a digital array type that produces a number of fixed multiple beams with predetermined directions in space, followed by a switching mechanism to choose the setting that gives the best performance, usually in terms of received power. Though they resemble traditional sectored antennas from some aspects, they have many more advantages to UMTS over them: better beam shaping, higher sectoring, orthogonal beams, and trunking efficiency.

Of course, simplicity will be on the account of some disadvantages like cusping loss and the degraded performance in rich multipath environment. A number of suggestions are made to enhance their benefits including the use of windowing techniques to gain more suppression in sidelobes directions [96], the use of angular diversity to combine multiple paths coming through different angles, and a number of suggestions to add some adaptivity to the fixed beams systems thereby enhancing their performance.

In Chapter 4 a model for capacity/coverage interaction for WCDMA on the uplink was set up. This model takes into account, amongst other parameters, the interference within the cell and the interference from the surrounding cells when applying the basic equation for QoS in WCDMA. However, smart antennas of any type filter the interference in the spatial domain, which necessitate that the interference from others be re-evaluated. This filtering will affect the boundaries derived for capacity and coverage for WCDMA with conventional antenna. In the next chapter, the model will be re-derived and compared to the omnidirectional case taking into consideration the interference filtering by an antenna of the fixed switched beam type (the SBSA) fitted at the base station.

Chapter 6 User Capacity Modelling with SBSA

6.1 Introduction

In CDMA concept, interference from other users within the same cell and from neighbouring cells limits the maximum admissible connections below which the required quality of service requirements are met. The spatial filtering by antenna of the switched beam type will alter the interference value and consequently the maximum levels. At the same time, the capability of the antenna to have more gain in one direction than in the other directions will produce coverage gain. However, capacity and coverage in CDMA are interrelated and cannot be treated separately. Therefore, in this chapter, a re-derivation of the capacity-coverage interaction model of Chapter 4 with SBSA at the base station will be executed.

In doing so, at first, the interference levels at the beam level must be analyzed and quantified. An effective interference ratio that depends on the omnidirectional ratio and the main parameters of the antenna of gain, beam width (resolution) and side lobe levels through a simple model of the antenna will be derived. This will be used to arrive at the upper capacity bounds. The effect of power limitation on capacity/coverage will then be evaluated using these parameters. Capacity and coverage interaction in a multi-service environment will then be analyzed.

The approach used will be similar to the one used in Chapter 4 to arrive at the capacity/coverage model for WCDMA in general, however, the analysis will be given in three steps: firstly upper interference bounds, secondly the limitation by the user power, and thirdly, the interaction between different services. In every step, a comparison of the gains, if any, for both capacity and coverage with the case of the conventional WCDMA with the use of omnidirectional antenna will be given.

6.2 The Model

In this section, the antenna and system model that will be used throughout this chapter is described. In this model, communication is achieved using CDMA with mobile units equipped with an omnidirectional antenna of unity gain, whereas the base station antenna is a switched beam smart antenna of the UCA type with B main beams covering the cell in an an omnidirectional like coverage. The gain in the direction of the main beam for each of the switchable beams is G_d, and in the direction of other auxiliary beams is G_s (Figure 23-a). A more simplified model shall be used (Figure 23-b) in which the gain is assumed constant and equal to the gain in the maximum direction G_d over the angle covered by the 3 dB bandwidth of the main beam. Similarly, the gain in all other directions is assumed constant and equal to that of the maximum gain G_s in the direction of the auxiliary beams.

The cellular model is a normal hexagonal model in which we have N users requesting a single service and they are uniformly distributed in the cell. Thereafter, with B beams SBSA, N/B users communicate using the same main beam and different scrambling codes. The system is power controlled with the power received being P_r for all users, assuming, at the beginning that they are all requesting the same data rate and the same QoS.

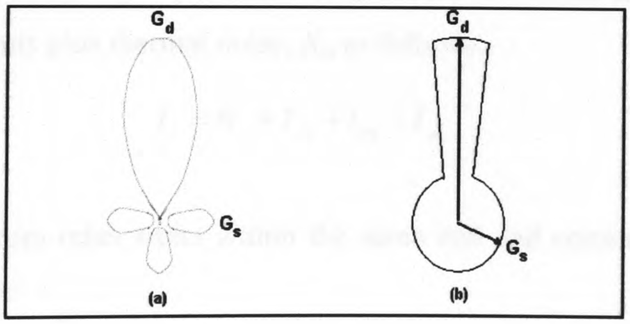

Figure 23: (a) Beam pattern for one beam of a switched beam smart antenna (b) Simplified pattern

As previously described, the interference effect of all users in other cells on the uplink connection reception by an antenna at the base station of an omnidirectional type of the cell under consideration is accounted for using the relative other-cell to same-cell interference ratio, called the omnidirectional interference ratio, f (Section 3.4.2.5), thus,

$$f = I_{oc} / I_{sc} \Big|_{in\ the\ omnidirectional\ case} \tag{6.1}$$

where,

I_{oc}: total interference power contributed by all other mobile units in other cells.

I_{sc}: total interference power contributed by all other mobile units in the same cell.

Therefore, the interference I seen by any user (excluding thermal noise) may be written as:

$$I = (1+f)I_{sc} \Big|_{in\ the\ omnidirectional\ case} \tag{6.2}$$

The use of directional antennas will subdivide the cell into areas that receive different interference levels due to the directional properties of the antenna. Therefore, the demodulator for a given user communicating with the base station over a certain beam will receive interference from all other users (whether in his cell or in any other cell). The magnitude of interference depends on the angle of arrival of the incoming interference. This results with either the main beam or the auxiliary beams at the reception antenna (assuming a line of sight (LOS) environment with no scattering of signals or the scattering angle is much less than the beam width). Thereafter, the total interference and noise power I_t, as perceived by any user of interest, can be attributed to the sum of three interference components plus thermal noise, N_t, as follows:

$$I_t = N_t + I_{sb} + I_{ob} + I_{oc} \tag{6.3}$$

Where

I_{sb}: the interference from other users within the same cell and communicating over the same beam,

I_{ob}: the interference from other users communicating over other beams within the same cell and are coming through the side lobes. Notice that same cell interference, I_{sc}, is the sum of these two sources, or $I_{sc} = I_{sb} + I_{ob}$.

6.3 Effective Interference Ratio

Deriving capacity bounds will depend on the interference level seen by any user, which is contributed to by all users of the same beam, users of other beams and users in other cells as explained in the previous section. Equations (6.1) and (6.2) facilitate the calculation of interference levels in an omnidirectional case. However, for the smart antenna case, the interfering signals are shaped by the beamforming pattern of the antenna at the base station. Therefore, the main beam forms a sector in which interference limits within it determine its capacity and the performance of the links established over it. For clarity, three interference ratios defined as follows are used:

1- f_{inter} : intercellular interference ratio or the ratio of other cell interference, I_{oc}, to same cell interference, I_{sc}, when using beamforming by smart antenna of the simplified model, is expressed as $f_{inter} = I_{oc} / I_{sc}$,

2- f_{intra} : intracellular interference ratio or the ratio of interference from others in the same cell communicating on other main beams, I_{ob}, to interference from others communicating on the same beam, I_{sb}, is expressed as $f_{intra} = I_{ob} / I_{sb}$, and

3- f_{eff} : effective interference ratio or the ratio of other total interference, $I_{ot}=I_{ob}+I_{oc}$, to same beam interference, I_{sb}, is expressed as $f_{eff} = I_{ot} / I_{sb}$.

Thereafter, using these definitions, the total interference I_t given in (6.3) can be written as:

$$I_t = N_t + (1+f_{eff})I_{sb} \tag{6.4}$$

or

$$I_t = N_t + I_{sb}(1+f_{intra})(1+f_{inter}) \tag{6.5}$$

Comparing (6.4) and (6.5) yields,

$$f_{eff} = (1+f_{intra})(1+f_{inter}) - 1 \tag{6.6}$$

When the simplified model of the base station antenna is applied, the equations for I_{sb} and I_{ob} can be expressed as

$$I_{sb} = \frac{N}{B} G_d \upsilon P_r \tag{6.7}$$

$$I_{ob} = N(1-\frac{1}{B})G_s \upsilon P_r \tag{6.8}$$

Therefore, the intracellular interference ratio, f_{intra}, is given by:

$$f_{\text{intra}} = (B-1)\frac{G_s}{G_d} \tag{6.9}$$

Similarly, $1/B$ proportion of other cell interference will be amplified by G_d and the remainder proportion $1\text{-}1/B$ will be amplified by G_s. It is then possible to rewrite the intercellular interference ratio, f_{inter}, for the simplified SBSA pattern as a function of the corresponding intercellular interference ratio f for the omnidirectional as

$$f_{\text{inter}} = \frac{I_{oc}}{I_{sc}} = \frac{1}{B}G_d f + (1-\frac{1}{B})G_s f \tag{6.10}$$

Let $G = G_d / G_s$ be the gain over the side lobe (or front-to-side lobe ratio). Substituting the values of f_{intra} and f_{inter} given in (6.9) and (6.10) in (6.6) yields;

$$f_{eff} = \frac{G(B-1)B + f\,G_d(G+B-1)^2}{G^2 B} \tag{6.11}$$

Clearly, f_{eff}, is linearly related to f and is dependent on antenna constants G, B and G_d.

6.4 Interpreting the Effective Interference Ratio

The new interference ratio, f_{eff}, given by (6.11) determines the level of interference seen by any user as given in (6.4). An antenna with f_{eff} of the same value as the omnidirectional interference ratio f implies that a single beam of the SBSA will have the same capacity as that of an omnidirectional antenna, while a B beam antenna has B times the capacity of the omnidirectional one. Additionally, an antenna with f_{eff} higher/lower than its corresponding omnidirectional f value implies a lower/higher capacity per beam than the omnidirectional case.

For a fair comparison with omnidirectional antennas, it is important to select antenna parameters so that the total power absorbed by any antenna at any given instance of time is the same as that absorbed by an omnidirectional antenna of unity gain in its place. This is to ensure that the comparison will highlight the spatial filtering effect of the smart antenna while other parameters neutralized.

When the comparison is applied, together with the power density plot (that represents the radiation pattern of an antenna), the analysis simplifies to a geometrical problem of ensuring that the area of the surface (formed by the radiation pattern) encompassing an omnidirectional antenna is the same as the area encompassing the SBSA.

However, when the comparison is done in a plane, the geometrical problem simplifies to comparing the circumferences of the polar plots encompassing both antennas, i.e. the unity gain circle of the omnidirectional antenna versus the circumference of the simplified polar plot of a single beam of SBSA accumulated B times.

As a result, the degree of freedom in choosing antenna constants is reduced, i.e. starting with an antenna with certain G and B, the value of G_d (and subsequently $G_s=G_d/G$) must be selected to satisfy the fair comparison rule; therefore yielding $G_d = G/(G+B-1)$. Substituting in (6.11) for f_{eff} yields

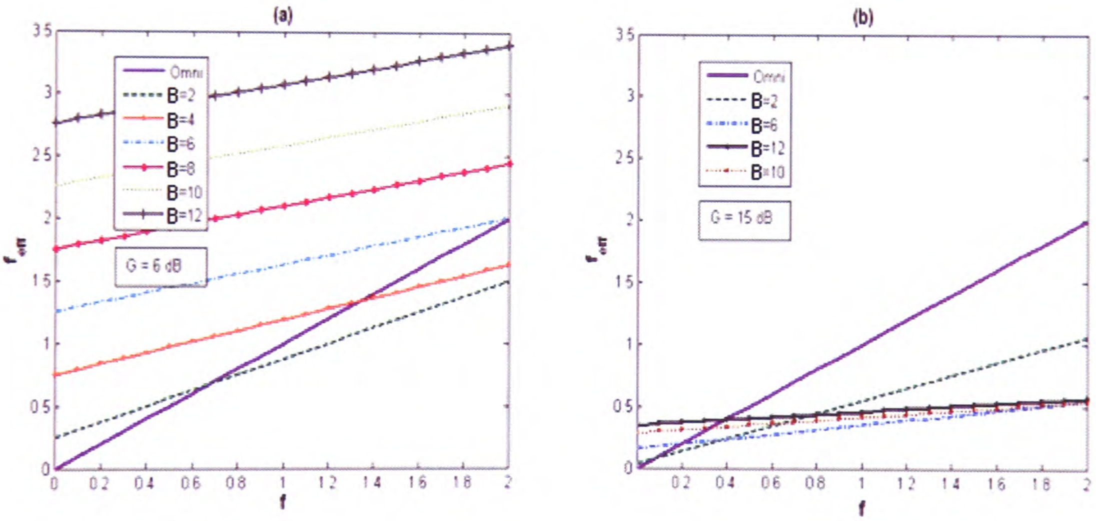

Figure 24: Effective interference ratio variation with omnidirectional intercellular ratio for an antenna with front to sidelobe ratio of (a) $G = 6$ dB (b) $G = 15$ dB

$$f_{eff} = \frac{(B-1)B + f\,(G+B-1)}{GB} \tag{6.12}$$

Equation (6.12) facilitates capacity gain comparisons without violating the fair comparison rule of the omnidirectional and SBSA of the simplified form.

The variation of the effective interference ratio, f_{eff}, with changes in the omnidirectional intercellular interference ratio f is plotted in Figure 24 for different values of G* (Figure 24-a) and B (Figure 24-b). At low f values, the effective ratio f_{eff} tends to be larger than its f equivalent especially for a smaller front to sidelobe ratio as shown in -a. While at high f values, the effective ratio f_{eff} tends to be smaller than its f equivalent, especially for larger front to side lobe ratio as shown in Figure 24-b. Although in both cases, we could have increased capacity because f_{eff} corresponds to single beam interference level as explained earlier in this section.

Hence, it can be deduced that the capabilities of smart antennas to enhance capacity of CDMA manifests themselves more at high interference environments rather than at low interference environments. In other words, in low interference environments the need for spatial filtering of smart antennas to suppress the low interference is less stringent and yields less benefit, while the opposite occurs in high interference environments. The upcoming sections of this chapter deal with capacity and coverage enhancements using SBSA under power limits and multiservice conditiond, hence, they will shed more light on this conclusion.

6.5 Pole Capacity

In CDMA-based systems, quality of service (QoS) must be guaranteed for all users by ensuring that the ratio E_b/N_o at the demodulator input is greater than the threshold required for the modulation type. Therefore, at the threshold of QoS of any service, with the assumption of that outage due to power control error taken into consideration through the factor Γ, i.e. $\gamma = \Gamma . E_b/N_o$, and the received power is P_r, the following equality, which is analogous to the one (Equation (4.3)) given for WCDMA with conventional antennas in Chapter 4, holds

$$\gamma = \frac{W}{R} \frac{P_r G_d}{N_t + (1+f_{eff}) I_{sb} - G_d \upsilon_1 P_r} \tag{6.13}$$

In the previous equation, it is assumed that the intended signal is received through the main beam with a gain G_d, while the interference effect is accounted for using (6.4).

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* The side lobe levels of antennas based on Butler matrices is -13.6 dB with practical values less than -10dB [99], which justifies the selection of the G values in this figure and the rest of the chapter.

Substituting I_{sb} from (6.7) and solving for the maximum number of connections N beyond which QoS is not guaranteed yields

$$N_{\max} = \frac{BW\,G_d P_r - BR_b N_t \gamma}{R_b(1+f_{eff})G_d\,\upsilon\gamma P_r} + \frac{B}{1+f_{eff}} \tag{6.14}$$

The interference limit is the upper limit on the number of users, N_{max}, due to the interference resulting from others without applying a limit on the received power, P_r, i.e. $N_{upper} = \lim_{P_r \to \infty} N$. Applying this limit yields

$$N_{upper} = \frac{BW}{\upsilon R\gamma} F_{eff} + BF_{eff} \quad \text{, where } F_{eff} = \frac{1}{1+f_{eff}} \tag{6.15}$$

With $B = 1$ and $f_{eff} = f$, Equation (6.15) is simplified to (6.16) which represents the interference limit for the omnidirectional case, usually called the *pole capacity*, e.g [72] [48] (also it is the value given by the upper capacity for any class N_{upper} as given by (4.9) in Section 4.3), or

$$N_{upper} = \frac{W}{\upsilon R\gamma} F + F \quad \text{, where } F = \frac{1}{1+f} \tag{6.16}$$

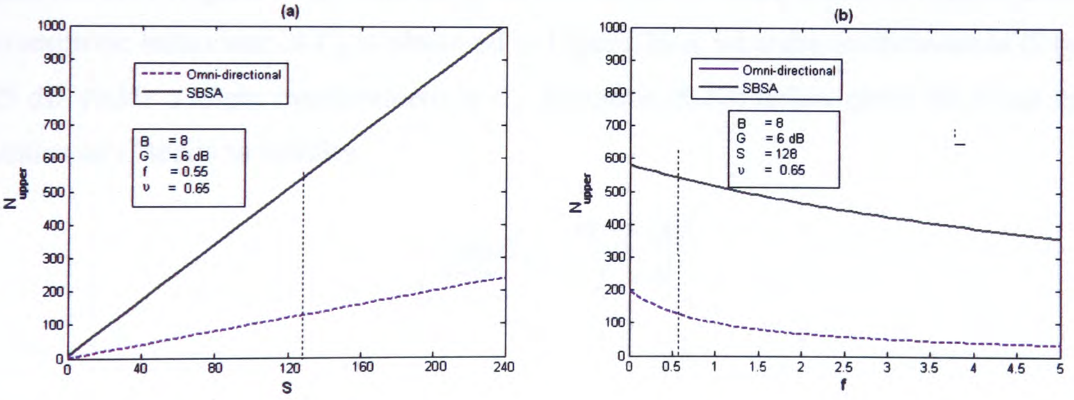


Figure 25: Comparison of the upper limit on connections between an SBSA and an omnidirectional antenna against variation in (a) Service factor *S* (b) Omnidirectional interference ratio *f*

It is noticeable that only the effect of the number of beams appears in (6.15) compared to (6.16) while the antenna gain $\underline{G}$ is not a direct parameter as expected. Of course, all parameters are represented in the interference parameter, the effective interference ratio f_{eff}. Let $S = W / R\gamma$ be called the *service factor* [30]. Figure 25 plots the upper limit on the number of connections for an omnidirectional antenna and for an SBSA against variation in the service factor S (Figure 25-a), and against variation in the omnidirectional intercellular interference ratio f (Figure 25-b). It can be deduced that the use of SBSA improves the upper interference limit in comparison with the omnidirectional case, especially at high interference conditions.

Dividing (6.15) by (6.16) yields the gain C_g of the interference limited capacity (the upper capacity) when using SBSA over its value when using an omnidirectional antenna. An approximation to C_g that is valid for a large number of connections is given by:

$$C'_g = B\frac{F_{eff}}{F} = B\frac{1+f}{1+f_{eff}} \tag{6.17}$$

The previous equation demonstrates the two main sources for capacity improvement with beamforming, SDMA effect or the frequency multiplication factor given by the number of beams B, and SFIR effect given by the ratio of F_{eff} to F (in fact F, and similarly F_{eff}, is a measure of frequency re-use distance [22] in UMTS resulting from interference sharing). SDMA and SFIR are introduced in the previous chapter.

Figure 26 shows how C_g varies with the interference level in the cell for different gain ratios G (Figure 26-a), and for different number of main beams B (Figure 26-b). An asymptotic behaviour of C_g is observed in Figure 26-a, whereby an increase in G beyond 25 dB yields a slight improvement in C_g. Equation (6.18) below gives the value that Cg attains as G tends to infinity.

$$\lim_{G\to\infty} C_g \cong \frac{(1+f)B^2}{f+B} \tag{6.18}$$

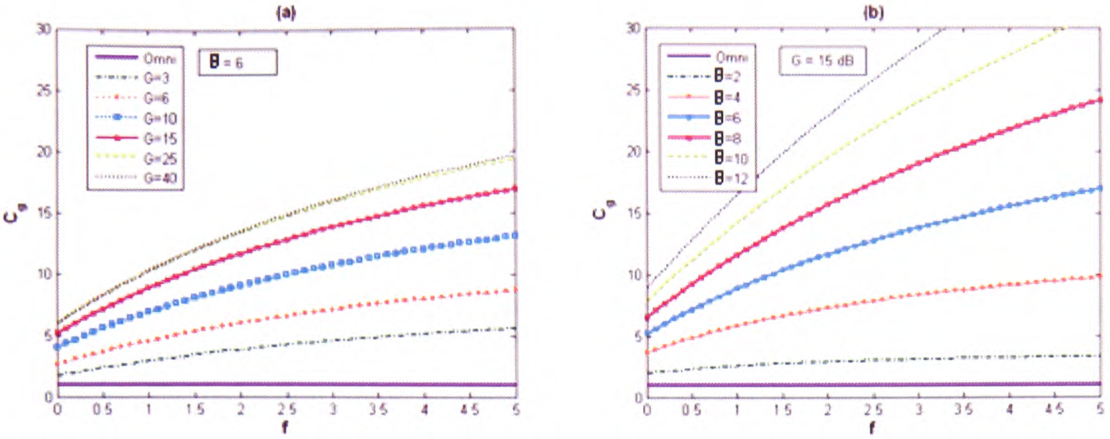


Figure 26: Capacity gain C_g against omnidirectional interference ratio f for (a) different front to sidelobe ratio G in dBs (b) different numbers of main beams K

In the analysis so far, the capacity bounding N_{upper} was obtained, typically for the case of theoretically unlimited power with Switched Beam Smart Antenna. This value can be a value of interest the same way the omnidirectional pole capacity value is used in initial dimensioning and as a rough estimate of capacity in resource management algorithms. In real situations, the antenna is expected to increase the coverage as well. However, in WCDMA the coverage can be increased as we accept to accommodate fewer users in the cell and visa versa as described in [85]. This is attributed to the limited power available to mobile stations and the increased/decreased power requirements as more/less users are in the cell.

In the following section, the analysis will be extended to take into account the effect of this power limitation on both capacity and coverage of the uplink in WCDMA system utilizing SBSA. This will set another bound on capacity, enable coverage bounding and model the capacity coverage interaction. Capacity analysis will resume from the point just before it was assumed that an infinite power was available to any mobile station (i.e. Equation (6.14)) but with finite power received. Coverage analysis will be given also in the section after that.

6.6 Analysis for Limited Uplink Power

6.6.1 Capacity Analysis

In (6.14) the term

$$N_{power} = \frac{BF_{eff}N_t}{G_d \upsilon P_r}, \text{ where } F_{eff} = \frac{1}{1+f_{eff}} \tag{6.19}$$

represents the reduction value in capacity due to power limitation caused by path loss and the limited power on the uplink. Thereafter, the maximum number of users N can be written as $N_{max} = N_{upper} - N_{power}$.

Using $P_s = P_{Smax}$, the maximum available power, in (3.2) and the path loss from Appendix II for a LOS environment give the received power P_r which when plugged in (6.19) yields the maximum number of connections N_{LOS} for a given cell radius r

$$N_{\max}(LOS) = \left(\frac{W}{\gamma R} - \left(\frac{4\pi r}{\lambda}\right)^2 \frac{N_t}{G_d \cdot P_{S\max}}\right)\frac{B \cdot F_{eff}}{\upsilon} + B \cdot F_{eff} \tag{6.20}$$

Using the omnidirectional parameters B=1, G_d=1 and F_{eff}=F, Equation (6.20) simplifies to (6.21), which represents the omnidirectional result, similar to one obtained in [30] (with ε set to 1 and the last F omitted in the reference)

$$N_{\max}(LOS) = \left(S - \left(\frac{4\pi r}{\lambda}\right)^2 \frac{N_t}{P_{S\max}}\right)\frac{F}{\upsilon} + F, \text{ where } S = {}^{W}\!/_{R\gamma} \tag{6.21}$$

Similarly, using the general form of the path loss (L_p=$K_p.d^{C_p}$) in (6.19) yields the capacity equation for the general propagation model

$$N_{gen} = \left(\frac{W}{\gamma R} - \frac{N_t.K_p \cdot r^{C_p}}{G_d \cdot P_{Smax}}\right)\frac{B \cdot F_{eff}}{\upsilon} + B \cdot F_{eff} \tag{6.22}$$

Therefore, the reduction in capacity from the upper capacity (given in the previous section) due to limits on power N_{power} is given by the following two equations

$$N_{power} = \left(\frac{4\pi r}{\lambda}\right)^2 \frac{B \cdot N_t \cdot F_{eff}}{\upsilon \cdot G_d \cdot P_{S\max}} \quad \text{in LOS} \tag{6.23}$$

$$N_{power} = \frac{B \cdot N_t \cdot F_{eff} . K_p \cdot r^{C_p}}{\upsilon \cdot G_d \cdot P_{S\max}} \quad \text{in general model} \qquad (6.24)$$

6.6.2 Coverage Analysis

The maximum distance $d = d_{max}$ is the one at which the mobile unit transmits at its maximum power $P = P_{Smax}$. With these maximum values and using (3.2), (6.7) and the path loss for free space model $L_p(d) = \left(\frac{4\pi d}{\lambda}\right)^2$ (Appendix II) in (6.13) yields the LOS coverage equation when using the switched antenna

$$d_{max} = \frac{\lambda}{4\pi}\sqrt{\left(\frac{W}{\gamma R} - \left(\frac{N}{B} - F_{eff}\right)\frac{\upsilon}{F_{eff}}\right)\frac{G_d \cdot P_{Smax}}{N_t}} \qquad (6.25)$$

Also, the omnidirectional parameters B=1, G_d=1 and F_{eff}=F, Equation (6.25) is simplified further to get (6.26), again similar to one obtained in [30]

$$d_{max}(omni) = \frac{\lambda}{4\pi}\sqrt{\left(S - (N - F)\frac{\upsilon}{F}\right)\frac{P_{Smax}}{N_t}}, \quad \text{where } S = {}^{W}\!/_{R\gamma} \qquad (6.26)$$

Equation (6.25) can be rewritten in the following form

$$d_{max}^2 = d_{intr}^2 - d_{same}^2 \qquad (6.27)$$

where d_{intr} is the free space distance between one transmitter and one receiver limited only by thermal noise, and will be referred to here as the *intrinsic distance*, and d_{same} is the reduction in coverage due to the presence of n interferers. These can be written as in the following two equations (for LOS)

$$d_{intr}^2 = \left(\frac{\lambda}{4\pi}\right)^2\left(\frac{W}{\gamma R} + \upsilon\right)\frac{G_d \cdot P_{Smax}}{N_t} \qquad (6.28)$$

$$d_{same}^2 = \left(\frac{\lambda}{4\pi}\right)^2 \frac{\upsilon \cdot G_d \cdot P_{Smax}}{B . F_{eff} \cdot N_t} N \qquad (6.29)$$

Similarly*, we may write the coverage equations for the generalized path loss model as

---

* Using (3.2), (6.7) and the path loss for the general model $L_p(d) = K_p \cdot d^{C_p}$ (Appendix II) in (6.13).

$$d_{max} = \left(\left(\frac{W}{\gamma R} - \left(\frac{N}{B} - F_{eff} \right) \frac{\upsilon}{F_{eff}} \right) \frac{G_d \cdot P_{S\,\max}}{N_t \cdot K_p} \right)^{1/C_p} \tag{6.30}$$

and

$$d_{\max}^{C_p} = d_{intr}^{C_p} - d_{same}^{C_p} \tag{6.31}$$

where d_{intr} and d_{same} given by the following two equations

$$d_{intr}^{c_p} = \frac{1}{K_p} \left(\frac{W}{\gamma R} + \upsilon \right) \frac{G_d \cdot P_{S\,\max}}{N_t} \tag{6.32}$$

$$d_{same}^{c_p} = \frac{1}{K_p} \frac{\upsilon \cdot G_d \cdot P_{S\max}}{B.F_{eff} \cdot N_t} N \tag{6.33}$$

The defaults for coverage gain over omnidirectional systems in literature, especially when handling resource management issues, is usually of a very simplified nature that overlook other parameters of the antenna system and the interaction between the coverage and capacity given by the second part (d_{same} of (6.31)). A default coverage gain that is proportional to the $\sqrt{G_d}$ (or G_d^{1/c_p} in general) compared to omnidrectional is assumed in [122] [123] This is only true for the intrinsic coverage in (6.32).

6.6.3 Capacity/Coverage Variations with Antenna Parameters

In this section, results for capacity/coverage variation with antenna parameters B and G are presented. Table (1) shows the system and service parameters in the investigation. Plots are generated using MATLAB.

Table 3: System parameters.

PARAMETER	VALUE
Chip Rate, W	**3.84x10^{6}Mcps**
Data Rate, R_b	**30 Kbps**
Voice Activity, υ	**0.65**
E_b/N_o ratio	**3 dB**
Service Factor, S	**64**
Wave Length, λ	**0.15 m**

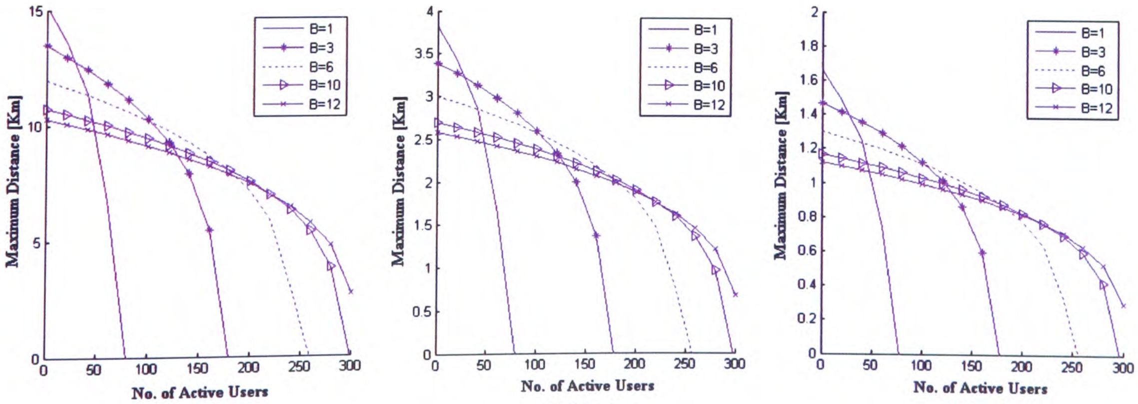
Power Control Correction Factor. Γ	**1**
Thermal Noise Power, N_t	**-103 dBm**
Maximum Transmission Power, P_{Smax}	**125 mW**
Omnidirectional Antenna Gain for the UE	**0 dB**
Inter-Cellular Interference Ratio, f	**0.55**
Height of the basestation, h_b	**50 m**
Height of the mobile, h_m	**1.5 m**

6.6.3.1 Coverage Results

Figure 27 shows coverage variation with number of active-users for different values of the number of main beams, B, and for three different environments. From these plots, we deduce the following:

i. For certain B, the maximum distance is smaller than (Range deterioration) that for omnidirectional antenna or an antenna with a smaller B for a number of users N less than a certain threshold N_{th}. The opposite occurs above the threshold (Range Extension).

ii. The capacity at the threshold of coverage improvement N_{th} increases as we increase B. This demonstrates that directional antennas are more beneficial in improving coverage for cells with higher user densities (higher interference levels).

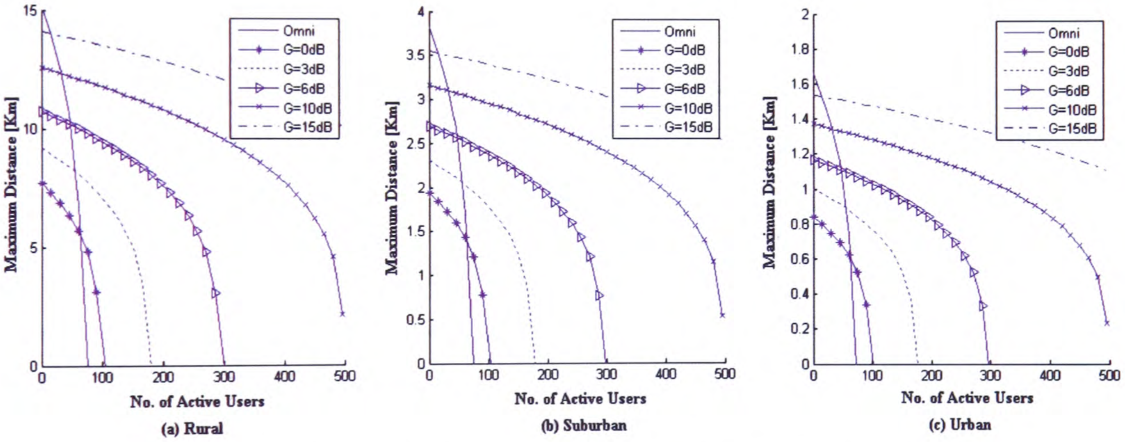


(a) Rural (b) Suburban (c) Urban

Figure 27: Range variation with number of users for different B's (G=6 dB) in 3 environments.

Figure 28 shows coverage variation with number of active-users for different values of the antenna gain *G* (small values of *G* like 0 and 3dB are non-practical), and for three different environments. From these plots, we can deduce the following:

i. As *G* increases cell coverage increases, as expected, for the same number of beams (*B*=10 here) and the same number of users.
ii. Again, for any antenna of a given *B* and *G* coverage improvement over omnidirectional antenna does not happen unless after a certain threshold of number of users is exceeded.
iii. However, the more gain, the less the capacity threshold for coverage improvement over the omnidirectional.



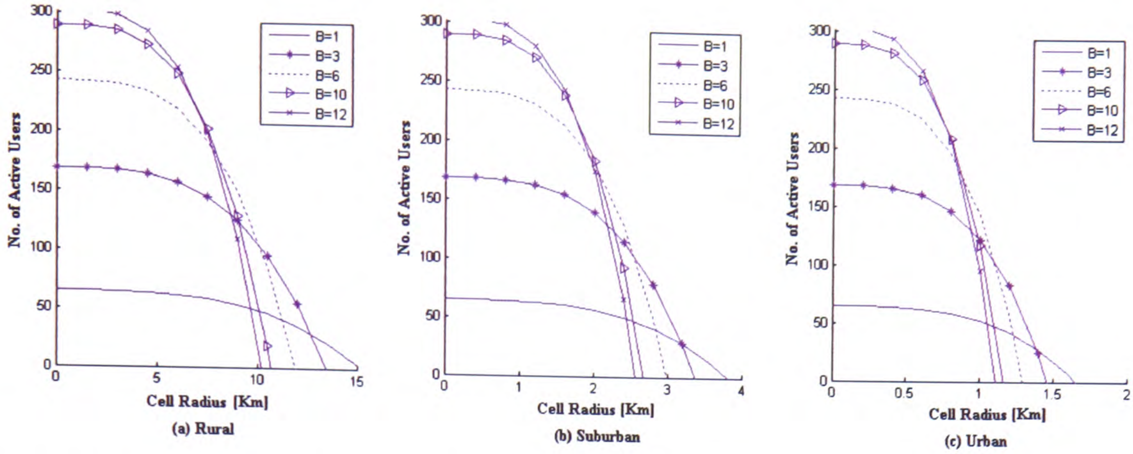
(a) Rural (b) Suburban (c) Urban

Figure 28: Range variation with number of users for different *G*'s (*B*=10) in different environments.

6.6.3.2 Capacity Results

Figure 29 shows capacity variation with cell radius for different values of the number of main beams *B* and for 3 different environments. From these plots we deduce the following:

i. For certain *B*, the capacity is larger (capacity increase) than that for the omnidirectional antenna, or an antenna with a smaller *B*, for a cell radius less than a certain threshold. The opposite occurs above the threshold (Capacity deterioration).
ii. The radius at the threshold of capacity deterioration decreases as we increase *B*.



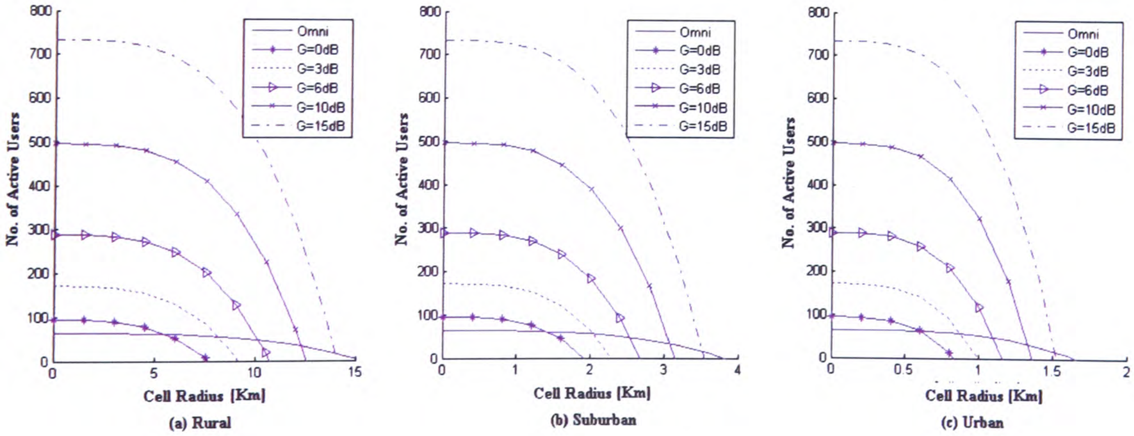
(a) Rural (b) Suburban (c) Urban

Figure 29: Capacity variation with cell radius for different *B*'s (*G*=6 dB) in different environments.

Figure 30 shows capacity variation with cell radius for different values of the antenna gain *G*. and for three different environments. From these plots, we can deduce the following:

i. As *G* increases cell capacity increases as expected, for the same antenna (*B*=10 here) and cell radius.

ii. Again, capacity improvement over omnidirectional antenna does not happen unless the cell radius is less than a certain threshold (for the given gain).



(a) Rural (b) Suburban (c) Urban

Figure 30: Capacity variation with cell radius for different *G*'s (*B*=10) in different environments.

6.7 Multi-Service Capacity/Coverage Analysis

In this section, the analysis continues for capacity / coverage on the uplink of WCDMA system with SBSA type antenna at the base station, however, a more realistic assumption of having more than one service class in the cell is now assumed. Again, analysis is done at first by extending the single service analysis earlier in this chapter to a case of two (and three) services from which a generalization is made to the case of any number of services in a similar way to the analysis given to WCDMA in Chapter 2. The same basic assumptions, namely, even distribution of users of all classes in the cell, path loss models and simplified SBSA model will be used also in the coming analysis.

6.7.1 Capacity Analysis

For two service classes, the threshold of satisfying a certain QoS for the service class 1, the following equality holds:

$$\gamma_1 = \frac{W}{R_1} \frac{P_{r_1} G_d}{N_t + (1+f_{eff}) I_{sb} - G_d \upsilon_1 P_{r_1}} . \tag{6.34}$$

where γ_1 is the $\Gamma.E_b/N_o$ for service 1, R_1 is the bearer data rate for service 1, and I_{sb} is now given by the contribution of the two services as

$$I_{sb} = \left(\frac{N_1}{B}\right) G_d \upsilon_1 P_{r_1} + \left(\frac{N_2}{B}\right) G_d \upsilon_2 P_{r_2} . \tag{6.35}$$

Using (6.34) and (6.35) we may find the maximum number of users of service 1, N_1, beyond which QoS is not satisfied as

$$N_{\max_1} = \frac{B(S_1 + \nu_1)}{(1+f_{eff})\upsilon_1} - \frac{BN_t}{(1+f_{eff}) G_d \upsilon_1 P_{r_1}} - \frac{N_2 \upsilon_2 P_{r_2}}{\upsilon_1 P_{r_1}} \text{, where } S_1 = W / \gamma_1 R_1 .$$

Similarly, for service class 2 we may find the maximum number of users of this service, N_2, to be

$$N_{\max_2} = \frac{B(S_2 + \upsilon_2)}{(1+f_{eff})\upsilon_2} - \frac{BN_t}{(1+f_{eff}) G_d \upsilon_2 P_{r_2}} - \frac{N_1 \upsilon_1 P_{r_1}}{\upsilon_2 P_{r_2}} \text{, where } S_2 = W / \gamma_2 R_2 .$$

We may then use the last two formulae for 2 service classes to generalize the case of arbitrary Q services. The maximum number of users of service q, N_{max}, beyond which QoS is not satisfied can then be written as the combination of three parts (as in Chapter 4, Equation (4.8), rewritten here for ease of referencing)

$$N_{\max_q} = N_{upper_q} - N_{power_q} - N_{others_q}, \qquad q = 1,2,\ldots,Q \tag{6.36}$$

The first and second parts are as given by the previous analysis in this chapter (with the index q to distinguish results for one class from the other). Namely, the first term, on the right side in (6.36), N_{upper} which is the upper limit on capacity for service q, is given by

$$N_{upper_q} = \frac{BW}{\upsilon_q R_q \gamma_q} F_{eff} + BF_{eff} \quad , \tag{6.37}$$

The second term, N_{pl} in (6.36), which is the power limited capacity reduction for service q, is given by

$$N_{power_q} = \frac{BF_{eff} N_t}{G_d \upsilon_q P_{r_q}} \quad , \tag{6.38}$$

Also, N_{pl}, for service q, may be generally written as

$$N_{power_q} = \alpha_q d_q^{C_p} \text{ , where } \alpha_q = K_p \frac{BN_t F_{eff}}{\upsilon_q G_d P_{Smax}} . \tag{6.39}$$

Again, define N_{class} as the capacity of service class q if no other classes exist and is given by $N_{class_q} = N_{upper_q} - N_{power_q}$. The third term in (6.36), N_{others}, for service q, represents the reduction in capacity of service q due to the presence of users of other services $\hat{q}$ ($q, \hat{q} = 1,2 \ldots Q,\ \hat{q} \neq q$). N_{others} is given by

$$N_{others_q} = \sum_{\substack{\hat{q}=1 \\ \hat{q} \neq q}}^{Q} \alpha_{q\hat{q}} N_{\hat{q}} \quad \text{, where } \alpha_{q\hat{q}} = \frac{\upsilon_{\hat{q}} \gamma_{\hat{q}} R_{\hat{q}}}{\upsilon_q \gamma_q R_q}, \tag{6.40}$$

This term, unlike the first 2 terms, is the same given for WCDMA with omnidirectional antenna (Equation (4.15)) with no antenna parameters included. This can be explained on the basis that this term reflects the mutual interference effect of one or more users of one class on the capacity of the users of other classes. Mutual interference is only affected by parameters of rates ratio and activities ratio as given by (6.40). Parameters of the antenna like gain and number of beams tend to influence different classes by the same amount as defined by the model given for the SBSA herein*.

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* Of course, if the model is different, i.e., different classes are treated differently by the antenna, we would expect that the mutual factor to include antenna parameters.

6.7.2 Coverage Analysis

Similar to the capacity case, we start with the two-service case. With $L_p(d) = K_p \cdot d^{C_p}$ and (6.35) in (6.34), the maximum coverage distance for service classes 1 and 2 when the mobile unit transmits at maximum power $P_{S\max}$, can be approximated as

$$d_{\max_1}^{C_p} \cong \frac{S_1 G_d P_{s\max_1}}{K_p N_t} - \frac{N_1 G_d \upsilon_1 P_{s\max_1}}{K_p B F_{eff} N_t} - \frac{N_2 G_d \upsilon_2 R_2 P_{s\max_1}}{K_p B F_{eff} R_1 N_t}$$

$$d_{\max_2}^{C_p} \cong \frac{S_2 G_d P_{Smax_1}}{K_p N_t} - \frac{N_2 G_d \upsilon_2 P_{Smax_2}}{K_p B F_{eff} N_t} - \frac{N_1 G_d \upsilon_1 R_1 P_{Smax_2}}{K_p B F_{eff} R_2 N_t}$$

We may generalize using the previous two equations to the case of a multi-service environment with arbitrary Q services, $d_{max_q}^{C_p} = d_{intr_q}^{C_p} - d_{same_q}^{C_p} - d_{others_q}^{C_p}$ and $d_{class_q}^{C_p} = d_{intr_q}^{C_p} - d_{same_q}^{C_p}$ where

$$d_{intr_q}^{C_p} = \frac{S_q G_d P_{Smax}}{K_p N_t}. \tag{6.41}$$

$$d_{same_q}^{C_p} = \beta_q N_q, \text{ where } \beta_q = \frac{\upsilon_q G_d P_{Smax}}{K_p B F_{eff} N_t} \tag{6.42}$$

$$d_{others_q}^{C_p} = \sum_{\substack{\hat{q}=1 \\ \hat{q}\neq q}}^{Q} \beta_{q\hat{q}} N_{\hat{q}}, \text{ where } \beta_{q\hat{q}} = \frac{G_d \upsilon_q R_{\hat{q}}}{K_p B F_{eff} R_q} \frac{P_{Smax}}{N_t} \tag{6.43}$$

6.7.3 Capacity / Coverage Interaction with SBSA

Based on the previous analysis we may visualize the process of coverage/capacity interaction as follows:

a. Having a single user in a cell with an omnidirectional antenna (B=1), the coverage (an intrinsic coverage) is given by (6.28) for LOS model and by Equation (6.32) for the generalized model. This lucky user can therefore communicate at the intrinsic distance $d=d_{intr}$ (or $d_{same}= d_{others} =0$), for that service class, governed only by the maximum power that its battery allows P_{Smax}, gain of the base station antenna G_d, thermal noise level, N_t, and its service factor, $S(=W/R.\gamma)$. This is the maximum distance any user of the service can attain. It is noticeable that the intrinsic coverage is the one amplified by $\sqrt{G_d}$ (or G_d^{1/C_p} in general) compared to omnidirectional. This is why many research papers, e.g. [122] [123] assume this amplification when handling switched beam antennas at the medium access layer in general. This is more quantified herein.

b. If others, of the same service type, are now in other beams and in other cells for a switched beam antenna such that $N \geq B$, F_{eff} ,by definition, will be less than 1, a reduction in distance (raised to C_p power) proportional to the number of users of this service is given by d_{same} , given by (6.29) for LOS model, that is proportional to $\sqrt{N}$, and by (6.33), for the generalized model, is proportional to N^{1/C_p} , and d_{same} can as approximated as

$$\begin{cases} d_{same}^{2} = \beta_q' N d_{intr}^{2} \text{ , in LOS.} \\ d_{same}^{C_p} = \beta_q' N d_{intr}^{C_p} \text{ , in generalized path loss model.} \end{cases} \tag{6.44}$$

where $\beta_q' = \dfrac{1}{S_q} \dfrac{\upsilon_q}{BF_{eff}}$.

Thus, d_{max} can then be approximated as

$$\begin{cases} d_{max_q}^{2} \cong (1-\beta_q' \cdot N) d_{intr}^{2} \text{ , in LOS.} \\ d_{max_q}^{C_p} \cong (1-\beta_q' \cdot N) d_{intr}^{C_p} \text{ , in generalized path loss model.} \end{cases} {}^{*} \tag{6.45}$$

c. If others, of other service classes, are also in other beams and other cells for a switched beam antenna. The reduction in distance (raised to C_p power) due to a certain other service is proportional to the number of users in that service with a proportionality factor that depends on the service, antenna and system parameters (6.43). This reduction can also be re-written as well in terms of the intrinsic distance as

$$d_{others_n}^{C_P} = \sum_{\substack{\hat{q}=1 \\ \hat{q}\neq q}}^{Q} \beta'_{q\hat{q}} N_{\hat{q}} d_{intr_q}^{C_p} \text{, where } \beta'_{q\hat{q}} = \frac{1}{S_q} \frac{\upsilon_q R_{\hat{q}}}{F_{eff} B R_q}$$

Thus $d_{\max}$ for service q can be approximated as:

---

[*] Therefore, the gain from the antenna directivity is either embedded as coverage gain or capacity gain and the more users the less coverage gain and visa-versa.

$$d^{C_p}_{max_q} \cong (1-\beta'_q N_q - \sum_{\substack{\hat{q}=1\\ \hat{q}\neq q}}^{Q} \beta'_{q\hat{q}} N_{\hat{q}}) d^{C_p}_{i_q}$$

However, when, $q \neq \hat{q}$, $\beta'_{q\hat{q}}$ converges to $\beta'_{\hat{q}}$, and thus we may write the last equation as

$$d^{C_p}_{max_q} \cong (1-\sum_{\hat{q}=1}^{Q} \beta'_{q\hat{q}} N_{\hat{q}}) d^{C_p}_{intr_q}$$

d. Having more and more users of any service in the cell, more and more shrinkage in coverage occurs for the coverage of this service approaching the upper interference limit N_{upper} given by (6.37).

e. Of course, the capacity in the previous clause is for (theoretically) zero coverage (or for users who do not have a limit on their power output). Designing for a certain coverage radius r, which is the typical situation (together with limited power output of the mobile unit $P_{S\max}$), the capacity will be reduced by an amount N_{power} given by (6.39) proportional to the coverage radius r (raised to C_p power). Also, the following approximation applies to N_{power}:

$$N_{pl} \cong \begin{cases} \alpha'_q r^2 N_{upper}, \text{ in LOS} \\ \alpha'_q r^{C_p} N_{upper}, \text{ in generalized model} \end{cases}$$

$$\alpha'_q = \begin{cases} \left(\dfrac{1}{S}\left(\dfrac{4\pi}{\lambda}\right)^2 \dfrac{N_t}{G_d \cdot P_{Smax}}\right), \text{ in LOS} \\ \left(\dfrac{1}{S} K_p \dfrac{N_t}{G_d \cdot P_{Smax}}\right), \text{ in generalized model.} \end{cases}$$

The value N_{class} can be re-written as

$$N_{class_q} = (1-\alpha'_q r_q^{C_p}) N_{upper_q}$$

f. The effect of other users of other services on the capacity of any service q is given by (6.40). Note that the effect of any other service, $\hat{q}$, depends on the number of users of that servisce, $N_{\hat{q}}$, the relative weights of voice activity factors $v_{\hat{q}}/v_q$, and the relative weights of data rates $R_{\hat{q}}/R_q$.

6.7.4 Capacity/Coverage Variation with Antenna Parameters

In this section, as an example on the use of the formulae given in the previous sections, a network with 2 services is analyzed and results are obtained and plotted for capacity/coverage variation with antenna parameters B and G. System parameters used are given in Table (1). Plots were obtained using MATLAB.

Table 4: System parameters.

PARAMETER	**VALUE** Service 1	**VALUE** Service 2
Chip Rate , W	**3.84 Mcps**	**3.84x10^{6}Mcps**
Data Rate, R_b	**15 Kbps**	**60 Kbps**
E_b/N_o Ratio	**3 dB**	**3 dB**
Service Factor, S	**128**	**32**
Wave Length, λ	**0.15 m**	**0.15 m**
Power Control Correction Factor. Γ	**1**	**1**
Thermal Noise Power, N_t	**-103 dBm**	**-103 dBm**
Maximum Transmission Power, P_{Smax}	**125 mW**	**125 mW**
Omnidirectional Antenna Gain (MS)	**0 dB**	**0 dB**
Inter-Cellular Interference Ratio, f	**0.55**	
Service Activity Factor, v	**0.65**	**1**
Height of the base station, h_b	**50 m**	**50 m**
Height of the mobile, h_m	**1.5 m**	**1.5 m**

Figure 31 shows capacity bounds variation for different values of the number of main beams B in suburban environment with cell radius of 1.5Km. It is clear from the plot as B increases the improvement due to using an antenna with more beams diminishes. This is more obvious if we refer to capacity bounds plot in Figure 32 plotted for a larger cell of radius of 2.5Km. In the last figure, capacity even deteriorates for $B=8$ and more. The edge of deterioration will depend on cell radius, the larger the radius the faster this occurs. This again demonstrates that the capacity benefits of switched beam antenna are only manifested in microcells (higher interference conditions).

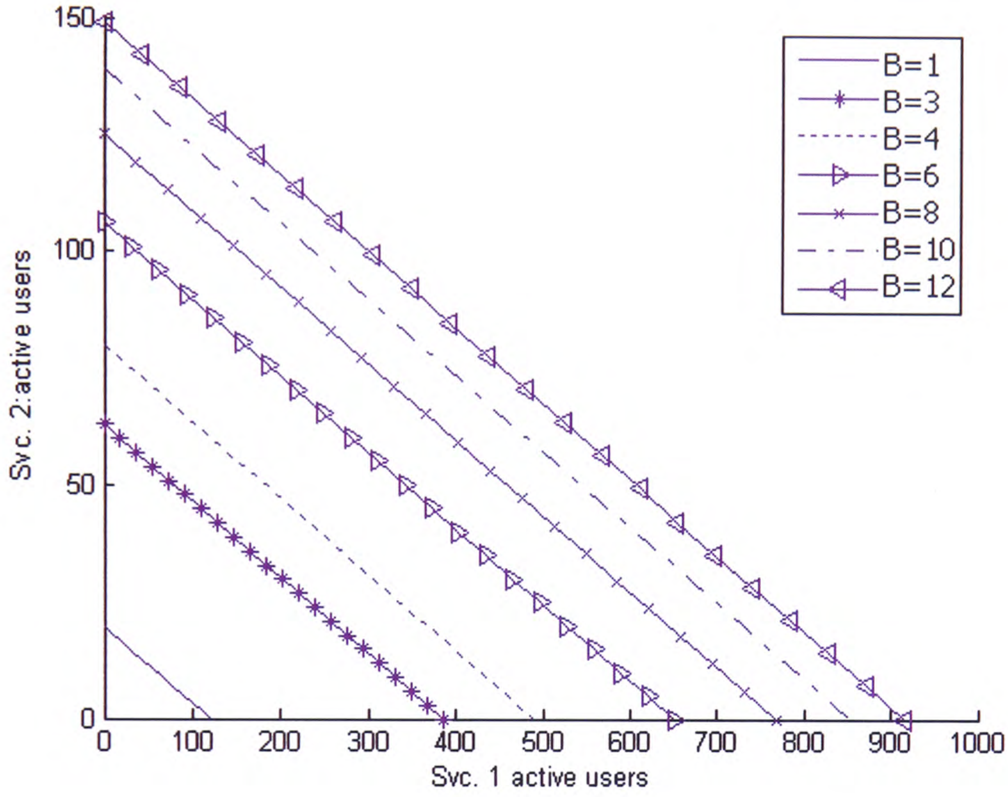

Figure 31: Capacity Bounds Variation with the number of beams in suburban environment (G=10 dB, Cell radius =1.5Km).

6.8 Discussion

A new interference ratio (called the *effective interference ratio*) that is analogues to the intercellular interference ratio for the omnidirectional case was defined for CDMA systems with directional beamforming antennas of the multiple fixed beam type (switched beam antenna). This ratio represents the ratio of the total interference generated outside the beam to the interference generated within the beam itself. Hence, the effective interference ratio can be used to compare the tolerable interference levels in one beam of the *B* beams of a switchable beam smart antenna to that in a complete cell utilizing an omnidirectional antenna. In [89] a similar methodology was used to evaluate the interference at the downlink whereby an *interference rejection ratio* (IRR) was defined and is analogous somehow to the *effective interference ratio* defined herein for the uplink. The IRR considers the loading while f_{eff} does not because the loading in the model herein is taken into consideration using the α and β parameters.

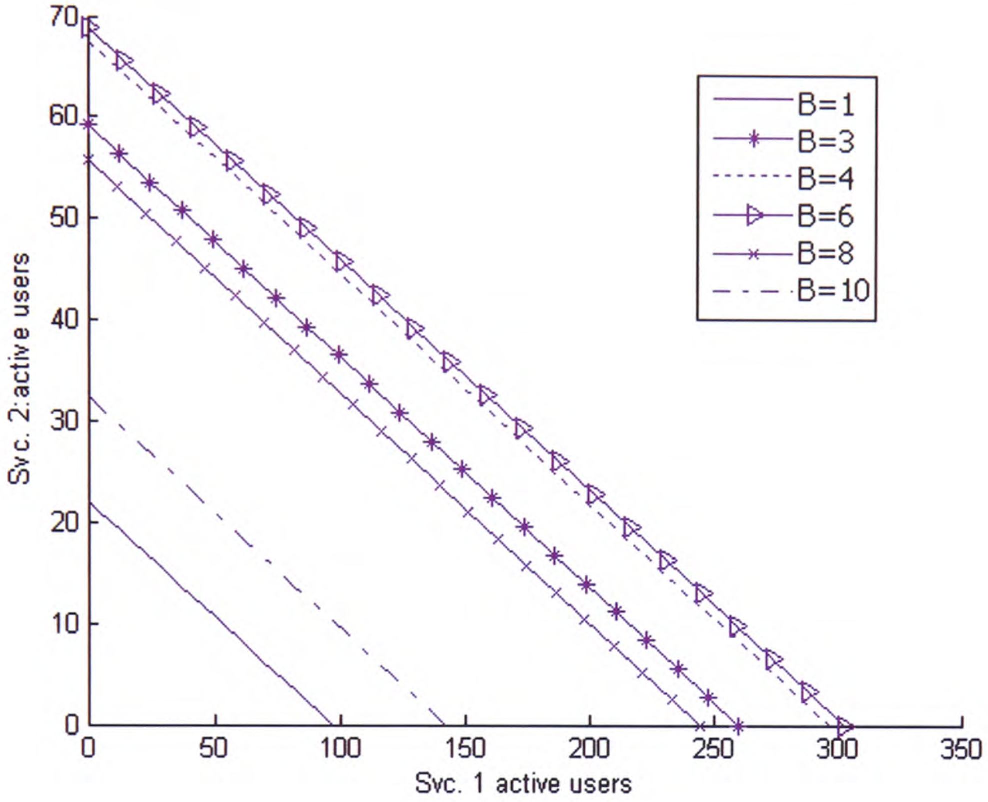

Figure 32: Capacity Bounds Variation with the number of beams in suburban environment (G=10 dB, Cell radius =2.5Km).

Equation (6.12) for the effective interference ratio was obtained for switched beam smart antenna using a simplified model of the antenna radiation pattern (Figure 23-b). The effective interference ratio was found to be dependent on antenna parameters as well as on the omnidirectional interference ratio. Higher values of the effective interference ratio of an SBSA imply a lower capacity in a beam of an SBSA than in a complete cell with omnidirectional antenna (and vice versa). However, the total capacity in the cell will be B times the beam capacity, which means that even if the effective interference ratio is higher than the corresponding omnidirectional case, capacity gain will still, be attainable. It is also shown that the effective interference ratio tends to be higher than its corresponding omnidirectional case as we decrease the front-to-side lobe ratio (gain over side lobes) or increase the number of main beams, which becomes more significant at low interference levels (Figure 24).

Using the model described and the effective interference ratio obtained, the upper limit on the maximum number of connections (equivalent to the pole capacity in WCDMA but with SBSA at its base station) is derived and expressed in (6.15) with equivalent format to that for the CDMA case. In Chapter 4 (Equation (4.9)); i.e. W for the omni case is replaced by $B.W$, with both representing bandwidth, but it is B (number of beams) times increased when SBSA is used. In addition, F for the omni is replaced by F_{eff}, which takes into account the interference filtering of the antenna. Figure 25-a shows the great advantage the pole capacity of a system with SBSA compared to omnidirectional case for the same service (same service factor S ($S=W/R_b\gamma$)). On the other hand, Figure 25-b, , plots the capacity of the same antenna against the variation in the interference coming from neighbouring cells represented by the omnidirectional (intercellular) interference ratio, clearly, capacity with either omni and SBSA will reduce with increased interference from others.

Additionally, Interference limited capacity gain of an SBSA over the omnidirectional case was plotted in Figure 26 against variation of interference conditions in the cell and for different antenna parameters. It is shown that increasing the suppression of sidelobes in order to attain more capacity become non-economical at high front-to-side lobe ratio values due to asymptotic limiting behaviour.

The pole capacity limit is a theoretical limit requesting that all users have no limit on their output power (or theoretically at a zero distance from the receiving antenna). It is independent from distance and propagation conditions. As users have a practical limit on their output power, the power limitation causes the maximum to fall below this limit. A formula for the number of dropped connections due to limited uplink power of mobile units was obtained (Equation (6.23) in LOS and (6.24) in general path loss model). This number is distance/propagation dependent. The effect of antenna gain is to reduce this (thus increasing total capacity) because it boosts power, while the more beams (B) the more reduction due to the increased sidelobe aperture compared to beamwidth aperture. The net capacity is obtained by subtracting this part from the upper capacity limit.

In the case where another service (or more than one service) exists in the cell, the effect any one user of these (other) services on the net capacity so far is more reduction with a reduction (given by (6.40)). The reduction is proportional to their numbers with a proportionality factor(s) that depends on the relative interference effects of the two services dictated by the relative rates, the relative activities and the relative quality requirements (same as in Chapter 4, (4.15)). These proportionality factors are independent from the parameters of the antenna. This is because the reductions are attributed to the relative effects and not to the absolute effects that are dependent on antenna parameters like gain and beam resolution.

Similarly, for coverage, three parts are distinguished. The first part, called the intrinsic coverage, which represents the maximum coverage for a single user in the network, not affected by interferences from others and only limited by thermal noise and the propagation conditions. The second part accounts for the shrinkage in coverage due to the presence of interferers in the network. The net distance (raised to the power of the path loss exponent), when one service exists only, is obtained by subtracting the second part (raised to the same power), shrinkage, from the first part, intrinsic distance (also raised to the same power). The third and final part accounts for further shrinkage in coverage due to the presence of other users of other service types. These are given by (6.41), (6.42) and (6.43) respectively. The net coverage is also obtained by a simple combination of the three parts.

The equations obtained were plotted to highlight the effect of antenna parameters on capacity and coverage (Section 6.6, Figure 27-Figure 30). It was found that coverage improvement by switching from an omnidirectional antenna to directional SBSA of a certain B, number of main beams, and G, gain, cannot be obtained unless the number of served users exceeds a certain threshold. Similarly, increasing the power of the SBSA, by increasing G or B, requires the number of served users exceeds a higher threshold before the benefits of the more powerful antenna appear.

A careful investigation into these results (Section 6.6) reveals that these should be an expected behaviour when combining the coverage-capacity interaction behaviour for conventional UMTS [85] with the SBSA characteristic of increasing the gain in the direction of certain signals within its aperture. In conventional UMTS, increased coverage tends to be accompanied by reduced number of users [85] while an increased gain by the antenna improves the link budget [61] and therefore the coverage. This trend is clearly shown in Figure 30.

Conversely, capacity improvement by switching from an omnidirectional antenna to directional SBSA of a certain *B* and *G* cannot be obtained unless the radius of the serviceable area is less than a certain threshold. Similarly, increasing the power of the SBSA, by say increasing *G* or *B*, requires the threshold descends to a lower value.

The results above can be stated as follows: the improvements by the directional SBSA to either capacity or coverage are only attained at high interference conditions; i.e. higher number of users when considering coverage improvement or smaller coverage areas when considering capacity. The higher the interference conditions are the higher gain over side lobes or an SBSA with more beams is needed to attain improvement. Similar conclusion was found in [89] for the case of the downlink with the use of switched beam antenna: *"The amount of interference experienced by a user during fractionally loaded periods is relatively small, making the impact of employing a switched beam antenna system much less."*.

Finally, a network case with two services were analyzed using the formulae for capacity to study the effect of increased complexity (increased number of beams) of the antenna. The result showed (as before) that the antenna will provide improvements (widening the admissible region for the multiservice case) as complexity increases. However, after a certain number of beams, the increased complexity can be of little advantage to the capacity or even a disadvantage (capacity reduction). Thus, the selection of an antenna of a certain number of beams and gain in a multiservice environment has to be studied in light of the improvement obtained from it against complexity.

The scattering angle parameter was not considered in this analysis and an assumption that the spread is smaller than the beamwidth. In cellular environments, the higher the elevation of the base station results in smaller spread. Considering angle spread results in reduction of the received signal power by the beam due to the spilled power outside the beam. A simple approach suggested in [96] is to modify the gain by an angle spread factor, L_{AS}, computed as $L_{AS}=1-BW/AS$, where *AS* stands for angular spread and *BW* for the beamwidth. In the results obtained, L_{AS} shall modify the gain, G, wherever it appears as a multiplying factor. However, this simple approach does not take into consideration the spilling from other users within the same beam or the possible spilling from users from outside the beam into the beam itself. Extending the model to take into consideration scattering and many of the other simplifications associated with the mode given here (non-ideal flat beam,...etc) is suggested as a further research in the last chapter.

Chapter 7 Conclusions and Future Work

This work is about analysis of the capacity/ coverage problem of WCDMA in a multiservice environment with the use of omnidirectional antenna at the base station or with SBSA. The analysis is a distinctive one that relates the capacity and coverage in the cell to the number of users in each of the services, their activities, rates and other parameters in a multi-service environment obtained at the boundaries of operation. The technique opens the door as a useful tool for traffic analysis and radio resource management techniques in WCDMA and WCDMA with SBSAs.

7.1 Summary of the Thesis

- In Chapter 1, a background chapter for the research, journey through the mobile technology growth from the beginnings is given. An attempt was made to highlight the main joints in technology growth especially those related to capacity provisioning by mobile networks. The issue of space utilization in mobile communications for capacity provisioning and the main features of WCDMA as 3G system, which led to its high capacity, were discussed. This formed a background for the importance of the problem of capacity dimensioning , the motives, and the objectives of the research work that are discussed later together with the elements of the analytical approach of the research work.
- In Chapter 2, an overview of UMTS is given. In the beginning, the spreading spectrum technique as the multiple access technique of WCDMA is described. A description of the construction of UMTS networks and its channel structure is provided. Some of the basic concepts of UMTS that are of importance to the capacity analysis in the following chapters like power control, soft handover, Rake receiver and QoS classes are also presented.
- In Chapter 3 the concept of capacity provisioning and the factors influencing it in WCDMA in addition to traditional and non traditional techniques to enhance capacity are discussed. Soft capacity concept is discussed as a key attribute of WCDMA

allowing for capacity sharing between cells, users and services. The limits on the uplink/downlink in WCDMA are analyzed. A thorough investigation is given afterwards to the factors influencing capacity provisioning in WCDMA: activity factor, signal rate and spreading and orthogonality and spreading codes design as factors related to the signal and its processing, thermal noise level, path loss, shadow fading, multipath fading and multiple access interference as the factors related to the link conditions, adaptive multi-rate , sectored antennas, diversity antennas , code allocation, signalling as factors related to transceiver and antenna architecture.

Radio resource management tools like the call admission, handover control, packet scheduling, and load congestion make use of capacity bounding and their relation to capacity optimization are discussed. Planning for capacity and coverage in WCDMA is generally discussed and together with the basic tools in this planning process of rise over thermal, loading analysis and link budget. Finally, multi-user detection and the new standardized link enhancements HSDPA/HSUPA of the new 3GPP releases are discussed.

- In Chapter 4 based on the understanding of the basic factors influencing capacity provisioning in the previous chapter, a class based capacity and coverage bounding model for the active-user in conventional WCDMA was derived. The analysis performed to arrive at the model uses at first most of the basic factors studied in the previous chapter, the MAI, thermal noise, characteristics of the services, QoS requirements, and other parameters. Later in the chapter guidelines on how the model can be altered to take into consideration many of the practical issues and omitted factors and from the basic model. The provisioning for flexible data rates is also exploited in light of the model given. The model is related to ATM models and therefore a dimensioning approach for traffic capacity using the model is introduced. Comparing of the model and its use in dimensioning with others in research is also given.
- In Chapter 5 the revolutionary methods for enhancing capacity using beamforming antennas and smart antennas in general is discussed. Both analogue and digital techniques for beamforming are discussed. The rest of the chapter is dedicated to the

description of the ***switched beam smart antenna systems*** which are the subject of the capacity/ coverage analysis in the following chapter.

- In Chapter 6 the capacity/ coverage analysis of WCDMA with the use of this antenna (SBSA) at the base station to arrive at the appropriate conditions for attaining its benefits. In doing so, at first, the interference levels at the beam level must is analyzed and quantified. An effective interference ratio that depends on the omnidirectional ratio and the main parameters of the antenna of gain, beam width (resolution) and side lobe levels through a simple model of the antenna is derived. This is used to arrive at the upper capacity bounds. The effect of power limitation on capacity/coverage is evaluated using these parameters. Capacity and coverage interaction a multi-service environment is analyzed.

  The approach used is similar to the one used in Chapter 4 to arrive at the capacity/coverage model for WCDMA in general, however, the analysis is given in three steps: firstly the upper interference bounds, secondly the limitation by the user power, and thirdly, the interaction between different services. In every step, a comparison of the gains, if any, for both capacity and coverage with the case of the omnidirectional antenna is given. The result shows the great advantage the pole capacity of a system gains with SBSA compared to omnidirectional case. The results showed that the antenna will provide advantage as complexity increases. However, after a certain number of beams, the increased complexity can be of little advantage to the capacity or even a disadvantage (capacity reduction). Hence, it is been concluded that the selection of an antenna of a certain number of beams (and gain) have to be studied in light of the improvements obtained from it.

7.2 Main Contributions of the Thesis

In this section, the main contributions of this research work are given. Some of these results are already published/submitted for publication (listed on page 14) in Journals [III] [VII], in conferences [I] [VI] and in research student workshops [II] [IV] [V]. The main contributions/results are as follows:

7.2.1 For WCDMA with the Use of Omnidirectional Antennas

a) The analysis at the edge of satisfying certain QoS requirements in WCDMA results in a model for active-user capacity in WCDMA. Formulae for capacity and coverage bounding are derived for the multiservice case. The resulting formulae are class-based. The formulae obtained take into consideration important features of WCDMA, the services and the environment such as power control, activities of the users, QoS requirements, interference from within the same cells as well as from other cells and the environment urbanizations parameters. Details are in Section 4.3 for the capacity and in Section 4.4 for the coverage, also a quick guide to the symbols is given in the List of Symbols on page xii, results are also in [VII]. A summary of the model is given as follows:

First: Capacity

- Maximum capacity for any class q is given as the result of three parts

$$N_{\max_q} = N_{upper_q} - N_{power_q} - N_{others_q}, \qquad q = 1,2,\dots,Q$$

- N_{upper} is the absolute maximum capacity (interference limited)

$$N_{upper_q} = \frac{WF}{\upsilon_q R_q \gamma_q} + F$$

- N_{power} is the reduction in capacity due to power limit on the uplink

$$N_{power_q} = \alpha_q d_q^{C_p} \text{ ,where } \alpha_q = K_p \frac{N_t F}{\upsilon_q P_{Smax}}.$$

- Class capacity for service q, N_{class}, is defined as the result of

$$N_{class_q} = N_{upper_q} - N_{power_q}.$$

- The reduction due to other classes, N_{others}, is given by

$$N_{others_q} = \sum_{\substack{\hat{q}=1 \\ \hat{q}\neq q}}^{Q} \alpha_{q\hat{q}} N_{\hat{q}} \quad \text{, where } \alpha_{q\hat{q}} = \frac{\upsilon_{\hat{q}} \gamma_{\hat{q}} R_{\hat{q}}}{\upsilon_q \gamma_q R_q}.$$

- Additionally, the upper throughput of service q is

$$T_{upper_q} = N_{upper_q} \upsilon_q R_q = \frac{W}{\upsilon_q \gamma_q} + \upsilon_q R_q F.$$

- For services that accept flexible rating, an up-rating increase ratio ξ_q must satisfy a set of inequalities given by

$$\xi_q \le \frac{N_{upper_q} - \sum_{\hat{q}=1, \hat{q}\ne q}^{Q} \xi_{\hat{q}} \alpha_{q\hat{q}} N'_{\hat{q}}}{N'_q + N_{power_q}}, q = 1...\mathrm{Q}$$

Second: Coverage (N.B. all the terms below are raised to exponent C_p)

- The maximum coverage distance, d_{max}, for any user of any service

$$d_{max_q}^{C_P} = d_{intr_q}^{C_P} - d_{same_q}^{C_P} - d_{others_q}^{C_P} \quad , q = 1, \dots, \mathrm{Q}.$$

- Thermal noise limited distance for a certain service class (intrinsic distance), d_{intr}, is given by

$$d_{intr_q}^{C_P} = \left(\frac{WF}{R_q \gamma_q} + \upsilon_q \right) \frac{P_{Smax}}{K_p N_t F}.$$

- The decrease in distance, d_{same}, for a service q due to the presence of a number of users of this service is

$$d_{same_q}^{C_P} = \beta_q N_q, \text{ where } \beta_q = \frac{\upsilon_q P_{Smax}}{K_p F N_t}$$

- The *class coverage* of service q , d_{class}, is defined as the result of

$$d_{class_q}^{C_P} = d_{intr_q}^{C_P} - d_{same_q}^{C_P}$$

- The reduction in maximum distance for a service q due to other classes, d_{others},

$$d_{others_q}^{C_P} = \sum_{\substack{\hat{q}=1 \\ \hat{q}\ne q}}^{Q} \beta_{q\hat{q}} N_{\hat{q}}, \text{ where } \beta_{q\hat{q}} = \frac{\upsilon_{\hat{q}} R_{\hat{q}} \gamma_{\hat{q}}}{R_q \gamma_q} \frac{P_{Smax}}{K_p F N_t}$$

- In the relevant sections, a discussion of capacity coverage interaction using the above model formulae is given together with other formats of these formulae.

b) Guidelines on how the model can be modified to take into account some of the parameters of system / services are given in Section 4.7 and summarized below:

- Section 4.7.1:Including Shadow Fading ,

  Knowing the outage factor Γ for a given outage probability and shadow fading, both the upper interference capacity N_{upper}, and the intrinsic coverage, d_{intr}, will be modified by a factor of $1/\Gamma$, giving

$$N_{upper_q} = \frac{WF}{\upsilon_q R_q \Gamma \gamma_q} + F$$

$$d_{intr_q}^{C_p} = \left(\frac{W}{R_q \Gamma \gamma_q} + \upsilon_q \right) \frac{P_{smax}}{K_p N_t}$$

  Correspondingly, class capacity N_{class} and class coverage d_{class} will decrease by the same amount in N_{intr} and N_{upper}. For different outage requirements of the different services, the mutual factors will be affected by the ratio of the outage factors, or

$$\alpha_{q\hat{q}} = \frac{\upsilon_{\hat{q}} \gamma_{\hat{q}} \Gamma_{\hat{q}} R_{\hat{q}}}{\upsilon_q \gamma_q \Gamma R_q}$$

$$\beta_{q\hat{q}} = \frac{\upsilon_{\hat{q}} R_{\hat{q}} \Gamma_{\hat{q}} \gamma_{\hat{q}}}{R_q \Gamma \gamma_q} \frac{P_{s\max}}{K_p F N_t}$$

- Section 4.7.2: Including Mobility,

  The same service with different speeds is subdivided into more than one (speed) class, e.g. pedestrians and low speeds, medium speeds and high speeds, each having a corresponding E_b/N_o. Soft handover is treated similarly.

- Section 4.7.3: Including of other Link Gains and Losses,

  The inclusion of these can simply be done by modifying the propagation-multiplying factor K_p by their values.

- Section 4.7.4: Including of Multi-User Detection Effect in the Model,

  In MUD, the interference seen by any user is reduced by ψ (MUD factor). The total interference becomes $I_t = N_t + (1 - \psi + f)I_{sc}$. Hence, simply f shall be replaced by f-ψ in the formulae for capacity and coverage in the model.

- Section 4.7.5: Including Signalling and Control Channels : simply by putting these channels in a class (or more) by themselves.

c) The model is linked to ATM statistical modelling for the multiservice capacity sharing. This enabled the use of ATM results to arrive at a dimensioning tool for traffic (Erlang) capacity in UMTS with capacity sharing between the different users/services considered. This is given in Section 4.8.3. A summary of the steps are as follows:

- From the equation for the maximum number of connections for the limiting class

$$N_{max_q} = N_{class_q} - \sum_{\substack{\hat{q}=1 \\ \hat{q}\neq q}}^{Q} \alpha_{q\hat{q}} N_{\hat{q}} \quad \text{, where } \alpha_{q\hat{q}} = \frac{\upsilon_{\hat{q}}\gamma_{\hat{q}}R_{\hat{q}}}{\upsilon_q \gamma_q R_q}.$$

- Normalizing by the smallest value α_{qm}, then resource units of the different classes are given by

$$c_1 = \alpha_{q1} / \alpha_{qm} \quad c_2 = \alpha_{qm} / \alpha_{qm} \ \ldots \ c_q = 1/\alpha_{qm} \ \ldots \ c_Q = \alpha_{qQ} / \alpha_{qm},$$

- The maximum capacity

$$C = N_{service_q} / \alpha_{qm}$$

- The blocking of the different classes is given by

$$B_q = P(S_q) = P\left\{ (n_1, n_2, \ldots, n_Q) \middle| C - c_q < \sum_{q=1}^{Q} n_q c_q \leq C \right\}$$

This is know a traditional ATM problem that can be solved using different methods (e.g. product form solution described in Section 4.8.2).

7.2.2 For the case of WCDMA with the Use of SBSA:

a) Results for interference analysis at the beam level were obtained (Section 6.3). Hence, the pole capacity (interference-limited capacity) of WCDMA with the use of SBSA is obtained and compared to the case of the omnidirectional antenna in Section 6.5 (Also in [I]). These results are given below:

- The capability of the antenna to reject interference is expressed by the *effective interference ratio* $f_{eff} = I_{ot} / I_{sb}$ is defined and obtained

$$f_{eff} = \frac{(B-1)B + f\,(G + B - 1)}{G\,B}$$

- An expression for the upper interference capacity (a pole capacity)

$$N_{upper} = \frac{BW}{\upsilon R \gamma} F_{eff} + BF_{eff} \quad \text{, where } F_{eff} = \frac{1}{1+f_{eff}}$$

- The gain C_g of the interference-limited capacity with SBSA over that with omnidirectional antenna is approximated as

$$C'_g = B\frac{F_{eff}}{F} = B\frac{1+f}{1+f_{eff}}$$

- An asymptotic limit for capacity gain C_g with increased gain over side lobes is given by

$$\lim_{G \to \infty} C_g \cong \frac{(1+f)B^2}{f + B}$$

b) Capacity/ coverage formulae obtained (Section 6.6.1 for capacity and 6.6.2 for coverage) when considering the limits on the user equipment uplink power in addition to limits imposed by interference from others (for the single service case) with the use of SBSA antenna. Formulae obtained take into consideration many of the important parameters of either the antenna or the WCDMA system. Results are also in [III].These formulae are given below:

- The capacity formula considering the general propagation model

$$N_{gen} = \left(\frac{W}{\gamma R} - \frac{N_t.K_p \cdot r^{C_p}}{G_d \cdot P_{Smax}} \right) \frac{B \cdot F_{eff}}{\upsilon} + B \cdot F_{eff}$$

- While the coverage formula

$$d_{max} = \left(\left(\frac{W}{\gamma R} - \left(\frac{N}{B} - F_{eff} \right) \frac{\upsilon}{F_{eff}} \right) \frac{G_d \cdot P_{S\,max}}{N_t \cdot K_p} \right)^{1/C_p}$$

- The above two equations are given also in the form for free space.

c) A sectional view of improvement gains with SBSA, if any, of either capacity or coverage upon antenna upgrading/downgrading is provided (Section 6.6.3). It is shown that improvements by the directional SBSA of either capacity or coverage, are only attained at high interference conditions; i.e. higher number of users when considering coverage improvement or smaller coverage areas when considering capacity. The higher the interference conditions are the higher gain over side lobes or more beams SBSA are needed to attain improvement. Results are also in [III].

d) Capacity/ coverage formulae in a multi service UMTS environment with consideration of SBSA antenna system were derived. This is analogue to the formulae obtained for the multiservice case for WCDMA in general referred to earlier herein. This is given in Section 6.7.1 for capacity and in Section 6.7.2 for coverage. Results are also in [IV]. A summary of the formulae obtained is as follows

__First: Capacity__

- N_{upper} is the absolute maximum capacity (interference limited)

$$N_{upper_q} = \frac{BW}{\upsilon_q R_q \gamma_q} F_{eff} + BF_{eff} \quad ,$$

- N_{power} is the reduction in capacity due to power limit on the uplink

$$N_{power_q} = \alpha_q d_q^{C_p} \text{ , where } \alpha_q = K_p \frac{BN_t F_{eff}}{\upsilon_q G_d P_{S max}} .$$

- The reduction due to other classes, N_{others} , is given by

$$N_{others_q} = \sum_{\substack{\hat{q}=1 \\ \hat{q} \neq q}}^{Q} \alpha_{q\hat{q}} N_{\hat{q}} \quad \text{, where } \alpha_{q\hat{q}} = \frac{\upsilon_{\hat{q}} \gamma_{\hat{q}} R_{\hat{q}}}{\upsilon_q \gamma_q R_q}$$

__Second: Coverage (N.B. all the terms below are raised to exponent C_p)__

- Thermal noise limited distance for a certain service class (intrinsic distance), d_{intr}, is given by

$$d_{intr_q}^{C_p} = \left(\frac{WF}{R_q \gamma_q} + \upsilon_q \right) \frac{P_{S max}}{K_p N_t F} .$$

- The decrease in distance, d_{same}, for a service q due to the presence of a number of users of this service is

$$d^{C_p}_{same_q} = \beta_q N_q, \text{ where } \beta_q = \frac{\upsilon_q G_d P_{Smax}}{K_p B F_{eff} N_t}$$

- The reduction in maximum distance for a service q due to other classes, d_{others},

$$d^{C_p}_{others_q} = \sum_{\substack{\hat{q}=1 \\ \hat{q}\neq q}}^{Q} \beta_{q\hat{q}} N_{\hat{q}}, \text{ where } \beta_{q\hat{q}} = \frac{G_d \upsilon_q R_{\hat{q}}}{K_p B F_{eff} R_q} \frac{P_{Smax}}{N_t}$$

e) The results obtained showed again (in the case of more than one service, specifically two services were studied) that the antenna increased complexity (increased number of beams) can be of a little advantage to the capacity or even a disadvantage (capacity reduction). Hence, the selection of an antenna of a certain number of beams, gain over side lobes and directional gain have to be done in light of the improvements obtained from it. Results are also in [IV].

7.3 Suggestions for Further Research Work

➢ In fact, Section 4.7 give guidelines on how some of the practical parameters can be inserted in the model and any one of these parameters can form the basis for a more work.

➢ The integration of the model in the dimensioning of WCDMA networks as described in Section 4.8 can form a basis for a wide rang of research ideas. This is because the model given in this study converts the soft capacity of WCDMA somehow into a form like the statistical multiplexing model in ATM networks, which is a well studied subject [49] [88]. Examples of these are

i. The increased rates and differences between the different services in the cell with the introduction of link enhancements like the HSPA enhancements. A number of techniques aare suggested in ATM like the reservation techniques to reform or equalize the blocking probabilities [49] [88]. Additionaly, the dimensioning on a network level, rather than on a cell level, can be a good extension. In this last case, the multi-dimensional Erlang problem will have new dimensions based on the combination of cells involved in the dimensioning or at least one dimension to reflect a variable interference ratio assumption.

ii. Additionally, the study of the blocking at the burst level is also given in these references for the ATM. An adaptation of these techniques with this model will lead to study of throughput and delay-based capacity, efficient techniques for scheduling of grants (packet streams) in WCDMA with enhancements of HSUPA and HSDPA.

iii. An interesting phenomena [49] called *imaginary blocking* which occurs when there exists a big difference between the rates of the services is described in [49]. In this phenomena, low data rate services may exhibit further (non-monotonic reduction in their blockings rates for a certain combination of services, rates and traffic values. The phenomena can be of further importance to the scheduling in WCDMA enhancements characterized by a wide range of rates.

- To modify/upgrade the model for capacity/coverage with SBSA systems to the cases when certain adaptive systems are used at the base station. This will necessitate some modification to the effective interference ratio developed in light of the characteristics of the adaptive antenna.
- Based on the results obtained with SBSA, it was shown that either capacity or coverage improvements using SBSA are attained for certain environment environments only. For dynamic environments, where it is expected that the user densities to change from time to time, the adoption of a certain SBSA of a certain fixed configuration can be a disadvantage at certain times. Advantages can be kept at all times by having a re-configurable antenna (especially digital arrays) in which the maximum number of beams is adaptable (for example, by combining beams) to the environment. The re-configuration shall be in light of the capacity or coverage needs and the model for capacity- coverage interaction given in this thesis can be used.
- In the model given, a uniform user density was assumed, for hot spot analysis, the effective interference ratio obtained may be re-derived taking into consideration a certain interference conditions (e.g. the interference coming from a certain direction being larger than from the other directions). In such a case, this ratio will be different for the beams in the direction of the hot spots than in the other directions. By linking

it to the beam resolution, an optimum configuration can be obtained for the SBSA system.

- To include the directional parameters of the wireless channel [124] in the bounding model for WCDMA (with beamforming antennas) with a consideration of the effect of higher scattering on the model. Other parameters of the antenna ignored by the simplifying model (with flat top) can be subject to more research analysis as well.
- To repeat the research to arrive at a similar model for the downlink of WCDMA. The model in the downlink will have to take into consideration the orthogonality of signals. In addition, the downlink is different in that the location of any user will affect the results (this is in contrast to the uplink in which it is the furthest user only). Another difference is the interference from other cells is mainly contributed by a limited number of base stations.

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Appendix I: OVSF and Scrambling Codes

OVSF Codes

In WCDMA, data is segmented on the physical channels in 10 ms blocks (Release 99 and Release 4) called *frames*. The data in these frames must be spread to achieve a final transmitted chip rate of 3.84 Mcps of the WCDMA. Therefore, in total there will be 38400 chips per frame. To accommodate different bit rates coming into the spreading block, the spreading length must be different. When physical channels are multiplexed into the same frame, the codes should be orthogonal to each other so as to separate them at the receiver. The technique of using orthogonal codes to separate physical channels in the same frame is termed *channelization*.

Orthogonal Variable Spreading Factor (OVSF) codes are used for spreading. The OVSF codes can be explained using the code tree given in Figure 33. In the figure, the codes are represented as $C_{ch,k,n}$. The subscripts uniquely describe a code word in the code tree.

The channelization code has 3 subscripts (ch, k, n). The first subscript "ch" denotes that the code is a channelization code, $C_{ch,k,n}$ where k= length of the code, n = branch of the tree. The first bit transmitted is the leftmost bit in the sequence. Each level in the code tree defines spreading codes of length SF. All codes in the same level (same value of k) are orthogonal to each other. Generating spreading codes can be done using the Hadamard transform [67]. For uplink transmission, DPCCH has a data rate of 150 kbps, and a spreading factor of 256 is used. The OVSF code $C_{ch,256,1}$ is used by the control channel. All the channels having the same data rate are allotted the same spreading code in the uplink.

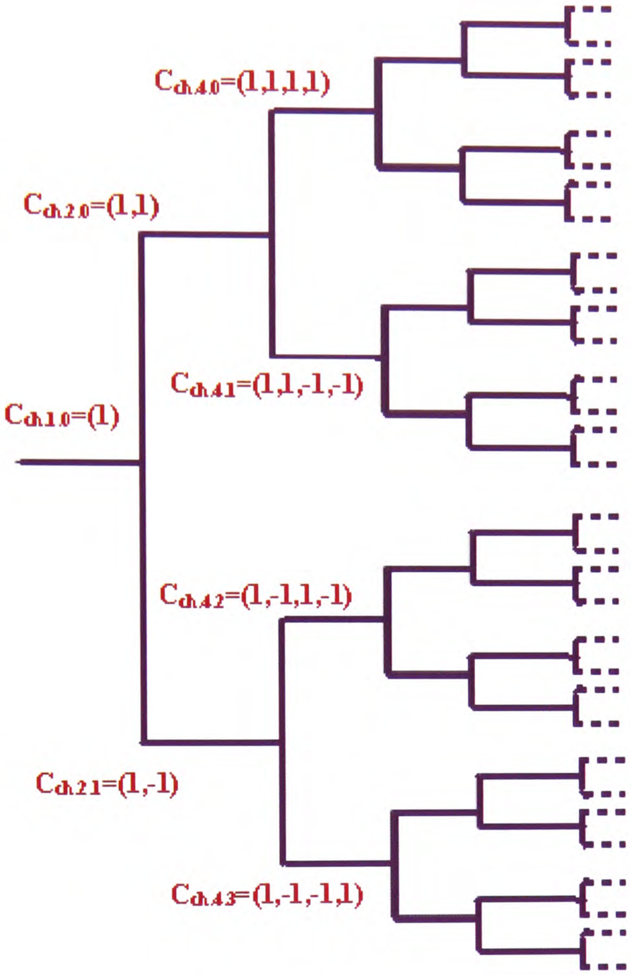

Figure 33: Code Tree.

Scrambling Codes

After channelization using the spreading codes, the code sequence will have 38400 chips/frame. Scrambling is used on top of the spreading. It does not change the signal bandwidth; i.e the chip rate is not altered by scrambling. This is clear from Figure 34. Scrambling codes are used to separate the transmissions from different sources.

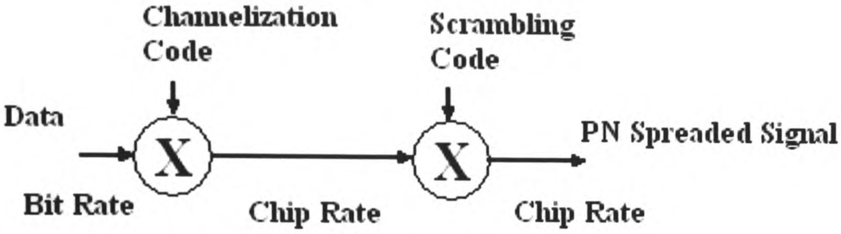

Figure 34: Relation between spreading and scrambling [48].

Scrambling codes (called the pseudo noise, PN codes) are generated using a linear shift register generator with feedback, depicted in Figure 35. Scrambling codes may be long or short codes. The long scrambling codes are Gold codes. The long scrambling codes are used if the base station uses a Rake receiver. The short scrambling code length is 256 chips and they are used when the multi-user detection is adopted [10].

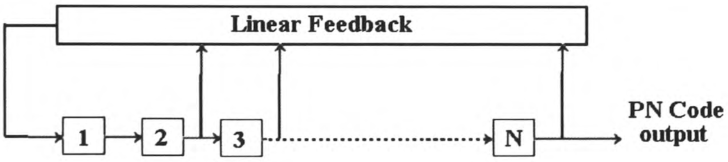

Figure 35: Generating PN code [10].

Appendix II: Path Loss models

Line of Sight Model (Free Space Propagation)

It is the easiest for purposes of mathematical tractability and results obtained using it form an upper bounds on the improvement gains when using the other models under all conditions of propagation (except for conditions like waveguides formed by street canyons which may give rise to path loss exponent of value lower than the 2 of the free space). This is because in any other model much more rapid path loss is expected than in the free space model. The free space model can be looked at as the direct non-vague imprint of the original signal, and all the techniques employed over the two sides of the communication channel like diversity, equalization, and the use of antenna arrays aim to collect the image fragments that are reflected, scattered, and diffracted in order to reproduce a signal as close as possible to the LOS imprint.

In free space communications

$$L_p(d) = \left(\frac{4\pi d}{\lambda}\right)^2 \qquad \text{(II- 1)}$$

which can be written in decibels as

$$L_p(dB) = 32.44 + 20 \cdot \log f_c + 20 \cdot \log d \ . \qquad \text{(II- 2)}$$

where f_c is in MHz and d in Kilometres.

COST 231-Hata Model

The European Co-operative for Scientific and Technical research (EURO-COST) worked on developing an extension of well-known Hata model given for the frequencies 150-1000Hz to cover the PCS bands up to 2000MHz [56]. This combination is called "COST 231-Hata" model. A shorter name "COST-Hata" will be used sometimes in this thesis. The path loss formulae given by this model in different environments is given by

$$
\begin{aligned}
&L_{urban}(dB) = 46.3 + 33.9\log f_c - 13.82\log h_{te} - a(h_{re}) + (44.9 - 6.55\log h_{te})\log d \\
&L_{denseurban}(dB) = L_{urban}(dB) + 3 \\
&L_{rural}(dB) = L_{urban}(dB) - 4.78\cdot(\log f_c)^2 + 18.33\cdot\log f_c - 40.94 \\
&L_{suburban}(dB) = L_{urban}(dB) - 2\cdot(\log(f_c/28))^2 - 5.4
\end{aligned}
\tag{II- 3}
$$

where

$$
a(h_{re}) = \begin{cases} (1.1\cdot\log f - 0.7)h_{re} \text{-} (1.56\cdot\log f - 0.8) \text{ dB, in urban/suburban areas} \\ 3.2\cdot(\log(11.75\cdot h_{re}))^2 - 4.97 \text{ dB, in dense urban, and} \end{cases}
$$

$$
C_M = \begin{cases} 0 \text{ dB in urban areas} \\ 3 \text{ dB in metropoliten centers.} \end{cases}
$$

The model is suitable within the following ranges:

f_c = frequencies in the range 1500 MHz to 2000 MHz,

h_{te} = base station height ranging from 30 m to 200 m,

h_{re} = mobile station height from 1 m to 10 m, and

d = distance from 1 km to 20 km.

The propagation path loss formulae given the model above (or generally any other empirical model) can be written as a function of the distance, d, in the general form

$$
L_p(d) = K_p \cdot d^{C_p} \tag{II- 4}
$$

where

C_p: is a path loss coefficient, which is model dependent

$$
C_p = \begin{cases} 2 & \text{in free space propagation model,} \\ 4.49 - 0.655\log h_{te} & \text{in COST-HATA} \end{cases}
$$

and K_p is a constant (independent of distance), which may be expressed as

$$K_p = \begin{cases} (4\pi/\lambda)^2 & \text{in free space propagation model,} \\ \dfrac{10^{0.456+0.07\cdot h_{re}-0.478\cdot(\log f_c^{\,2})}\cdot f_c^{\,5.379-0.11\cdot h_{re}}}{h_{te}^{1.382}} & \text{in cost 231 model (rural)} \\ \dfrac{10^{4.01+0.07\cdot h_{re}-0.2\cdot(\log(f_c/28))^2}\cdot f_c^{\,3.546-0.11\cdot h_{re}}}{h_{te}^{1.382}} & \text{in cost 231 model (suburban)} \\ \dfrac{10^{4.55+0.07\cdot h_{re}}\cdot f_c^{\,3.546-0.11\cdot h_{re}}}{h_{te}^{1.382}} & \text{in cost 231 model (urban)} \\ \dfrac{10^{5.427-0.32\cdot(\log(11.75\cdot h_{re}))^2}\cdot f_c^{\,3.39}}{h_{te}^{1.382}} & \text{in cost 231 model (dense urban)} \end{cases} \quad \text{(II- 5)}$$

The COST-Hata model is an empirical model that is widely adopted when the land cover is known only roughly, and the parameters required for semi-deterministic models cannot be determined.

COST 231 Walfish-Ikegami Model

The COST 231-Hata model applies only for the cases when the distance to the cell antenna is larger than 1 kilometre. For the distances less than that, the COST 231 Walfisch-Ikegami model [56] may be used (also called COST-WI). The model allows for improved path-loss estimation by consideration of the characteristics of the urban environment of heights of buildings, widths of the roads, building separation, and road orientation with respect to the direct radio path. The accuracy of this empirical model is quite high because in urban environments the propagation over the rooftops (multiple diffractions) is the most dominant part. This model can be used in cases when the base station antenna is placed either above or below the roofline in the urban area.

The model gives the path loss for the case of existing line of sight, LOS, and for non-LOS (NLOS) conditions. In LOS conditions the loss is given by

$$L(dB) = 42.6 + 26\log d\,(Km) + 20\log f\ (MHz)$$

In NLOS the signal loss is given as the sum of three terms*

---

* In cases where $L_{rts} + L_{msd}$ evaluates to < 0, the value of L_b shall be L_{FS}.

$$L = L_{FS} + L_{rts} + L_{msd}$$

where

L_{FS} is the free space path loss .

L_{rts} is the roof-top-to-street diffraction and scatter loss,

L_{ms} is the multi-screen diffraction loss.

The second term, L_{rts}, is caused by diffraction of the signal waves on the building roofs. As a result, the signal reaches the mobile station moving along the street. The third term, L_{ms} , is caused by multiple diffractions from the row of buildings. In the analysis to follow, results (as examples on the capacity/coverage model obtained) will be obtained using the COST-Hata model. Details of the COST-WI model can be found in Chapter 4 of the COST Action final report [56].
