Third generation mobile communications: Capacity of a time-division duplex code-division multiple access cellular system

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Abstract

This thesis describes the work done in evaluating the capacity of a multi-service third generation (3G) wireless communication system based on the Universal Mobile Telecommunication System (UMTS). More specifically, the study presented in these pages examines the Time Division Duplex (TDD) paradigm supported by the 3G Partnership Project (3GPP).

The goal is to establish the probability that a new connection attempt be successful as a function of the instantaneous load on the network. The sought capacity is evaluated with the help of an analytical model and a simulation tool. Both tools used a so-called system-level approach. The model and the simulator were developed based on 3GPP’s standard and available data from link-level simulations.

Some of the significant results presented are:

1. A maximum of around 7 to 9 orthogonal codes can be used per timeslot.

2. A UMTS TDD CDMA system should be used in pico- and micro-cellular environments in order to support efficient data transmissions.

3. The multicode interference is often wrongfully neglected in capacity studies.

4. Capacity is downlink interference-limited, even with a modest MUD efficiency.
Sommaire

Ce mémoire décrit le travail effectué pour évaluer la capacité d’un système multi-services de communication sans fil de troisième génération (3G) basé sur le standard du Système de Télécommunication Mobile Universel (UMTS). De façon plus spécifique, l’étude contenue dans ces pages se penche sur le paradigme d’accès du mode duplex à répartition dans le temps (TDD) tel que proposé par le Projet de Partenariat pour 3G (3GPP).

Le but est d’établir la probabilité qu’une nouvelle connexion soit acceptée en fonction de la charge instantanée du réseau. La capacité est évaluée à l’aide d’un modèle analytique ainsi que d’un outil de simulation. Les deux approches utilisent une technique dite au niveau du système. Le modèle et le simulateur sont développés en se basant sur le standard de 3GPP et sur les données disponibles au niveau de la liaison.

Certains des résultats les plus significatifs peuvent être résumés comme suit :

1. Un maximum d’environ 7 à 9 codes peuvent être employés dans un même intervalle de temps.

2. Un système UMTS TDD CDMA devrait être déployé en pico et microcellules afin de supporter efficacement les transmissions de données.

3. L’interférence de transmission multi-code est souvent négligée à tort dans certaines études portant sur la capacité de systèmes TD-CDMA.

4. La capacité est limitée due à l’interférence sur la liaison descendante, même en utilisant un mécanisme de détection multi-usagers modeste.
Remerciements

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List of Acronyms

3G  Third Generation
3GPP  3rd Generation Partnership Project
ARP  Autonomous Reuse Partitioning
BER  Bit Error Rate
BS  Base Station
CDMA  Code-Division Multiple Access
DCA  Dynamic Channel Allocation
DS-CDMA  Direct-Sequence Code-Division Multiple Access
DTX  Discontinuous Transmission factor
$E_b/N_0$  Energy per Bit to Noise ratio
ETSI  European Telecommunication Standard Institute
FDD  Frequency-Division Duplex
FDMA  Frequency-Division Multiple Access
FRAMES  Future Radio wideAnd Multiple accEss Systems
IMT-2000  International Mobile Telecommunications 2000
kbps  Kilo Bits Per Second
LCD  Long Constraint Delay
LIC  Least-Interfered Channel
MS   Mobile Station
MUD  Multi-User Detection
OVSF Orthogonal Variable Spreading Factor
PC   Power Control
PG   Processing Gain
RACH Random Access CHannel
RU   Resource Unit
SCH  Synchronization CHannel
SEG  channel SEGregation
SF   Spreading Factor
SINR Signal to Interference and Noise Ratio
TD-CDMA Time-Division Code-Division Multiple Access
TDD  Time-Division Duplex
TDMA Time-Division Multiple Access
TS   TimeSlot
UMTS Universal Mobile Telecommunication System
UTRA UMTS Terrestrial Radio Access
W-CDMA Wideband Code-Division Multiple Access
## List of symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{th}$</td>
<td>Additive white Gaussian thermal noise</td>
</tr>
<tr>
<td>$P_{\text{received}}$</td>
<td>Total received power</td>
</tr>
<tr>
<td>$P_{\text{received/code}}$</td>
<td>Received power per OVSF code</td>
</tr>
<tr>
<td>$P_{\text{req}}$</td>
<td>Total required transmit power</td>
</tr>
<tr>
<td>$P_{\text{req/code}}$</td>
<td>Required transmit power per OVSF code</td>
</tr>
<tr>
<td>$L_T$</td>
<td>Total path loss</td>
</tr>
<tr>
<td>$I_{IC}$</td>
<td>Intracell interference</td>
</tr>
<tr>
<td>$I_{\text{ICOM}}$</td>
<td>$I_{IC}$ coming from other mobiles</td>
</tr>
<tr>
<td>$I_{\text{ICMC}}$</td>
<td>$I_{IC}$ due to multicode transmission</td>
</tr>
<tr>
<td>$I_{OC}$</td>
<td>Intercell interference</td>
</tr>
<tr>
<td>$nc$</td>
<td>Number of OVSF codes per TS for one service</td>
</tr>
<tr>
<td>$\theta_c$</td>
<td>Channelization code orthogonality factor</td>
</tr>
<tr>
<td>$f_{MC}$</td>
<td>Multicode transmission interference factor</td>
</tr>
<tr>
<td>$D$</td>
<td>BS separation</td>
</tr>
<tr>
<td>$P_{\text{voice}}$</td>
<td>Voice users proportion</td>
</tr>
<tr>
<td>$P_{\text{LCD64}}$</td>
<td>LCD64 user proportion</td>
</tr>
<tr>
<td>$P_{\text{LCD144}}$</td>
<td>LCD144 user proportion</td>
</tr>
<tr>
<td>$P_{\text{LCD384}}$</td>
<td>LCD384 user proportion</td>
</tr>
<tr>
<td>$P_{\text{ind}}$</td>
<td>Indoor pedestrian user proportion</td>
</tr>
<tr>
<td>$P_{\text{ped}}$</td>
<td>Outdoors pedestrian user proportion</td>
</tr>
<tr>
<td>$P_{\text{veh}}$</td>
<td>Outdoors vehicular user proportion</td>
</tr>
<tr>
<td>$R_c$</td>
<td>Channel coding rate</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Mean of Gaussian random variable</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard deviation of Gaussian random variable</td>
</tr>
<tr>
<td>$\chi$</td>
<td>Shadowing loss</td>
</tr>
</tbody>
</table>
List of symbols

\( \xi \) Building penetration losses
\( \zeta \) \( \chi \) and \( \xi \) combined losses
\( L_k \) Total path loss for MS of interest to \( k^{th} \) BS
\( D_k \) Distance between MS of interest and \( k^{th} \) BS
\( P_k \) Transmission power of \( k^{th} \) BS
\( \Theta_k \) \( \theta_e \) between the signals of cell 0 and cell \( k \)
\( \phi_n^{(i)} \) User \( n^{th} \)’s power proportion for service (i)
\( \psi \) Fraction of the BS power used for traffic channels
\( \eta \) Average power compensation factor
\( I_{OC}/S_0 \) \( I_{OC} \) power to received signal power ratio
\( N^{(i)} \) Number of users in a cell using service (i)
\( \rho^{(i)} \) Service-dependent activity factor
\( G \) Total link gain in dB
\( G_w \) Total link gain in Watt
\( P_m \) MS transmit power requirement
\( I_{bs} \) Interference power at the BS
\( P_{m,\text{max}} \) Maximum MS transmit power
\( \beta \) MUD efficiency
\( I_{IC-MUD} \) Intracell interference with MUD
\( P_b \) BS transmit power requirement
\( I_{ms} \) Interference power at the MS
\( P_{b,\text{search}} \) Broadcast signaling BS transmit power
\( P_{b,\text{min}} \) Minimum BS transmit power
\( P_{b,\text{su,max}} \) Maximum BS transmit power to a single user
\( P_{b,\text{tot,max}} \) Maximum BS transmit power to all users
\( t_s \) Subscript for the parameters of \( I_{OC}/S_0 \)
\( \lambda \) Natural base to dB conversion constant
\( p_{cov} \) Circular cell coverage % with respect to hexagonal cell coverage
Chapter 1

Introduction

Rapid and reliable access to information stands at the apex of our society. To have such an access anywhere and at any time seems to be a promising venue in many fields of life. Simply consider what a stockbroker or a journalist can do with such a possibility.

This research studies a technology that can fulfill the aforementioned task of delivering high-speed information virtually everywhere. This technology is part of the so-called third generation (3G) of personal wireless communication systems.

Tremendous standardization efforts have been displayed during the development phases in order to harmonize the different wireless communication paradigms in operation today [1]. An effort lead by the European Telecommunications Standard Institute (ETSI), resulted in the release of a radio access scheme for third generation mobile radio systems named the Universal Mobile Telecommunications System (UMTS) [2]. This effort is now supported by the influential Third Generation Partnership Project (3GPP), a collaboration of many standardization bodies, and telecommunications companies from all across the globe [3].

The driving force behind the third generation has weakened somewhat in the past year. The deployment of 3G networks was first anticipated for the year 2000 but fate decided otherwise. Fortunately, 2001 saw the first commercial 3G network deployed in Japan by NTT Docomo. Although using a different standard, SK Telecom also commercially released high-rate data services in South Korea. Several operators in Europe have already bought the rights to spectral resources in their countries, hinting that the networks will eventually be deployed. The owners of these highly paid licenses will likely desire a head start on
recovering spectrum investments.

A 3G communication network can support telephone calls, Web browsing, emails, streaming audio and video, and so forth. This network communicates via the antennas of the mobile terminals and the network’s antennas. Thus, the over the air link is a critical part of the system as it is this wireless access that allows the subscribers to be online almost everywhere. This access is specified by the UMTS Terrestrial Radio Access (UTRA). The UTRA consists of two modes:

1. a frequency division duplex (FDD) mode [4], [5], and
2. a time division duplex (TDD) mode [6].

Readers unfamiliar with these concepts will be able to better understand them, as they will be explained in due time. The only noteworthy aspect at this point concerning FDD and TDD is that they are two distinct access methods each having their advantages and disadvantages.

1.1 Scope and Goal of the Thesis

The objective of this study is to investigate the performance of the time division duplex (TDD) version of the third generation of wireless communications currently under standardization within 3GPP. Roughly speaking, the study attempts to provide an estimate of the maximum number of active subscribers cohabiting in a UMTS-TDD network. The subscribers use different services and evolve in different environments. For example, one subscriber could speak with someone while being inside her house. Another subscriber could access a road map while driving her car.

This maximum number of active subscribers is also referred to as the capacity of the network. Evaluating the capacity of a 3G system will be helpful in inferring the new opportunities offered by deploying it, both technologically and economically.

Reaching this goal will require the development of an analytical model. This model will be based on work found in the literature but will also incorporate some original development. A simulation tool will also be constructed to validate the analytical model and to consider various aspects that can hardly be mathematically modeled. Moreover, various capacity-impacting considerations will also be investigated, such as:
1. Introduction

1. the distance between adjacent base stations,
2. the presence of multicode transmission interference,
3. the efficiency of a multiuser detection scheme, and
4. the radio resource management algorithm used.

This study will be done in collaboration with Microcell Connexions, a wireless operator in Canada. The cooperation will mostly be focused on the simulation efforts and on the gathering of data for the model.

The TDD transmission mode is elected because it looks promising in being able to provide high speed, broadband Internet access for both nomadic and mobile users. For reasons that will become clear shortly, TDD’s inherent ability to handle traffic asymmetry and to dynamically allocate spectral resources makes it the next logical step in the investigation of the UMTS (the FDD mode has already been worked upon in Microcell [7]).

Field trials are expected to follow the analysis as well as simulation efforts to validate results and test the technology’s features. This part of the project could be done in collaboration with Siemens AG. Note that these trials will not be included in this thesis. They will, however, influence the simulation parameters.

1.2 Previous Works: Capacity Estimation

The literature is rich in the consideration of different aspects in order to assess the capacity of 3G systems in both duplex modes. From the fundamental deterministic approach [8] to the more thorough investigations of specific systems and hypothesis [9–13], the capacity of CDMA systems has already been studied. The section identifies the main contributions that have been used to guide the elaboration of the analytical and simulation models developed in this thesis.

The analytical model is inspired by work done in [14] for a downlink, CDMA system. The model requires further refinements in order to include UMTS CDMA TDD considerations. As such, interference scenarios and impacts need to be efficiently addressed. The following studies will come in handy for these perpensions [15–20]. Moreover, the different multirate transmission methods’ effect on capacity must be understood. Previous works can be used to reach this goal [21–24].
The simulation tool is based on work previously executed in Microcell [7]. The tool needs to incorporate aspects that can hardly be mathematically modeled. As such, an understanding of the power control mechanism is appreciable. The imperfections and capacity impacts of this mechanism can be severe and need to be consciously modeled. The literature provides several studies on which this work is based [25–28].

The simulation approach offers more flexibility in managing the radio resources of the system. As such, different dynamic channel allocation algorithms will be studied. The following papers were useful in grasping the concepts, in establishing which algorithms are better suited, and in estimating the capacity impacts of using specific algorithms [29–33].

Moreover, the UMTS CDMA TDD system will most likely use multiuser detection schemes in order to reduce interference. This eventuality requires deeper inquiries. The papers [34, 35] are helpful in understanding the concepts and the potential impacts of multiuser detection while [36] presents a simple model to incorporate such schemes in a capacity study.

1.3 Original Contributions

Some original contributions will be presented in this thesis. As such, this study proposes a closed-form expression for the multicode transmission interference. This expression is used in both the analytical model and the simulation tool. The expression allows a concise way of introducing the effect of multicode transmission interference to previous capacity studies.

Secondly, an analytical model based on a previously proposed model for a DS-CDMA system with mixed multirate service bearers is presented. The shown analytical model is an extension of the DS-CDMA model for the capacity study of a UMTS TDD system.

Moreover, some of the displayed results are original. This is especially true for the multicode transmission interference’s influence on the capacity of the system.

1.4 Chapter Contents

The next chapter presents discussions on the capacity of the communication system considered. It also presents the major assumptions that will be considered throughout the work. Chapter 3 develops an analytical model that will be used to evaluate the capacity of
the network and Chapter 4 describes the simulation tool employed to gauge the analytical model and offer more realistic results. Results and interpretations for both the analytical model and the simulation tool are then shown in Chapter 5. Finally, the results and the gained experience are recapitulated in a closing discussion.
Chapter 2

On the Basis of this Study

This chapter offers introductory discussions on the capacity of a code-division multiple access (CDMA) system. It includes a concise introduction to CDMA as well as to the time-division duplex variant. Definitions used throughout this study can be found in this chapter. An original analytical development used to consider various transmission methods is also given. It is followed by a presentation of the principal assumptions made to establish the network’s capacity.

2.1 Short Introduction to Code-Division Multiple Access

This section briefly introduces the concepts of spread spectrum communication and of CDMA. It highlights important concepts used throughout the current study.

The United States’ military developed spread spectrum technology during World War II. It was adopted by commercial entrepreneurs at the beginning of the 1980’s. Its evolution has continued ever since [37].

2.1.1 Advantages of Spread Spectrum Communications

The basic concept of spread spectrum communication is to spread out the information on a much larger bandwidth than the original signal [37]. Proceeding in such a manner offers several advantages, including:

1. permitting the access to a common communication channel by several users at the same time (also known as multiple access);
2. providing resistance to signal interference from multiple propagation paths (or multipath propagation);

3. providing means for hiding the transmitted signal in the surrounding background noise in order to lower the probability of interception by a third party.

These advantages will become explicit in the following sections.

2.1.2 Orthogonal Spreading Codes and Spreading Factors

In any communication medium, it is paramount to be able to distinguish different messages. For example, when two persons are talking to each other, they can easily understand one another if they do not speak at the same time. They separate their messages in time! Thus no inter-message interference occurs.

In CDMA, the signals are not separated in time or in frequency. Instead, they are distinguished by channelization codes, whence the name code division. In mathematical terms, it means that distinct transmitted signals are orthogonal in code space. The inner product of orthogonal signals is zero [38], i.e.

$$< s_i(t), s_j(t) > = \int_a^b s_i(t)s_j^*(t)dt = 0,$$

where $s_i(t)$ and $s_j(t)$ are the orthogonal signals, $[a, b]$ is the interval where the signals are orthogonal and $s^*(t)$ denotes the complex conjugate of $s(t)$. Transmitting several orthogonal signals over a common channel is what is called multiple access.

This study considers the use of the so-called Direct-Sequence-CDMA (DS-CDMA). In DS-CDMA, the channelization code $c(t)$ (or spreading sequence) is multiplied by the information bearing signal $i(t)$, resulting in the transmitted signal $s(t)$. This process is called spreading and is illustrated in Figure 2.1.

Noise and interference corrupt the transmitted signal before it is recovered at the receiver. Denote this received signal as $r(t)$. This signal is then despreaded by multiplying it by the same spreading sequence $c(t)$. This operation is often referred to as correlation of the received signal [37]. The resulting despreader signal $d(t)$ has maximum correlation with $i(t)$. The information signal is thus recovered. Despreading is presented in Figure 2.2.

The channelization codes are relatively long pseudo-random sequences with nice orthogonal properties, such as the Gold codes [37]. The channelization codes are defined by the
chip rate of the spreading system expressed in chips per second (cps) and often denoted as $W$. This study considers a chip rate of 4.096 Mcps even though the current standard defines a chip rate of 3.84 Mcps [39]. The reason for not following the integrity of the standard is simply a matter of finding coherent data for all the aspects of UMTS TDD CDMA communication. Here, most data is coming from a unique source: [40].

Note that the chip rate is greater than the information rate $R$, which typically varies between 8 and 2048 kbps. This is where the spreading comes into play. The rate of the product of a low rate information sequence $i(t)$ by a high rate spreading sequence $c(t)$ is also high. High rate corresponds to large bandwidth, hence the expression signal spreading.

The ratio of the chip rate to information rate in symbols per second $W/R$ is often referred to as the spreading factor and expresses the number of chips per data symbol. The spreading factor gives a good idea of the processing gain ($PG$) of the system. The processing gain of a spread spectrum communication system gives an indication of its resistance to jamming signals. It efficiently reduces the maximum power required for transmission by spreading the power in a wider bandwidth. This means that the energy perceived at the receiver is lower than what would be required without spreading. Note that the spreading factor does not exclusively represent the processing gain [38]. Another form is shown later
in Section 2.3.7.

The signal-to-interference-and-noise ratio (SINR) symbolizes the minimum energy at
the receiver (before de-spreading) required to meet the link quality target per CDMA
code, or the energy-per-bit-to-noise ratio $E_b/N_0$. The SINR is related to the $E_b/N_0$ as
follows:

$$\text{SINR} = \frac{E_b}{N_0} \cdot \frac{1}{PG}.$$  \hfill (2.2)

To see the effect of the processing gain in mathematical terms, consider that $W > R$,
therefore $R/W < 1$, i.e. $PG > 1$. Thus, from equation 2.2, $\text{SINR} < E_b/N_0$, whence the
conclusion of the preceding paragraph.

Spreading factors vary in a CDMA system in order to offer different transmission rates.
Orthogonal variable spreading factor (OVSF) codes are often chosen in many realistic sys-
tems to ensure code orthogonality with multiple spreading factors [22]. The representation
of OVSF code tree with different spreading factors is shown in Figure 2.3.

In the OVSF code tree, each level is labelled as $C_{SF,\text{codenumber}}$, where $SF$ ranges from 1
to 16 and the code number is an identifier that varies from 1 to SF. Choosing codes from
different branches without choosing any of its children guarantees code orthogonality [37].

The interference due to other users could be neglected if the codes were perfectly or-
thogonal. This assumption must be disregarded in most wireless communication systems
due to the multipath propagation of the signals.
2.1.3 On the Time Division Duplex Paradigm

3GPP’s UMTS defines two paradigms for uplink (from the mobile station MS to the base station BS) and downlink (from the BS to the MS) transmissions (i.e. duplex transmissions). They are the (1) Frequency-Division Duplex (or FDD), and the (2) Time-Division Duplex (or TDD) [41]. The goal of these duplex schemes is to assure that no interference occurs between uplink and downlink transmissions.

FDD’s uplink transmissions use a separate frequency band from the downlink transmissions, thus attaining the aforementioned objective. The transmissions can be simultaneous. Each of the two frequency bands is 5 MHz wide. The two bands are separated by a guard band, thus ensuring that no interference is present between uplink and downlink transmissions. FDD is often referred to as Wideband-CDMA (W-CDMA). Figure 2.4 illustrates this approach.

\[\text{Fig. 2.4 Illustration of the FDD duplex scheme}\]

On the other hand, and of particular interest here, TDD separates uplink and downlink by transmitting them at different times (i.e. in different timeslots (TS)). They can therefore use the same frequency band and remain interference-free. Timeslots are separated by relatively short guard periods. See Figure 2.5 for details. This study assumes that no inter-slot interference is possible [17]. Note that TDD is often referred to as Time Division-CDMA (TD-CDMA).

TDD offers more flexibility than FDD since the number of timeslots dedicated to uplink/downlink transmission can vary as a function of the service demand. This is indeed interesting when considering today’s Internet traffic asymmetry [42]. This is also where the
Dynamic Channel Allocation strategies play an important role in managing the available resources.

The 3GPP standard [43] defines the maximum number of orthogonal codes per timeslot to be 16 (meaning that the maximum spreading factor is also 16). There are 15 timeslots per 10 ms radio frames. This is illustrated in Figure 2.6. Note that, because of the very nature of TDD, the base stations need to be synchronized.

This timeslots organization offers great flexibility for asymmetric transmission. As many as 14 timeslots can be assigned to downlink transmission (14:1 transmission ratio) and 13 can be allocated to uplink transmission (13:2 transmission ratio). Please refer to Figure 2.7 for illustration of different but not exhaustive traffic possibilities using TD-CDMA.

In a TD-CDMA system, resources are a combination of OVSF codes and timeslots. The number of resources is limited and the users must share them. Clearly, the required number of resources is service-dependent. A service with high transmission rate will require more
resources than a low rate one.

Many strategies are possible in order to support multiple rates of transmission. One of them is to use several parallel codes with a relatively large spreading factor, as is the case for downlink transmission. This technique was presented in [44]. Another way is to use a smaller spreading factor thus reducing the number of chips per data symbol and increasing the date rate. This scheme was studied in [45]. A combination of the two techniques is also possible, as is the case for uplink transmission.

Another advantage of TD-CDMA is that the channel used for uplink is very similar to the one used on the downlink since they occupy the same frequency band and use the same antennas. Therefore, the propagation characteristics could be estimated on the downlink and used to improve uplink transmissions, thus reducing the signaling needs.

For further information on spread spectrum communication and CDMA, the reader is invited to consult books by Proakis [38] and Rappaport [46] for general information and by Peterson et al. [37] and Prasad [47] for more detailed inquiries.

2.2 Definitions Used Throughout the Work

In this section, important definitions are given as a reference for the forthcoming chapters. The concepts introduced will frequently be encountered throughout this work. Also en-
closed is an original analytical development used to consider various transmission methods enumerated in Section 2.1.3.

2.2.1 What is Meant by Capacity

Roughly speaking, the sought capacity can be defined as the maximum number of subscribers that can cohabit the network at any given time with acceptable performance. This statement requires clarification.

The subscribers use different services. Some are simply talking on the phone, others are browsing the Web for recipes, and some are listening to music videos of their favorite performer. The possibilities are, of course, endless. Each of these subscribers thus requires different resources from the network and with different levels of quality. A delay in loading a Web page is not as critical as a delay in the voice of a person in terms of subscriber perception and satisfaction. That is, in part, what is meant by acceptable performance.

The number of subscribers connected to the network will vary in time since, for example, a phone call inevitably ends when people have finish talking to each other. However, this study is not interested in the time varying characteristics of the subscribers. Instead, it focuses on the maximum number of subscribers that can cohabit the network at the peak usage time with acceptable performance. This means that the study is interested in the saturation state of the network.

To further understand capacity in mathematical terms, consider the well-known formula presented by Gilhousen et al. in [8] (using the notation from previous sections)

\[ \frac{E_b}{N_0} = \text{SINR} \cdot PG = \frac{P_{\text{received}} \cdot PG}{I + N_0}, \]  

(2.3)

where \( P_{\text{received}} \) is the received signal power, \( I \) denotes the interference from other users, and \( N_0 \) is the power of the background noise. A very simple and straightforward assumption is to consider that all of the users’ signals in the system are received at equal power \( P_{\text{received}} \), hence \( I = (N - 1) \cdot P_{\text{received}} \), where \( N \) is the total number of users in a cell. Including this simplification in equation 2.3 yields

\[ \frac{E_b}{N_0} = \frac{P_{\text{received}} \cdot PG}{(N - 1) \cdot P_{\text{received}} + N_0}. \]  

(2.4)

Isolating \( N \) comes down to expressing the system’s capacity. Note that CDMA provides
a graceful trade-off between the number of users and the perceived interference. That is, as the number of users increases, so does the interference. This is singularly different from the traditional multiple access schemes (TDMA and FDMA). Hence, CDMA has [46]:

1. a soft capacity limit reached when too much interference prevents new users from being accepted to the network, and
2. a hard capacity when all of the codes in the OVSF code tree and in every timeslot are exhausted.

Note that equation 2.4 serves as a basis for the model in Chapter 3 but is further refined to consider various important aspects.

2.2.2 Blocking Connections

Subscribers attempting to connect to the network can either be accepted or blocked. Accepted users simply complete their transactions. Blocked users are denied service. The reasons for rejecting a user are:

1. insufficient power available for the downlink connection;
2. insufficient power available for the uplink connection;
3. there is a shortage of resources (codes/timeslots) for this connection;
4. the new connection would make existing connection(s) drop.

The results presented in Chapter 5 of this study are oriented to give network designers an indication of the number of subscribers with respect to the blocking probability. In other words, operators considering a network rejecting $p$ percent of the requests could support around $N$ users, based on the results of this study. This could translate to the Erlang capacity.

2.2.3 Dropping Connections

Once a subscriber is accepted on the network, she will leave the network when her transaction is completed or when the network drops her. A dropped user did not intend to have its current operation stopped.
This phenomenon can occur when the user is located near the cell’s edge and the load in the cell increases, causing \textit{cell breathing}. This means that the actual size of the cell shrinks [46].

Another cause of a user being dropped is the near-far phenomenon. The power consumption of users closer to the base station tends to overshadow the signals transmitted by users further away. This problem can be overcome by using power control techniques. However, power control cannot be perfect [26] and thus dropping is still a possibility.

Note that dropping is very bad in terms of subscriber’s satisfaction since it is felt directly. It is quite annoying to have a telephonic conversation abruptly stopped. Hence the importance of minimizing this eventuality.

\subsection*{2.2.4 On Multipath Propagation}

Wireless communications mainly relies on transmission of electromagnetic waves in free space. These waves are affected by their environment in a similar way that sound waves are. For example, the wireless signals are absorbed and reflected by obstacles such as trees and buildings. The absorbed part of the signal is forever lost. However, the reflected parts eventually arrive at the receiver. These reflected signals are delayed since they usually travel longer distances than the unobstructed signal. This causes the so-called \textit{multipath} propagation interference.

Figure 2.8 illustrates the multipath propagation phenomenon. In this Figure, the distance for the direct wave is smaller than the one reflected by the building and the one reflected by the trees.

In CDMA, since the signal gets corrupted by itself (i.e. its own reflected components), it is impossible to consider that it is any longer perfectly orthogonal to the other signals. However, the additional information provided by the different paths can be used to better decipher the information, as can be seen in [48]. These detection techniques use the \textit{diversity} of the signal of interest to enhance the receiver’s performance.

\subsection*{2.2.5 Single User Multi-Spreading Factor Transmission}

The uplink transmission must be power efficient in order to preserve battery life. By using a single (or two in some cases) code per timeslot and different spreading factors, a smaller peak-to-average transmission power ratio is achieved [49]. This results in a lower power
consumption than the multicode technique used on the downlink. Hence, it is attractive as an uplink transmission architecture.

What is the required transmission power at the base station to achieve acceptable quality of service on the air interface? That question is answered by using equation 2.3 and the following development.

The received power at the end of the transmission link $P_{\text{received}}$ will be equal to the transmitted power $P_{\text{req}}$ attenuated by the path loss $L_T$ and affected by the imperfect downlink power control $PC$:

$$P_{\text{received}} = P_{\text{req}} L_T / PC.$$  \hfill (2.5)

Replacing equation 2.5 in equation 2.3 results in

$$P_{\text{req}} = (I + N_0) \cdot \frac{SINR \cdot PC}{L_T}.$$  \hfill (2.6)

$$= (I_{IC} + I_{OC}) \cdot \frac{SINR \cdot PC}{L_T},$$  \hfill (2.7)

where $I_{IC}$ and $I_{OC}$ are the intracell and intercell interferences, respectively, and $SINR$ is the required SINR to achieve proper quality of service per transmitted code. All of these powers are in Watt. Equation 2.7 splits the interference into intra- and intercell interferences and considers that the noise $N_0$ is part of the intercell interference $I_{OC}$. Note that $L_T$ is always smaller than 1 and that a $PC > 1$ denotes an unfavorable power control error.
The required power $P_{\text{req}}$ illustrates the power needed to overcome the environment constraints affecting the transmission link. The constraints include the path loss, the shadowing, the interference (including the background noise), and the requirement in terms of signal to noise ratio.

The $SINR$ per code was expressed in equation 2.2 when $E_b/N_0$ was defined as being the energy-per-bit-to-noise ratio per CDMA code, as is the case in [40] and here.

### 2.2.6 Single User Multicode Transmission

It is preferable to use a large spreading factor for the downlink transmission [6] since it facilitates the development of low cost terminals. An original analysis of the resulting interference from using multicode transmission is given in this section. It is partly based on analysis showed in [21] and [24].

**Multicode interference contribution**

When a base station transmits information on multiple codes, it will suffer interference from its own codes as well as inter- and intracell interference and background noise. The multipath environment will inevitably remove part of the code orthogonality, thus introducing interference between the codes. In this analysis, the background noise is treated within the intercell interference.

Based on equation 2.7, the required transmit power in the case of multicode transmission can be expressed as

$$P_{\text{req}} = (I_{IC} + I_{OC}) \cdot \frac{nc \cdot SINR \cdot PC}{L_T},$$

with the only difference residing in the definition of the intracell interference $I_{IC}$ and in the $nc$ factor. $I_{IC}$’s definition will follow shortly and $nc$ denotes the number of codes used during a multicode transmission. Hence, $P_{\text{req}}$ symbolizes the required power for all transmitted codes.

To consider the different aspects of multicode transmission, it is imperative to adjust the transmitted power for the several codes. Since $nc$ different codes (i.e. $nc$ different signals) are transmitted, the total power required is $nc$ times greater than the power used to transmit one code, i.e. the power will be increased by a factor of $10 \cdot \log_{10}(nc)$ dB. The
power required to transmit one code is denoted $P_{\text{req/code}}$ and is given by

$$
P_{\text{req/code}} = \frac{P_{\text{req}}}{nc},
$$

(2.9)

The same applies to the received power $P_{\text{received}}$ and the received power per code $P_{\text{received/code}}$.

A user that uses $nc$ parallel codes to transmit information is equivalent to $nc$ similar and co-located users using 1 code each. Therefore, each of the $nc$ codes suffers from the interference of the other $nc - 1$ codes. If the codes are perfectly orthogonal, no interference occurs. Considering multipath fading, this assumption is an exaggeration. Hence, the intracell interference $I_{IC}$ is composed of two terms:

$$
I_{IC} \equiv I_{\text{othermobiles}} + I_{\text{multicode}} \equiv I_{\text{ICOM}} + I_{\text{ICMC}}.
$$

(2.10)

The $I_{\text{ICMC}}$ is the interference due to other codes. It can be expressed as [24]:

$$
I_{\text{ICMC}} = (nc - 1) \cdot P_{\text{received/code}} \cdot \theta_e
$$

(2.11a)

$$
= \frac{(nc - 1) \cdot P_{\text{req}} \cdot \theta_e \cdot L_T}{nc \cdot PC}
$$

(2.11b)

$$
= (nc - 1) \cdot (I_{IC} + I_{OC}) \cdot \text{SINR} \cdot \theta_e,
$$

(2.11c)

where $\theta_e$ denotes the orthogonality factor between spreading codes that varies from 0 (perfect orthogonality) to 1 (no orthogonality) and depends on the environment. Remember that the path loss affecting each code is the same and can be factored out, as shown in equation 2.11c.

Using equation 2.10 in 2.8 and substituting $I_{\text{ICMC}}$ from equation 2.11b, $P_{\text{req}}$ becomes

$$
P_{\text{req}} = \frac{(I_{\text{ICMC}} + I_{\text{ICOM}} + I_{OC}) \cdot nc \cdot \text{SINR} \cdot PC}{L_T}
$$

(2.12)

$$
= \frac{I_{\text{ICMC}} \cdot nc \cdot \text{SINR} \cdot PC}{L_T} + P_{\text{Other}}
$$

(2.13)

$$
= \frac{(nc - 1) \cdot P_{\text{req}} \cdot \theta_e \cdot L_T \cdot nc \cdot \text{SINR} \cdot PC}{L_T} + P_{\text{Other}},
$$

(2.14)

where

$$
P_{\text{Other}} \equiv \frac{(I_{\text{ICOM}} + I_{OC}) \cdot nc \cdot \text{SINR} \cdot PC}{L_T}.
$$

(2.15)
After some manipulations, it can be seen that the required transmission power is

\[ P_{\text{req}} = \frac{P_{\text{Other}}}{1 - (nc - 1) \cdot \theta_e \cdot \text{SINR}} \]  

(2.16)

if \((nc - 1) \cdot \theta_e \cdot \text{SINR} \neq 1\). Moreover, a negative denominator is proscribed since a power cannot be smaller than zero. Failure to comply would result in blocking of the connection. These unwanted events will never occur in this study (based on data from the following sections).

In extremes cases where \(nc\) is high and/or \(\theta_e\) is close to one, it is possible that a user be denied service even if no outside interference is present. This unwanted event would occur when \((nc - 1) \cdot \theta_e \cdot \text{SINR}\) approaches unity. The operating range of a real-world system would avoid these events by trading off the SINR requirements and the number of codes intelligently.

Hence, the multicode transmission interference factor is simply:

\[ f_{\text{MC}} = \frac{1}{1 - (nc - 1) \cdot \theta_e \cdot \text{SINR}}. \]  

(2.17)

This factor directly influences the required transmit power. Note that \(P_{\text{Other}}\) is the \(P_{\text{req}}\) typically considered in most capacity studies. Also note that the \(P_{\text{req}}\) with multicode interference will be greater than \(P_{\text{Other}}\) since \(f_{\text{MC}}\) is always greater than unity in this study.

### 2.3 Major Assumptions for the Network and for the Subscribers

This section presents the network layout as well as the principal characteristics of the subscribers. Whenever a new subscriber is candidate for admission to the network, there are a number of parameters that are randomly selected. The probability distributions of these parameters are described below. The presented assumptions are of a general nature and are used both in the analytical model of Chapter 3 and in the simulator of Chapter 4.

#### 2.3.1 Network Configuration

The layout of the base stations needs to be established before any user can be introduced. A clover-like arrangement of tri-sectored base stations is assumed for the network. This approach is typical for macro- and even micro-cellular environments [50]. The layout is
constituted of 25 sites, or 75 cells (sectors). The border effects in interference calculation are eliminated by using a \textit{wrap-around} technique, as illustrated in Figure 2.9. The distance $D$ between two adjacent base stations is a varying design parameter.

![Configuration of base stations assumed in the study](image)

Fig. 2.9  Configuration of base stations assumed in the study

The entire network operates at a constant chip rate and uses the same user bandwidth $B$ and modulation scheme. The chip rate is 4.096 Mcps. The bandwidth is 5 MHz and the modulation scheme is QPSK. Note that only one frequency carrier is considered on the network.

\subsection*{2.3.2 Geographic Positioning of the Subscribers}

A new subscriber is positioned according to a uniform two-dimensional distribution within the limits of the layout (i.e. excluding the wrap-around). This is reasonable since the subscribers do not have any \textit{a priori} knowledge of their relative position to the base stations.

\subsection*{2.3.3 Offered Services}

Four types of services (bearers) are considered in this study, namely:
1. Speech
2. LCD64 kbps
3. LCD144 kbps
4. LCD384 kbps

Throughout this study, the proportions of subscribers of each service are considered to be known \textit{a priori} and are denoted $P_{\text{voice}}$, $P_{\text{LCD64}}$, $P_{\text{LCD144}}$, and $P_{\text{LCD384}}$. Moreover, each service is characterized by:

- The number of resources taken by the mobile. Resources include the number of OVSF codes and the number of timeslots needed during transmission. The required resources depend on the transmission direction and on the service. This information can be found in Table 2.1 and Table 2.2.

- A set of nominal service thresholds for different propagation conditions (pedestrian/indoor, vehicular) in terms of SINR required to meet minimum performance. They are found in Table 2.3.

- A channel encoding rate. Since each service has its own requirement in terms of delays and errors, different channel coding schemes are advised. The channel encoding rate are given in Table 2.4.

Table 2.1 displays the required resources per service on the downlink transmission as presented in [40], which is a study done by Siemens based on 3GPP specifications and ITU recommendations. In that table, the number of resource units (RU) is the total equivalent number of resources (or codes in a OVSF tree) required for a given service. The details on how to compute the displayed transmission rates can be found in [40]. Observe that the spreading factor is constant and equal to 16. Also observe that the LCD384 bearer uses 3 different timeslots with 9 codes in each of them.

Table 2.2 exposes the uplink’s resource requirements as shown in [40]. Note that services LCD144 and LCD384 require two different spreading factors within the same timeslot. Additionally, service LCD384 requires 3 different timeslots.

Observe that all of these services have symmetric transmission, i.e. they transmit at the same rate on the uplink and on the downlink. Since 15 timeslots are available, only 14
Table 2.1  Radio resource units required per service in downlink transmission

<table>
<thead>
<tr>
<th>Bearer Service</th>
<th>Spreading Factor</th>
<th># codes per TS</th>
<th># TS</th>
<th># RUs</th>
<th>Rate (kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>16</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>LCD64</td>
<td>16</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>64</td>
</tr>
<tr>
<td>LCD144</td>
<td>16</td>
<td>9</td>
<td>1</td>
<td>9</td>
<td>144</td>
</tr>
<tr>
<td>LCD384</td>
<td>16</td>
<td>9</td>
<td>3</td>
<td>27</td>
<td>388.9</td>
</tr>
</tbody>
</table>

Table 2.2  Radio resource units required per service in uplink transmission

<table>
<thead>
<tr>
<th>Bearer Service</th>
<th>Spreading Factor</th>
<th># codes per TS</th>
<th># TS</th>
<th># RUs</th>
<th>Rate (kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>16</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>LCD64</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>64</td>
</tr>
<tr>
<td>LCD144</td>
<td>2 + 16</td>
<td>1 + 1</td>
<td>1</td>
<td>9</td>
<td>144</td>
</tr>
<tr>
<td>LCD384</td>
<td>2 + 16</td>
<td>1 + 1</td>
<td>3</td>
<td>27</td>
<td>388.9</td>
</tr>
</tbody>
</table>

will be used (i.e. 7 for uplink and 7 for downlink). Some broadcast information for either uplink or downlink can be sent through the remaining timeslot. Note that this timeslot will not suffice to broadcast all signaling information since the synchronization channel requires two codes in separate timeslots on the downlink or one code on the uplink [43]. Hence, resources on the remaining 14 timeslots are needed.

2.3.4 DTX Status (Speech Service)

The Discontinuous Transmission factor (DTX), or activity factor, indicates the portion of time that transmission is actually going on. For example, when a subscriber is using the speech service, she will not talk all the time. Part of the conversation time will be spent talking, another listening while the other is talking, and another will be complete silence. The percentage of activity for each of these parts is called the DTX factor.

The DTX status is used in calculating the amount of interference the subscriber is generating based on the percentage of activity on the link during the connection. Possible values are:

- Subscriber is in DTX mode on the uplink (with probability T);
• Subscriber is in DTX mode on the downlink (with probability $T$);

• Subscriber is in DTX mode on both links (with probability $1-2T$)

For voice services, the parameter $T$ is the percentage of time a person is talking. The default value is 37.5% [7]. For simplicity, it is assumed that at least one link has to be in DTX mode (i.e. both parties do not talk at the same time).

All other services do not consider interference reduction due to DTX. The transmission is thus continuous for those services.

### 2.3.5 Energy per Bit to Interference Ratio

In order to offer a reliable communications service, it is primordial to be assured of a certain quality of the communication link. As stated earlier, this quality is defined as an energy-per-bit-to-noise ratio $E_b/N_0$ threshold per CDMA code and varies from service to service. Remember that the energy threshold for $nc$ codes is $nc$ times greater than the energy per code [40].

The quality of the link is also service dependent. For example, voice services are less affected by transmission errors than data services. That is why voice service usually require a bit error rate (BER) of around $10^{-3}$ (i.e. 1 error every 1000 bits in average) while date services have BER of $10^{-6}$.

The performance of a link is affected in part by channel coding, interleaving techniques, digital modulation, diversity techniques, etc. [38] Note that spreading is not part of this link performance and is rather considered as a processing gain.

The $E_b/N_0$ thresholds are usually computed in link-level simulations. The only data available for TD-CDMA systems was found in [40] and will therefore be used throughout this study. Table 2.3 summaries the services’ thresholds extracted from [40].

Voice services use antenna diversity (2 branches) in uplink transmission but not on the downlink. All other services use antenna diversity on both links. This makes sense since data services will most likely be offered on different devices from voice services (e.g. wireless network cards and personal assistants).

**Important note:** This study assumes that the interference due to multicode transmission was not taken into account when evaluating the required $E_b/N_0$.\footnote{Data not present in [40] for downlink voice service with one user in the cell. Missing values are linearly interpolated from present results.}
Table 2.3  Service thresholds per code, $E_b/N_0$ in dB

<table>
<thead>
<tr>
<th>Service, environment</th>
<th>Uplink</th>
<th>Downlink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice, pedestrian/indoor</td>
<td>3.8</td>
<td>6.3</td>
</tr>
<tr>
<td>Voice, vehicular</td>
<td>5.3</td>
<td>7.8</td>
</tr>
<tr>
<td>LCD64, pedestrian/indoor</td>
<td>3.3</td>
<td>3.1</td>
</tr>
<tr>
<td>LCD64, vehicular</td>
<td>3.9</td>
<td>3.7</td>
</tr>
<tr>
<td>LCD144, vehicular</td>
<td>4.1</td>
<td>4.1</td>
</tr>
<tr>
<td>LCD384, pedestrian/indoor</td>
<td>1.4</td>
<td>1.4</td>
</tr>
</tbody>
</table>

2.3.6 Channel Coding

Reference [51] specifies the channel coding rate for the considered TD-CDMA system. Again, since the only fully coherent and extensive data available at the time of this writing was found in [40], the channel coding considered was taken from that document. Table 2.4 gives the channel coding schemes and channel coding rate for each service. The total coding rate takes into account some puncturing for rate matching purposes.

Table 2.4  Channel coding schemes and rates

<table>
<thead>
<tr>
<th>Bearer Service</th>
<th>Inner Coding Scheme</th>
<th>Outer Coding Scheme</th>
<th>Total Coding Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>convolutional 1/3</td>
<td>None</td>
<td>0.31</td>
</tr>
<tr>
<td>LCD64</td>
<td>convolutional 2/3</td>
<td>Reed-Solomon</td>
<td>0.58</td>
</tr>
<tr>
<td>LCD144</td>
<td>convolutional 2/3</td>
<td>Reed-Solomon</td>
<td>0.58</td>
</tr>
<tr>
<td>LCD384</td>
<td>convolutional 2/3</td>
<td>Reed-Solomon</td>
<td>0.52</td>
</tr>
</tbody>
</table>

2.3.7 Processing Gain

As was mentioned in Section 2.1.2, the processing gain is an important part of a CDMA system. It can be defined in several ways. This study considers the following. It can be defined using the channel coding rate, and the spreading factor $SF$. Using this approach, the processing gain can be expressed as [40].
\[ PG = \frac{B \cdot SF \cdot T_{cp}}{R_c \cdot \log_2 A}, \]  
where \( R_c \) is the rate of the channel encoder, \( A \) is the size of the data symbol alphabet\(^2\), \( B \) is the user bandwidth, \( SF \) is spreading factor, and \( T_{cp} \) is the chip duration (i.e. \( 1/T_{cp} \) is the chip rate). Reference [40] considers that the product of the user bandwidth \( B \) and the chip duration \( T_{cp} \) is equal to 1 and so does this study.

### 2.3.8 Environments

Three environments, or propagation conditions, are possible, namely pedestrian, vehicular, and indoor. The type of environment for a particular subscriber directly influences the SINR requirement and link losses calculation. The probabilities of assigning a subscriber to an environment (\( P_{\text{ped}} \), \( P_{\text{veh}} \), and \( P_{\text{ind}} \)) are assumed to be known \textit{a priori}. They are part of the so-called \textit{subscriber parameters} of the simulator in Figure 4.1.

Observe that a subscriber using the LCD384 bearer cannot be in the vehicular environment. Similarly, the LCD144 bearer is only available in vehicular environment [40].

The interference also varies based on the mobile’s environment. For example, an indoor mobile will suffer from building penetration losses.

### 2.3.9 Background Noise

The slightest movement of electrons causes thermal noise. Since electrons are always in motion (except at 0 K), noise is inevitable in most phenomena, including wireless communication. It affects the capacity of the system.

The value \( N_{th} \) for thermal noise depends on the noise figure of the receiver. Assuming a noise figure of 5 dB, a 3-dB-bandwidth of 4.1 MHz and a temperature of 290 K, the result is \( N_{th} = -102.9 \) dBm. It is further assumed that the value is the same for both downlink and uplink [7].

### 2.3.10 Source and Nature of Interferers

The interference is coming from other mobiles in uplink transmission and from other base stations in downlink transmission when considering symmetric traffic (for asymmetric,

\(^2\)\( A \) is 4 in the case of QPSK modulation [38]
please see the interference scenarios described in [32]). Refer to Figure 2.10 for illustration of these interference scenarios. The red dotted waves are the signals causing interference (1) to the mobile in a), and (2) to the base station in b).

![Figure 2.10](image)

**Fig. 2.10** Interference for symmetric traffic: a) downlink, b) uplink

The interference coming from the same cell is referred to as intracell interference, or intracellular interference and is denoted \( I_{IC} \) (see Figure 2.10). This interference is usually affected by the orthogonality factor [41]. The orthogonality factor \( \theta_e \) is dependent on the environment [52]. A vehicular environment is more affected by the multipath scattering. \( \theta_e = 0 \) denotes perfect orthogonality while \( \theta_e = 1 \) indicates that no orthogonality exists between signals. The values for \( \theta_e \) are given in Table 2.5 taken from [52]. These values are specified for FDD. They might be slightly better in TDD since the BS are synchronized. Likewise, the uplink is considered to preserve orthogonality because of synchronization.

**Table 2.5** Orthogonality factor per environment

<table>
<thead>
<tr>
<th>Environment</th>
<th>( \theta_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedestrian/indoor</td>
<td>0.1</td>
</tr>
<tr>
<td>Vehicular</td>
<td>0.4</td>
</tr>
</tbody>
</table>

In uplink transmission, this intracell interference can be further reduced by using multiuser detection schemes [36,53]. They are not implemented on the downlink since it would be unrealistic to implement such a scheme at the mobile level. It would prove too demanding to transmit the required information to the mobile in terms of signalization, thus wasting bandwidth. Moreover, the required computing power to efficiently lower interference would diminish the mobile’s battery life [6].
The interference due to sources outside of the cell of interest is called *intercell interference*, or out-of-cell interference (I\textsubscript{OC}). This interference is usually attenuated by the distance it has to travel to reach the receiver. In Figure 2.10, the red dotted waves from intercell interferers originate from more distant sources than the ones from intracell sources.

2.3.11 Propagation Characteristics

The mathematical representation of the interferers is mostly due to the fading and shadowing aspect of wireless transmissions. Taking into account free-space attenuation, long- and short-term fading, the total loss due to fading is often modeled as being attenuated by the distance in meters \( D \) to the power of 4 in wireless communication environment \([46]\), i.e.

\[
L\text{fading} \propto \frac{1}{(D)^4}.
\]  

(2.19)

Shadowing is the deviation in link gain due to features in or around the line-of-sight path between the base station and the mobile station (except building walls in indoor environment). It is generally modeled by a lognormal random variable\(^3\), i.e. Gaussian in dB, say \( \chi \), of mean zero and standard deviation \( \sigma_\chi \). The value for \( \sigma_\chi \) usually varies between 8 dB and 12 dB, depending on the environment considered. This study considers the values presented in Table 2.6 \([7]\). These values are consistent with \([40]\).

<table>
<thead>
<tr>
<th>Environment</th>
<th>( \mu_\chi )</th>
<th>( \sigma_\chi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor</td>
<td>0 dB</td>
<td>12 dB</td>
</tr>
<tr>
<td>Outdoors</td>
<td>0 dB</td>
<td>10 dB</td>
</tr>
</tbody>
</table>

Moreover, the indoor environment is faced with building penetration losses. These losses are modeled by a lognormal random variable \( \xi \) with mean \( \mu_\xi \) dB and standard deviation \( \sigma_\xi \) dB. Table 2.7 gives the default values used in this study \([7]\).

The total path loss due to interference can be expressed, in Watt, as

\[
L_T = L\text{fading} \cdot \chi \cdot \xi.
\]  

(2.20)

\(^3\)Details on lognormal distribution can be found in Appendix A
### Table 2.7 Parameters of building penetration loss effect

<table>
<thead>
<tr>
<th>Environment</th>
<th>$\mu_\xi$</th>
<th>$\sigma_\xi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor</td>
<td>12 dB</td>
<td>8 dB</td>
</tr>
</tbody>
</table>

#### 2.3.12 Power Control

As was previously mentioned in Sections 2.2.1 and 2.2.3, power control is a major part of a CDMA system. Power control mechanisms ensure that all signals received at the base stations are of equal power. This maximizes the capacity of the system [47] by reducing the interference of other users. However, errors in power control are inevitable in today’s systems [26, 54].

Since TD-CDMA uses multiuser detection techniques, the requirements on power control can be relaxed on the uplink [55]. Multiuser detection techniques compensate for inaccuracy of the power control mechanism.

TD-CDMA prescribes the use of closed loop power control on the downlink. From the reciprocity of the uplink and downlink channels, a looser open loop power control scheme is used on the uplink [56]. Hence, based on the path loss measurement on the downlink and on the interference level present at the base station (broadcasted on each cell), the mobile station weights the path loss and sets its transmission power accordingly.

Note that the uplink power control rate is 100 Hz or 200 Hz while the downlink power control rate varies from 100 Hz to around 800 Hz. For comparison purposes, FDD uses a fast closed loop power control mechanism with a rate of 1500 Hz [41].

#### 2.4 On Dynamic Channel Allocation

There are many types of Dynamic Channel Allocation (DCA) strategies in the literature. The Future Radio wideAnd Multiple accEss Systems (FRAMES) group studied the different possibilities for UTRA TDD mode and selected four prime candidates [31]: (1) the Link Gain Matrix approach [57], (2) the Interference Matrix approach [58], (3) the Autonomous Reuse Partitioning (ARP) [59], and (4) the Channel Segregation (SEG) [60]. The former two are Centralised DCAs (requiring more computational power and fast links between BS) while the latter two are Distributed DCAs (which trade accuracy for speed and simplicity).
After reviewing each approach, it was decided to restrict the study to the Channel Segregation. The Link Gain Matrix and the Interference Matrix were dropped since they can hardly be integrated in the existing FDD simulator, unless major changes are performed. The ARP was neglected because it simply gives poorer results than SEG and because it does not try to minimize the intercell interference [61].

If only symmetric services are offered (i.e. similar load of traffic on uplink and downlink), the aforementioned DCAs prove to contribute modest advantages compared to a simple symmetric allocation scheme [32]. Moreover, the DCAs require much more computation than the symmetric approach. Hence, this will be the default technique used until packet services are included in the model.

One must remember that the resource allocation in TD-CDMA system can be performed both in code-space and in time-space, yielding a tremendous flexibility. On the other hand, this flexibility makes it very complicated to find an optimal allocation scheme.

### 2.5 Summary: Uplink and Downlink Comparison

This section recapitulates the differences between uplink and downlink transmission. Firstly, the uplink uses a combination of OVSF and multicode transmission to achieve multirate. The downlink always considers a spreading factor $SF$ of 16 and uses multicode transmission to reach different transmission rates.

Table 2.8 summarizes the other considerations for uplink and downlink transmission.

<table>
<thead>
<tr>
<th></th>
<th>Uplink</th>
<th>Downlink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interferers</td>
<td>mainly other mobiles, some multicode interference</td>
<td>signals to in-cell users, other base stations,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and multicode interference</td>
</tr>
<tr>
<td>Interference reducing factors</td>
<td>multiuser detection schemes, and signals’ orthogonality</td>
<td>free-space attenuation, and signals’ orthogonality</td>
</tr>
<tr>
<td>Power control</td>
<td>Open outer loop at 100 Hz or 200 Hz</td>
<td>SINR-based closed inner loop at around $\leq 800$ Hz</td>
</tr>
</tbody>
</table>
Chapter 3

On the Analytical Model

This chapter presents the analytical model considered to study the capacity of the TD-CDMA system. It includes sections discussing the different capacity considerations as well as description and analysis of the model. The analytical model is partly based on work done for a UMTS FDD system found in [14]. It also uses the assumptions, definitions, and the original contribution shown in Chapter 2.

3.1 Focus on Downlink Capacity

In TDD, multiuser detection schemes drastically decrease the intracell interference on the up- (or reversed) link. Hence, it is likely that the downlink will limit capacity. Moreover, due to the typical Internet traffic asymmetry, a larger load will be present on the downlink. Moreover, the voice service uses antenna diversity on the uplink [40]. Therefore, this study is concerned with down- (or forward) link.

$K$ cells are considered for interference purposes. The cell of interest is denoted as $k = 0$ (refer to Figure 3.1). Observe that the tri-sectored network presented in Figure 3.1 shows the position of the mobile at the cell boundary for reasons that will be evident shortly.

$M$ different services are available to subscribers. The proportion of subscribers using each service is known \textit{a priori} and is uniform throughout the network. The position of the mobiles is also known and is considered to be at the boundary of the cell.

Different mobile environments are possible, namely the indoor or outdoors pedestrian (3km/h), or the vehicular outdoors (120 km/h).
3.2 Interference Model

The path loss was defined in equation 2.20. The path loss between the MS and the $k^{th}$ BS is defined as [14]:

$$L_k = D_k^{-l} \cdot \chi_k \cdot \xi_k,$$  \hspace{1cm} (3.1)

where $D_k$ is the distance between the MS and the $k^{th}$ BS, $l$ is the path loss exponent, $\chi_k$ is the shadow fading and $\xi_k$ is the building penetration loss. $\chi_k$ and $\xi_k$ are both lognormally distributed random variables with different means and variances. Clearly, $\xi_k$ is only considered in indoor environments, i.e. is equal to one in outdoors environments\(^2\). Figure 3.2 gives an example of $D_k$ for $k = 0$.

Hence, the intercell (or out-of-cell) interference ($I_{OC}$) can be expressed as

$$I_{OC} = \sum_{k=1}^{K} \Theta_k \cdot P_k \cdot L_k,$$  \hspace{1cm} (3.2)

where $P_k$ is the transmission power of the $k^{th}$ BS, and $\Theta_k$ is the orthogonality factor between

---

\(^1\) $D_k$ always greater than 0.

\(^2\) This is coherent with the fact that the building penetration loss mean will be of 0 dB and its variance will also be of 0 dB. Hence, $10^0 = 1!$
the signals of cell 0 and cell \( k \). \( \Theta_k \) will be 1 in almost all cases except two, namely the two other cells forming the site of cell 0. These cells are denoted with \( k = 1 \) and \( k = 2 \) in Figure 3.1. In those two cases, \( \Theta_k \) will be equal to the orthogonality factor \( \theta_e \).

A BS will use part of its transmit power for traffic channels and another part for control information channels. Following the model of [14], the traffic channels fraction is denoted as \( \psi \). Moreover, only a fraction of the traffic channel transmit power, say \( \phi_n \), is used by a particular user \( n \) for a given service. Therefore, and based on equation 2.5, the received power for all codes at a mobile station can be expressed as

\[
P_{\text{received}} = \psi \cdot \phi_n \cdot P_0 \cdot L_0.
\]

(3.3)

\( P_0 \) is the total transmission power of the BS of interest and \( L_0 \) is the path loss from the BS of interest to the user of interest. Note that a perfect power control mechanism is assumed, i.e. \( PC = 1 \).

Within a cell, the amount of power that will interfere with a user is also a function of \( \psi \), the fraction of the BS power used for traffic channels, \( \phi_n \), the relative power used by the \( n^{th} \) subscriber, and \( \theta_e \), the downlink orthogonality factor. The intracell (or in-cell) interference due to other mobiles (\( I_{\text{ICOM}} \)) is given by

\[
I_{\text{ICOM}} = (1 - \psi \cdot \phi_n) \cdot \theta_e \cdot P_0 \cdot L_0.
\]

(3.4)

Observe that \( I_{\text{ICOM}} \) also includes the interference due to the signaling.

Note that the multicode interference (\( I_{\text{ICMC}} \)) should be considered here. This inter-
ference is due to the transmission of multiple codes by a given subscriber. As shown in equation 2.11a of Section 2.2.6, and using the notation of this chapter, it can be expressed as

\[ I_{ICMC} = \frac{(nc - 1)}{nc} \cdot P_{\text{received}} \cdot \theta_e \]

\[ = \frac{(nc - 1)}{nc} \cdot (\psi \cdot \phi_n \cdot \theta_e \cdot P_0 \cdot L_0), \]

(3.5)

where \( nc \) is the number of codes used for transmission. Observe that when \( nc = 1 \) no multicode interference occurs. The multicode interference \( (I_{ICMC}) \) is considered to be part of the intracell interference \( (I_{IC}) \), as is the interference caused by users in the same cell \( (I_{ICOM}) \). Hence, as previously stated in equation 2.10, \( I_{IC} \) is defined as

\[ I_{IC} \equiv I_{ICOM} + I_{ICMC}. \]

(3.6)

3.3 Downlink Capacity

There are several ways to consider the transmitted power at the BS. One approach is to consider it as a random variable since the number and distribution of the users also are random variables. Another would be to use the \textit{Gilhousen} formula [8] (see equation 2.4 in Section 2.2.1) and compute the power required for some given signal to noise/interference ratio \( E_b/N_0 \) and number of users \( N \). The latter method is a deterministic approach while the former is a probabilistic approach. Both of these method have merits but if a worst-case approach is prescribed, it is better to consider that each base station is transmitting at its maximum power, i.e. \( P_k = P_{\text{max}}, \forall k \).

3.3.1 Perceived Energy per Bit to Interference Ratio

Based on previous derivations and equations 2.3, 2.8, and 2.11a, the energy per bit to interference ratio per code, \( E_b/N_0 \), can be represented by
where $W$ is the spreading bandwidth, and $N_0$ is the additive background white noise spectral density. Note that the processing gain $PG$ is given in equation 2.18 and is service-dependent. Assume that the noise can be neglected since the total power of the interference should be much more important. Therefore,

$$
\frac{E_b}{N_0} = \frac{PG \cdot P_{\text{received}}}{I_{OC} + I_{IC} + N} = \frac{PG \cdot \psi \cdot \phi_n \cdot P_0 \cdot L_0}{nc \left( \sum_{k=1}^{K} \Theta_k P_k L_k + (1 - \psi \phi_n)\theta_e P_0 L_0 + \left( \frac{nc - 1}{nc} \right) \cdot \theta_e \phi_n P_0 L_0 + N_0 W \right)},
$$

where $W$ is the spreading bandwidth, and $N_0$ is the additive background white noise spectral density. Note that the processing gain $PG$ is given in equation 2.18 and is service-dependent. Assume that the noise can be neglected since the total power of the interference should be much more important. Therefore,

$$
\frac{E_b}{N_0} = PG \cdot \frac{\psi \cdot \phi_n \cdot P_0 \cdot L_0}{\sum_{k=1}^{K} \Theta_k P_k L_k + (1 - \psi \phi_n)\theta_e P_0 L_0 + (nc - 1) \cdot \psi \phi_n \theta_e P_0 L_0}
$$

Using equation 3.2, denote the ratio of intercell interference power to received signal power at the MS from the BS of interest of equation 3.11 as:

$$
\frac{I_{OC}}{S_0} = \sum_{k=1}^{K} \Theta_k \frac{P_k L_k}{P_0 L_0} = \sum_{k=1}^{K} \Theta_k \frac{L_k}{L_0},
$$

where $S_0 \equiv P_0 \cdot L_0$. Remember that $P_k = P_{\text{max}}, \forall k$. Substituting equation 3.1 into equation 3.11 yields

$$
\frac{I_{OC}}{S_0} = \sum_{k=1}^{K} \Theta_k \left( \frac{D_k}{D_0} \right)^{-l} \cdot \frac{\chi_k \cdot \xi_k}{\chi_0 \cdot \xi_0}.
$$

Since the location of the mobile is considered to be known (i.e. at the cell boundary), the ratio of distances $D_k/D_0$ can be computed using simple geometry. $\chi_k$ and $\xi_k$ are lognormal random variables. Their product, say $\zeta_k$, is another lognormal random variable [62] (no
approximation). Moreover, the sum of lognormal random variables can be approximated by a lognormal variable [63]. Thus $I_{OC}/S_0$ is a lognormal random variable.

### 3.3.2 Users’ Power Proportion

The interesting part of the derivation is to find out the proportion of power used by each of the $N$ users as a function of the service used. In general, consider 1 voice service (superscript $(v)$) and $M$ data services (superscripts $(d_1), \ldots, (d_{M-1})$ respectively) for a total of $M$ services. Therefore, by isolating $\phi_n^{(i)}$ in equation 3.10, the power proportions per service of the $n^{th}$ user being served can be expressed as follows:

$$
\phi_n^{(v)} = \frac{nc}{\psi} \cdot \frac{E_b^{(v)}}{N_0} \cdot \frac{I_{OC}/S_0 + \theta_e}{PG^{(v)}} + \frac{E_b^{(v)}}{N_0} \theta_e 
$$

$$
\phi_n^{(d_1)} = \frac{nc}{\psi} \cdot \frac{E_b^{(d_1)}}{N_0} \cdot \frac{I_{OC}/S_0 + \theta_e}{PG^{(d_1)}} + \frac{E_b^{(d_1)}}{N_0} \theta_e 
$$

\vdots

$$
\phi_n^{(d_{M-1})} = \frac{nc}{\psi} \cdot \frac{E_b^{(d_{M-1})}}{N_0} \cdot \frac{I_{OC}/S_0 + \theta_e}{PG^{(d_{M-1})}} + \frac{E_b^{(d_{M-1})}}{N_0} \theta_e 
$$

These are all lognormal random variables since $I_{OC}/S_0$ is a lognormal random variable. The parameters of these random variables can be assessed using well-known techniques presented in Appendix B.

Observe that for perfect transmission:

$$
\sum_{n=1}^{N} \phi_n^{(i)} = 1, \quad (3.14)
$$

where $N$ is the total number of users. This means that every subscriber is correctly served.

---

$^3$ $\phi_n^{(i)}$ and $\phi_n$ are equivalent. The $(\cdot)$ superscript is only to illustrate that the $\phi_n^{(i)}$ is service-dependent.
If this summation exceeds 1, blocking occurs.

### 3.3.3 Average Power Compensation Factor

The worst-case scenario was considered with all of the subscribers being on the boundary of the cell. There exists a way to account for the fact that most of the subscribers will not be all located on the boundary.

Consider $\eta$, the *average power compensation factor*, as the fraction of power required by the traffic channel when the users are uniformly scattered in the cell with respect to the power required when they are on the boundary. The details of evaluating $\eta$ can be found in [14]. For a fourth power exponential path loss law ($l = 4$) and perfect power control, $\eta$ is around 0.4.

### 3.3.4 Probability of Blocking Connections

The proportion of users per service is known *a priori*. Denote these proportion as $P_v, P_{d_1}, \ldots, P_{d_{M-1}}$. By varying the total number of users in a cell, $N$, the number of users per service can be known. Denote the number of users per service as $N_v, N_{d_1}, \ldots, N_{d_{M-1}}$, respectively. Hence

\[
N_v = P_v \cdot N \\
N_{d_1} = P_{d_1} \cdot N \\
\vdots \\
N_{d_{M-1}} = P_{d_{M-1}} \cdot N.
\]

If the relative power for the $n^{th}$ user of each service is known, the likeliness that a specific realization is not possible can be verified, i.e. that some blocking occurs. In other words, for a given scenario of users on the network, the probability of blocking can be evaluated. This may be expressed as [14]

\[
P_{out} = \Pr \left[ \eta \left( \sum_{n=1}^{N_v} \rho^{(v)}_n \phi^{(v)}_n + \sum_{n=1}^{N_{d_1}} \rho^{(d_1)}_n \phi^{(d_1)}_n + \ldots + \sum_{n=1}^{N_{d_{M-1}}} \rho^{(d_{M-1})}_n \phi^{(d_{M-1})}_n \right) \geq 1 \right],
\]
where $\rho^{(\cdot)}$ is the activity factor of service $\cdot$. If the total power used by all the users is greater than the power available, then an outage will occur. This equation stands since power fractions per users ($\phi^{(\cdot)}$) are considered.

Note that the blocking probability defined in this study is different from the one that is sometimes defined in other studies where the steady-state characteristics of networks are investigated. In the present model, it is the probability that a given realization of users is possible to satisfy. It can tell whether some blocking occurs on the network but not which user is blocked.

Since $\phi^{(\cdot)}$ are lognormal random variables, the summation of such variables must be re-tackled in order to find $P_{out}$.

### 3.4 Major Assumptions for the Analytical Model

This section presents the major assumptions employed to derive the capacity using the aforementioned analytical model. In particular, it exposes the various network considerations. Values considered for different parameters are also stated.

#### 3.4.1 Four Cell Models

The network layout was presented in Section 2.3.1. Four cell models are considered in the analytical model. The reason for using different models is to present more realistic scenarios of interference where the intercell interference does not entirely drown the intracell interference thus making $I_{IC}$ negligible.

In general, the cells in red are the cells contributing to intracell interference. The cells in white are the cells considered as intercell interferers. The cells in green striped patterns are the cells that are considered in the simulation tool but not in the analytical model. The reasons are that (1) they are the least significant cells, and that (2) when adding too many lognormal random variables together, the techniques used lose precision [64].

The general form of equation 3.12 will be investigated in each scenario since only the $D_k/D_0$ ratios vary from one case to the next. It can be expressed as

$$\frac{I_{OC}}{S_0} = \sum_{k=1}^{K} \Theta_k \left( \frac{D_k}{D_0} \right)^{\tau} \frac{\zeta_k}{\zeta_0},$$  \hspace{1cm} (3.17)
where $\Theta_k$ is the orthogonality factor between signals of cell $k$ and cell 0, $\zeta_k$ is a lognormal random variable associated with cell $k$, $K$ is the total number of considered cells, $D_k$ is the distance from the base station associated with cell $k$ and the mobile of interest (located at cell’s $k = 0$ boundary), and $l$ is the path loss exponent. Remember that $\Theta_k$ is equal to 1 for all cells except cell 1 and cell 2 where it is equal to $\theta_e$.

The scenarios can be summarized as:

1. Same network layout as in Section 2.3.1, i.e. tri-sectored hexagonal sites;
2. Hexagon cells are approximated by circles;
3. Tri-sectored hexagonal site is approximated by one hexagonal cell;
4. Tri-sectored hexagonal site is approximated by one circular cell.

**Case 1: Tri-sectored hexagonal cells**

The first scenario considers tri-sectored sites with hexagonal cells, as was described in Section 2.3.1. Figure 3.3 illustrates this network.

![Case 1: Tri-sectored hexagonal cells](image)

*Fig. 3.3* Case 1: Tri-sectored hexagonal cells

This scenario has the smallest average $D_k/D_0$ ratio of distances. It implies that Case 1 has the **strongest** intercell interference.
Equation 3.17 becomes

$$\frac{I_{OC}}{S_0} = \theta_e \sum_{k=1}^{2} \frac{\zeta_k}{\zeta_0} + \left( \frac{D_3}{D_0} \right)^{-l} \sum_{k=3}^{5} \frac{\zeta_k}{\zeta_0} + \left( \frac{D_6}{D_0} \right)^{-l} \sum_{k=6}^{11} \frac{\zeta_k}{\zeta_0} + \left( \frac{D_{12}}{D_0} \right)^{-l} \sum_{k=12}^{17} \frac{\zeta_k}{\zeta_0}$$

$$+ \left( \frac{D_{18}}{D_0} \right)^{-l} \sum_{k=18}^{20} \frac{\zeta_k}{\zeta_0} + \left( \frac{D_{21}}{D_0} \right)^{-l} \sum_{k=21}^{22} \frac{\zeta_k}{\zeta_0} + \left( \frac{D_{23}}{D_0} \right)^{-l} \sum_{k=23}^{24} \frac{\zeta_k}{\zeta_0}$$

(3.18)

$$\frac{I_{OC}}{S_0} = \frac{1}{\zeta_0} \left\{ \theta_e \sum_{k=1}^{2} \frac{\zeta_k}{\zeta_0} + (1/2)^{-l} \sum_{k=3}^{5} \frac{\zeta_k}{\zeta_0} + \left( \sqrt{7}/2 \right)^{-l} \sum_{k=6}^{11} \frac{\zeta_k}{\zeta_0} + \left( \sqrt{19}/2 \right)^{-l} \sum_{k=12}^{17} \frac{\zeta_k}{\zeta_0}$$

$$+ (2.5)^{-l} \sum_{k=18}^{20} \frac{\zeta_k}{\zeta_0} + (2)^{-l} \sum_{k=21}^{22} \frac{\zeta_k}{\zeta_0} + \left( \sqrt{13}/2 \right)^{-l} \sum_{k=23}^{24} \frac{\zeta_k}{\zeta_0} \right\}.$$  

(3.19)

The distances can be computed using the formulae in Appendix C with the mobile position being $r = 2D/3$ and the angle $\theta = 60^\circ$.

**Case 2: Tri-sectored circular cells**

The second scenario also considers tri-sectored sites. However, the hexagonal cells are now approximated by circular cells. The coverage is not exactly the same. There could be some overlapping and some coverageless spots, depending on the radius of the circle.

The network is represented in Figure 3.4.

The parameter $p_{cov}$ denotes the percentage of the area covered by a circular cell with respect to the area covered by an hexagonal cell. Consider the distance between two base stations to be $D$ (see Figure 3.3). The area of an hexagon is $\sqrt{3}D^2/6$. Consider the radius of the circle as $R$ (see Figure 3.4). The area of the circle is $\pi R^2$. Therefore, the radius $R$ of the circle can be expressed as a function of the distance $D$ between base stations:

$$R = D \cdot \sqrt{\frac{p_{cov} \sqrt{3}}{6\pi}}.$$  

(3.20)

The $p_{cov}$ parameter is a design parameter. In practical applications, it should vary between 90% to 110%. In this scenario, for a 100% coverage, equation 3.17 is now
The ratio of distances for all 9 base stations can be computed using the formulae in Appendix C with the mobile position being $r = 2R$ and the angle $\theta = 60^\circ$. Table 3.1 summarizes the values of distance ratios for different $p_{cov}$ values.

Case 3: Tri-sectored hexagonal to single hexagonal cells

This scenario approximates a tri-sectored hexagonal site into a single hexagonal site with the antennas at the center of the site. The distance between two BS is still $D$. The power of the transmitter still contains three independent components, i.e. one per sector.

In this case, the coverage is uniform and complete. The radius of the hexagon will be $D/(2 \cos(30^\circ))$. This scenario lowers the effect of intercell interference with respect to scenario 1.

This cell configuration was used in [14] but without considering tri-sectored sites. The
Table 3.1 Summary of distances ratio for tri-sectored sites

<table>
<thead>
<tr>
<th>Distance ratio</th>
<th>Case 1</th>
<th>Case 2 $p_{cov} = 1.0$</th>
<th>Case 2 $p_{cov} = 0.95$</th>
<th>Case 2 $p_{cov} = 0.90$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_1/D_0$</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>$D_3/D_0$</td>
<td>0.50</td>
<td>0.65</td>
<td>0.69</td>
<td>0.74</td>
</tr>
<tr>
<td>$D_6/D_0$</td>
<td>1.32</td>
<td>1.44</td>
<td>1.47</td>
<td>1.51</td>
</tr>
<tr>
<td>$D_{12}/D_0$</td>
<td>2.18</td>
<td>2.32</td>
<td>2.36</td>
<td>2.40</td>
</tr>
<tr>
<td>$D_{18}/D_0$</td>
<td>2.50</td>
<td>2.65</td>
<td>2.69</td>
<td>2.74</td>
</tr>
<tr>
<td>$D_{21}/D_0$</td>
<td>2.00</td>
<td>2.30</td>
<td>2.39</td>
<td>2.48</td>
</tr>
<tr>
<td>$D_{23}/D_0$</td>
<td>1.80</td>
<td>2.05</td>
<td>2.13</td>
<td>2.20</td>
</tr>
</tbody>
</table>

network is shown in Figure 3.5. Observe that the base station’s numbering is changed for simplicity of notation in upcoming equation 3.22.

Equation 3.17, in this case, can be expressed as

$$\frac{I_{OC}}{S_0} = \frac{1}{\zeta_0} \left\{ \theta_e \sum_{k=1}^{2} \zeta_k + \sum_{k=3}^{5} \zeta_k + (1.73)^{-1} \sum_{k=6}^{11} \zeta_k + (2.65)^{-1} \sum_{k=12}^{19} \zeta_k + (3.00)^{-1} \sum_{k=20}^{24} \zeta_k \right\}. \quad (3.22)$$
Case 4: Tri-sectored hexagonal to single circular cells

The fourth and last scenario is a cross between cases 2 and 3. The tri-sectored site is approximated by one circular cell of radius $R$. Figure 3.6 exposes the layout of this network.

![Fig. 3.6 Case 4: Tri-sectored hexagonal to single circular cells](image)

The area of three hexagonal cells is $\sqrt{3}D^2/2$. The area of the circle is $\pi R^2$. Hence, the radius $R$ of the circle can be computed using $p_{cov}$. Here,

$$R = D \cdot \sqrt{\frac{p_{cov} \sqrt{3}}{2\pi}}. \quad (3.23)$$

Using the Appendix C with $\theta = 60^\circ$ and $r = R$, and a $p_{cov}$ of 100% yields

$$\frac{I_{OC}}{S_0} = \frac{1}{\zeta_0} \left\{ \theta_0 \sum_{k=1}^{2} \zeta_k + (0.91)^{-l} \sum_{k=3}^{5} \zeta_k + (1.65)^{-l} \sum_{k=6}^{11} \zeta_k + (2.56)^{-l} \sum_{k=12}^{17} \zeta_k ight. \\
+ (2.91)^{-l} \sum_{k=18}^{20} \zeta_k + (2.81)^{-l} \sum_{k=21}^{22} \zeta_k + (2.48)^{-l} \sum_{k=23}^{24} \zeta_k \right\}. \quad (3.24)$$

\[4\text{This angle yields the minimum average distances.}\]
This network layout has the advantage of being more realistic. Hexagonal cells are seldom encountered in real networks.

Table 3.2 summarizes the values of distance ratios for different $p_{cov}$ values. The data representing case 3 is based on the BS numbering of the three other cases.

<table>
<thead>
<tr>
<th>Distance ratio</th>
<th>Case 3</th>
<th>$p_{cov} = 1.0$</th>
<th>$p_{cov} = 0.95$</th>
<th>$p_{cov} = 0.90$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_1/D_0$</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>$D_3/D_0$</td>
<td>1.00</td>
<td>0.91</td>
<td>0.95</td>
<td>1.01</td>
</tr>
<tr>
<td>$D_6/D_0$</td>
<td>1.73</td>
<td>1.65</td>
<td>1.69</td>
<td>1.74</td>
</tr>
<tr>
<td>$D_{12}/D_0$</td>
<td>2.65</td>
<td>2.56</td>
<td>2.60</td>
<td>2.65</td>
</tr>
<tr>
<td>$D_{18}/D_0$</td>
<td>3.00</td>
<td>2.91</td>
<td>2.95</td>
<td>3.01</td>
</tr>
<tr>
<td>$D_{21}/D_0$</td>
<td>2.65</td>
<td>2.81</td>
<td>2.91</td>
<td>3.02</td>
</tr>
<tr>
<td>$D_{23}/D_0$</td>
<td>3.00</td>
<td>2.48</td>
<td>2.57</td>
<td>2.66</td>
</tr>
</tbody>
</table>

### 3.4.2 Other Assumptions

The first assumption is that the power control mechanism is perfect. The second assumption concerns the traffic power fraction $\psi$. Due to the symmetry of the traffic, one timeslot is left empty since a radio frame has 15 timeslots. It can be used to broadcast non-traffic information. Thus, the other 14 timeslots will have more codes available for traffic. Hence $\psi$ is close to 1 if the signaling is evenly distributed on each timeslot. The value considered is 0.987 based on [43].

Only voice traffic is affected by an activity factor $\rho^{(v)}$ different from 1. The DTX value is 37.5%. There are three data services: LCD64, LCD144, and LCD384. Thus $M$ is 4.

The $E_b/N_0$ considered are given in Table 2.3. The number of codes per service $nc$ and the service rates are shown in Table 2.1 for downlink transmission. The spreading bandwidth considered is 4.096 Mcps. The coding rates are given in Table 2.4. The orthogonality factor is given in Table 2.5. The path loss exponent $l$ considered is 4 [46].
Chapter 4

On the Simulation Procedure

The simulation tool was developed to explore the different aspects of the TD-CDMA technology and to validate the analytical model created in Chapter 3. The current chapter gives an outlook of the simulation approach used to generate results during a single trial. The first section states the major steps in a simulation. Details on these steps are given in the following sections.

As in the analytical model, the simulator is focused on system-level considerations. A system-level simulator, in contrast to a link-level simulator, works on a larger scale and considers the entire network. A link-level simulator will be concerned with performance evaluation at the chip or symbol level. Hence, the time of resolution is relatively fast, i.e. as fast as the chip rate. Moreover, the link-level simulations will focus on one radio link. On the other hand, the system-level simulator looks at all the active connections. Thus it needs a resolution in terms of timeslots.

Since this study aims at finding the maximum number of subscribers at the peak usage time on the network, a quasi-static approach is adopted. This means that time does not affect the capacity other than from a viewpoint of timeslots separation. In other words, the subscribers enter the network but never leave. They are assigned timeslots within a radio frame and the only way that these timeslot allocations will change is either because the subscribers are dropped from the network or because they are reallocated new resources.

The principal parameters of the simulator were already exposed in Chapter 2. Unless necessary, they will not be repeated here. The reader is invited to follow the references given throughout this chapter in order to correctly grasp the characteristics of the simulation tool.
4.1 The Algorithm’s Major Steps

The flow chart in Figure 4.1 illustrates the major steps required to complete a simulation trial. Definitions of the symbols used in Figure 4.1 are given in Figure 4.2.

The *basic physical parameters* of the simulation tools can be summed-up as:

1. the seed number for random number generation, and

2. the distance between two adjacent BS \( D \) (in meters) shown in Figure 2.9.

Next comes the *scenario specific parameters*, which can be summarized as:

1. service thresholds (see Section 2.3.5),

2. required resources per service (spreading factor, number of codes, coding rate, see Sections 2.3.3 and 2.3.6),

3. multi-user detection scheme efficiency (see Section 4.4.1),

4. orthogonality factor (see Section 2.3.10),

5. mobile station power (see Section 4.4.2),

6. base station power (see Section 4.5.1),

7. thermal noise power (see Section 2.3.9),

8. propagation characteristics (path loss, shadowing, antennas, etc., see Sections 2.3.11 and 4.3),

9. power control imperfection (see Sections 2.3.12 and 4.7.1), and

10. activity factor/DTX mode (see Section 2.3.4).

Note that the scenario specific parameters have default values and do not need to be re-entered for each simulation.

The *subscriber parameters* are randomly selected and are:

1. the geographic position (Section 2.3.2),
4 On the Simulation Procedure

**Fig. 4.1** Major steps during simulation

**Fig. 4.2** Definition of structures in Figure 4.1
2. the environment (pedestrian, vehicular, or indoor) (Section 2.3.8),
3. the service (voice, LCD64, LCD144, or LCD384) (Section 2.3.3), and
4. the link gain to surrounding base stations (Sections 2.3.11 and 4.3).

The four evoked conditions for a successful admission to the network are clearly stated in Section 2.2.2. Reallocation of resources is the topic of Section 4.6.2. Parameters \( n \) and \( t \) of the exit conditions will be specified in Sections 4.7 and 4.8.

### 4.2 Network Considerations

The network is composed of 25 tri-sectored sites (hence 75 cells) as explained in Section 2.3.1. The important simulation related parameter for the network is the distance between adjacent base stations \( D \) shown in Figure 2.9. However, the shape of the cells is not explicitly defined. It may vary from cell to cell since a mobile is considered to be within the cell with which its link gain\(^1\) is the smallest.

### 4.3 Link Gains

The link gain \( G \) between a subscriber and a base station is defined as the ratio between the received power (averaged over short-term fading) and the transmitted power, both taken at the antenna connectors.

The link gain has the same value for the uplink and the downlink since any gain difference owing to short-term fading differences between the uplink and downlink frequencies is removed by the averaging over short-term fading [7]. Moreover, both transmission links use the same transmission frequency, further lowering the gap in link gains [41].

The link gain includes the combined effects of fading, shadowing, building penetration loss, antenna gains, and body/cable losses (i.e. losses due to cabling and to the obstruction of the subscriber antenna by the head or the body of the user), and can be expressed as:

\[
G = G_a - L_b - L_d - L_s - L_i, \tag{4.1}
\]

\(^1\)The link gain is a random variable.
where $G_a$ is the antenna gain, $L_b$ the cable/body losses, $L_d$ the fading loss, $L_s$ the shadowing loss and $L_i$ the building penetration loss (for indoors subscribers), all in dB.

The fading loss was computed using the Hata-model [65] around 2 GHz frequency band for urban and suburban areas outside of the high rise core where buildings are of nearly uniform height. The resulting loss, as a function of the distance, can be expressed as [7]

$$L_d = 40(1 - 4.0 \times 10^{-3} \cdot \Delta hb) \log_{10} d - 18 \log_{10} \Delta hb + 21 \log_{10} f + 80,$$

(4.2)

where, $d$ is the distance between the mobile and the base station in km, $f$ is the carrier frequency in MHz, and $\Delta hb$ is the base station antenna height measured from the average rooftop level in meters. Considering a base station antenna height of 15 meters (typical case), and a carrier frequency of 1910 MHz [41] the formula becomes:

$$L_d = 37.6 \log_{10} d + 128[\text{dB}].$$

(4.3)

The antenna gain $G_a$ and the body/cable loss $L_b$ were investigated in [7] and are reproduced in Appendix D. The combined gain value used is given in Table 4.1. The values used for link gain are consistent with [40].

| Table 4.1 Combined antenna gain and body/cable loss |
|---------------------------------|--------|
| Gain | Combined $G_a - L_b$ | 12.5 dB |

In this section, $L_d$ was defined as being greater than zero (in dB) for distances of interest. $L_s$ and $L_i$ are positive lognormal random variable. Hence, in most cases, $G$ will be smaller than 0 in dB. $G$ is thus closely related to the path loss, $L_T$ and $L_k$, of preceding chapters. Moreover, since $L_d$ is pessimistic with respect to the fading of equation 2.20 from about 10 dB for distances between around 100 m and 2000 m, the combined gain of the antenna gain and the body/cable loss will have the effect of getting $G$ of equation 4.1 closer to the loss considered for the analytical model in equation 3.1.
4.4 Uplink Connection

A subscriber trying to connect to the network will contact the closest base station in terms of path loss. The postulant subscriber will try to obtain services from that base station. The service will be delivered on a specific timeslot. The availability of one timeslot on the uplink is verified in the following way:

1. **Check if enough OVSF codes are available for the required service**
   
   Each service requires a certain amount of codes in the OVSF tree. The connection assignment can only go on if enough codes are available at the base station.

2. **Compute the noise-plus-interference power at the base station**
   
   The interference level at a base station ($I_{bs}$) is computed by linearly adding thermal noise to the contributions of all mobiles located within the most important cells (considering the antenna pattern) as shown in Figure 4.3.

![Fig. 4.3 Uplink transmission interference considerations (mobile in cell 0)](image)

The interference contribution of a mobile is given by its transmit power multiplied by its link gain to the BS. Subscribers within the same site are considered to be intracell interferers. As such, they are affected by the code orthogonality and multiuser detection scheme. More details on computing $I_{bs}$ are given in Section 4.4.2.

If a subscriber is using the speech service and it is in DTX mode for the uplink, then
its interference contribution is reduced by 37.5%, or 4.77 dB.

3. **Compute the mobile’s required transmit power**

   The mobile transmit power requirement $P_m$ to a given base station is:

   $$ P_m = SINR + I_{bs} - G, \quad (4.4) $$

   where all powers are in dB. $G$ is the link gain to this BS defined in Section 4.3, and $SINR$ is the SINR requirement for one code on the uplink. This equation resembles equation 2.8 without power control imperfections and with one code transmitted (since only one code with the same spreading factor is used for uplink transmission). Note that the interference due to other codes of the same subscriber is included in $I_{bs}$.

   Observe that the DTX status is not considered when computing the mobile transmit power requirement. The rationale behind this is that a speech user cannot be considered satisfied if there is not enough power in both directions to support the transport of voice. The DTX status is considered only when estimating the interference generated to other mobiles. Reducing the transmit power requirement for subscribers in DTX would result in the artificial (and unwanted) effect of ending up with a greater proportion of DTX subscribers as the load on the network increases.

4. **Check if the required transmit power is lower than $P_{m,max}$**

   If the required transmit power is greater than the maximum attainable power by the mobile $P_{m,max}$, the postulant subscriber cannot be accepted on the network.

5. **Check if the new subscriber would cause a connected subscriber to drop**

   As mentioned in Section 2.2.3, it is critical for subscriber satisfaction that the probability of dropping calls be kept at a minimum. Thereof, it is relevant to ensure that the acceptance of a postulant subscriber does not cause other existing subscribers to drop. Existing subscribers could drop because they cannot maintain their transmit power level $P_m$ under $P_{m,max}$. $P_m$ increases since the perceived interference level at their base station $I_{bs}$ also increases due to the postulant subscriber’s interference.

   Any timeslot that satisfies these conditions and does not already transmit on the downlink can accept the requesting subscriber and begin serving it. In the case of failure, another timeslot could be considered for admission, based on the DCA scheme. Note that determining the timeslot on which the connection will be attempted is the Dynamic Channel Allocation’s (DCA) task.
4.4.1 Multiuser Detection Scheme

Multiuser detection (MUD), or joint detection, scheme have an exponential complexity with the number of interfering symbols [66]. Thus, performing MUD when many users are simultaneously present introduces unacceptable processing delays. The maximum number of simultaneous signals in one timeslot for TD-CDMA is 16 (maximum spreading factor of 16). Hence, the complexity incurred would not be too high for modern day processors and multiuser detection schemes are envisioned [41].

Moreover, the usage of conventional detectors such as a Rake receiver or matched filters require a tight power control on the uplink [9,41]. As seen in Section 2.3.12, a tight power control mechanism is not adopted for TD-CDMA since the uplink is not continuously available. Hence, the use of advanced receiver is prescribed.

Many multiuser detection schemes exist in the literature: [34, 35, 38, 55, 67–69] to cite but a few examples. They all have their own merits and flaws but they all have one goal in common: reducing intracell interference.

Implementing a thorough MUD in the simulator would require an excessive amount of work. A MUD requires knowledge of spreading codes and channel impulse responses. The system level simulator does not consider transmission at the bit level or knowledge of the channel other than its fading characteristics for link gain computation. It is interested in transmission power and resources consumption. Therefore, another link-level simulator would need to be called up every time a new power needs to be computed. This occurs every time a new subscriber enters the network and several times in the power control loop. It is unreasonable to include such an approach. However, a simple MUD model could be considered. [36] proposed a model on which this work is based. The following explains the basis of the model.

The MUD has a certain efficiency in reducing the intracell interference. Denote this efficiency as $\beta$. Denote the intracell interference when no MUD is present as $I_{IC}$. Thus, the intracell interference with MUD $I_{IC-MUD}$ can be expressed as

$$ I_{IC-MUD} = (1 - \beta) \cdot I_{IC}. \quad (4.5) $$

In other words, the interference coming from the red cells in Figure 4.3 is lowered by $10 \log_{10} (1 - \beta)$ dB. The weakness of this model is that the lowering of the intracell interference is not linear with the number of subscribers in the system [40]. Considering a
unique efficiency $\beta$ is suitable for this study because the capacity of the system is thought to be downlink-limited. The MUD is solely used on the uplink. Therefore, a simple MUD model is acceptable.

The default value for the MUD efficiency $\beta$ is 70%.

### 4.4.2 Power and Interference Considerations on the Uplink

This section offers details on different power-related topics, such as the default value for $P_{m_{\text{max}}}$, and how to compute the total interference at the base station.

The maximum transmit power that a mobile can achieve is denoted $P_{m_{\text{max}}}$. The default value is 1 W, or 30 dBm [7].

The total interference at the base station is composed of intracell interference $I_{IC}$ and intercell interference $I_{OC}$. As mentioned on the second point of Section 4.4, the interference at the base station comes from other mobiles. Considering MUD and code orthogonality ($\mu_e$), the total interference can be expressed as

\[
I_{bs} = \theta_e \cdot I_{IC-MUD} + I_{OC} + N_{th}
\]

\[
= \theta_e \cdot (1 - \beta) \cdot \sum_{i=1}^{N_{IC}} \rho_i P_{m_i} G_{w_i} + \sum_{j=1}^{N_{OC}} \rho_j P_{m_j} G_{w_j} + N_{th},
\]

where $\rho_i$ is the activity factor of the $i^{th}$ subscriber, $N_{IC}$ and $N_{OC}$ are the number of intracell and intercell interferers, respectively, $P_{m_i}$ is the transmit power of the $i^{th}$ interferer, $G_{w_i}$ is the link gain between the $i^{th}$ interferer and the base station, and $N_{th}$ is the thermal noise. All powers are in Watt. Note that $G_{w_i}$ was given in dB in equation 4.1.

For services LCD144 and LCD384 requiring both multi-code and multi-spreading factors, the uplink algorithm will go through every resources and evaluate their relative interference by brute force. That is, each resource unit will be considered individually and its effect on the other resources will be computed based on the uplink interference model.

### 4.5 Downlink Connection

In a similar way as uplink transmission, verifying the availability of the downlink connection is performed the following way:
1. Check if enough OVSF codes are available for the required service
   A connection requires that enough codes are available on the attempted timeslot.

2. Compute the noise-plus-interference power at the mobile station
   The interference level at a mobile station \( I_{ms} \) is computed by linearly adding thermal noise to the contributions of all base stations located within the most important cells as shown in Figure 4.4. The interfering cells on the downlink are different from the ones considered on the uplink due to different antenna patterns.

Fig. 4.4  Downlink transmission interference considerations

A base station is assumed to transmit at a minimum power level \( P_{b,perch} \) (in the absence of any subscriber) for signalling channels on specific timeslots. The default value for this parameter is given in Section 4.5.1. Moreover, the base station cannot transmit at a lower power than \( P_{b,tot,min} \) [7], also given later.

As justified in Section 2.3.10, MUD is not implemented on the downlink. However, the interference generated by the serving base station on the other subscribers must be attenuated by an orthogonality factor \( \theta_o \) whose value lies between 0 and 1. Details on the computing \( I_{ms} \) can be found in Section 4.5.1.

The downlink DTX status of the speech subscribers served by a base station must be considered when computing its interference contribution. The amount of interference reduction is the same as the uplink, i.e. 4.77 dB.

3. Compute the base station’s required transmit power
   The BS’s transmit power requirement, say \( P_b \), to one mobile station is given by
\[ P_b = SINR + I_{ms} - G + 10 \log_{10} nc, \quad (4.8) \]

where \( nc \) is the number of codes transmitted. Equation 4.8 is very similar to equation 4.4 except for the multicode transmission. Observe that \( P_b \) cannot be lower than \( P_{b,\text{tot,min}} \).

The DTX status is not considered when computing the transmit power requirement, as justified in Section 4.4.

4. **Check if the required transmit power is within acceptable ranges**

This condition is two-fold:

1. The transmit power to a subscriber is not greater than the maximum power allowed for one channel \( P_{b,su,max} \), and

2. the total transmitted power by the BS (i.e. to all mobiles) after the candidate subscriber is accepted does not exceed the maximum power of the BS \( P_{b,\text{tot,max}} \).

If both conditions are respected, the subscriber is accepted on the network. Otherwise, it is blocked.

5. **Check if the new subscriber would cause a connected subscriber to drop**

As explained in Section 4.4, it is important to ensure that the acceptance of a candidate subscriber does not cause other existing subscribers to drop.

Any timeslot that satisfies these conditions and does not already transmit on the uplink can accept the candidate subscriber and begin serving it.

### 4.5.1 Power and Interference Considerations on the Downlink

The default value for \( P_{b,su,max} \) and \( P_{b,\text{tot,max}} \) are 30 dBm and 40 dBm, respectively. \( P_{b,\text{tot,min}} \) has been set to 5 dBm while \( P_{b,\text{perch}} \) is 25 dBm [7].

The interference level at the mobile station is computed this way:

\[
I_{ms} = f_{MC} \cdot (\theta_e \cdot I_{ICOM} + I_{OC} + N_{th}) \quad (4.9)
\]

\[
= f_{MC} \cdot (\theta_e \cdot \sum_{i=1}^{N_{IC}} \rho_i P_{b_i} G_{w_i} + \sum_{j=1}^{N_{OC}} \rho_j P_{b_j} G_{w_j} + N_{th}), \quad (4.10)
\]
where $f_{mc}$ is the multicode factor of equation 2.17, $I_{ICOM}$ is the interference due to other mobiles, $P_{bh}$ is the transmit power of the $i^{th}$ interferer, and $G_{wi}$ is the link gain between the $i^{th}$ interferer and the mobile station. All powers are in Watt.

### 4.6 Dynamic Channel Allocation

The Dynamic Channel Allocation (DCA) schemes proposed here are means to allocate resources to postulant subscribers. The effectiveness of these schemes influences the interference suffered by postulant subscribers on a given system’s resource. Hence, the DCA potentially influences the capacity of the system.

The simulator considers a simple DCA scheme. Since only symmetric services are offered, a symmetric allocation scheme offers competitive performances [32]. The first eight timeslots in a radio frame are used for downlink transmission. The eighth timeslot is traffic-free. It is used for downlink signaling. The next seven timeslots are dedicated to uplink transmission. This is illustrated in Figure 4.5.

![Timeslot allocation strategy for all base stations](image)

**Fig. 4.5** Timeslot allocation strategy for all base stations

The DCA can be described as follows:

**Algorithm Dynamic Channel Allocation**

1. for both transmission directions
2. do
3. generate the first timeslot attempted with a *method*
4. while subscriber is not accepted OR run out of timeslots
5. do
6. if this timeslot is suitable
7. then accept the subscriber and update the network parameters
8. else mark the current timeslot as *tried* and select the next timeslot with the *method* as the new candidate for admission
The method evoked in the algorithm is the variant parameter in the DCA of this study. Three methods are considered: (1) least-interfered channel (LIC) [70], (2) pseudo-random, and (3) channel segregation (SEG) [30, 33, 60, 71].

The first version of the DCA, the LIC, consists in choosing the attempted timeslot in a devised fashion. The timeslot where the transmitting power of the own cell BS is lowest is chosen as the candidate timeslot for downlink transmission. On the uplink, the timeslot with the most OVSF codes remaining is elected as the candidate timeslot.

The pseudo-random method is straight-forward. Candidate timeslots are generated using a pseudo-random algorithm.

The SEG algorithm was briefly introduced in Section 2.4. This approach consists in building a priority list of channels according to its measured quality at every base stations. Channels are allocated using this priority list. The list is updated every time a new user attempts to enter the system using a priority function. This makes SEG a self-adaptive learning process that is able to dynamically follow traffic variations and slow fading conditions. This study considers a simple priority function based on successful or failed allocations, as described in [60].

4.6.1 Power Control Preloop

The DCA tries to ensure that a certain quality of service can be offered. Dropped calls are one criterion. This simulator tries to minimize this quantity. As such, the DCA needs to establish if allocating resources to a new subscriber will cause another existing subscriber to increase its transmitting power above a certain threshold.

This is achieved by running a power control preloop whereby the power requirements of every subscriber are updated repeatedly. However, the power control is not allowed to complete its usual cycle, as described in Section 4.7. Instead, the power control preloop will only run a predetermined $K$ iterations. The maximum deviation of the transmit power requirements is stored for each iteration. If this maximum power deviation is greater than a certain threshold $t_p$ for all $K$ iterations, it is decided that introducing this new subscriber would likely cause at least one other subscriber to drop. Of course, if during the $K$ iterations, a subscriber does drop, the attempted timeslot is deemed unacceptable for the postulant subscriber. Table 4.2 gives the values of $K$ and $t_p$. These values are found to give good results in most simulated cases.
4 On the Simulation Procedure

Table 4.2  Parameters for the power control preloop

<table>
<thead>
<tr>
<th>Service</th>
<th>$K$</th>
<th>$t_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice</td>
<td>5</td>
<td>0.5 dB</td>
</tr>
<tr>
<td>Others</td>
<td>10</td>
<td>0.5 dB</td>
</tr>
</tbody>
</table>

The power control preloop was necessary because the average required transmit power for TDD is higher than for FDD [41]. Hence, the interference level caused by a new subscriber is also higher and the probability of dropping an existing subscriber is heightened.

4.6.2 Resources Reallocation

Performing the power control preloop lowers the probability of dropping a subscriber but does not completely eliminate it. There exist other dropping protection mechanisms. If a timeslot is not suitable for a connected subscriber because the interference level is too high to maintain proper quality of service, that subscriber will be dropped. However, other timeslots could be suitable for this *would-drop* subscriber. Reassigning a timeslot to a would-drop subscriber is referred to as resources reallocation.

The procedure can be considered to be part of the DCA. The resources reallocation scheme considered in the simulator will run the resource allocation algorithms previously viewed in Sections 4.4 and 4.5 up to a maximum of 10 times per mobile. If the reallocation fails, the subscriber is dropped from the network. This algorithm is seen to significantly lower the dropping probability, thus increasing the capacity.

4.7 Power Control Loop

After a subscriber passes all the above conditions and is accepted on the network, power levels at the mobile and its serving base station must be updated. This has the effect of increasing the interference level of all subscribers already present on the network. Consequently, the power levels of all subscribers should also be updated after a new subscriber is added.

This is achieved by running a power control loop whereby the power requirements of every subscriber are updated repeatedly until the difference in power between two consecutive iterations for every subscriber is less than a certain threshold (2.5 dB based on
4 On the Simulation Procedure

observed data). During the course of this loop it may happen that some subscribers must exceed their maximum power limitations (either on the uplink or the downlink) to maintain service, and a drop event occurs if no reallocation is possible.

Because running a power control loop is a computationally intensive process, repeating it each time a single new subscriber is added would result in unnecessarily large computation time. It is possible to add a certain number of new subscribers before running a power control loop without compromising the validity of the results. The simulation tool establishes this number (the window length $n$) by using a heuristic formula that has the effect of assigning a large window length when the proportion of low-rate subscribers is large and a smaller length when the proportion of high-rate subscribers is larger.

4.7.1 Power Control Imperfection Model

Because of closed-loop power control imperfections on the downlink, the actual timeslot-averaged SINR is generally different from the target SINR determined by the outer loop power control mechanism. This effect can have a significant impact on the capacity. A subscriber of a given service that transmits only 3 dB more than its SINR requirement effectively “takes the room” of two subscribers of this service. The effect is accounted for by splitting the actual experienced SINR in two terms:

$$\text{SINR} = \text{SINR}_{\text{nom}} + \delta.$$  \hspace{1cm} (4.11)

The first term, $\text{SINR}_{\text{nom}}$, called nominal SINR requirement, is determined by the outer loop power control mechanism. It can be estimated given the service/environment combination assigned to the subscriber. The second term, $\delta$, is the difference between the actual experienced SINR and the nominal one due to imperfections in the closed-loop power control mechanism. This term is represented by a lognormal variable of standard deviation $\sigma_{\text{pc,dl}}$ [8]. The default value for $\sigma_{\text{pc,dl}}$ has been determined based on link-level simulation results presented in [26]. It has been found that a conservative value for $\sigma_{\text{pc,dl}}$ is 2 dB. Note that a perfect power control would have $\sigma_{\text{pc,dl}} = 0$ dB.

As mentioned in Section 2.3.12, the uplink uses an open loop power control. As such, it is exposed to greater power control errors. This error is modeled as an increase of the standard deviation $\sigma_{\text{pc,ul}}$. Since the performance of the uplink power control depends on measurements done on the downlink, the relative position of uplink and downlink trans-
mission on the radio frame will influence the error. This is modeled as [72]

\[ \alpha = 1 - \frac{D_{TS} - 1}{6}, \]

(4.12)

where \( D_{TS} \) is the delay, expressed in number of slots, between the uplink slot and the most recent downlink slot. The uplink power control error is also a lognormal random variable. The mean of the new random variable is still 0 dB. The considered standard deviation is:

\[ \sigma_{pc,ul} = \sigma_{pc,dl} \cdot \sqrt{(1 - \alpha)} \]

(4.13)

The random variable \( \sigma_{pc,ul} \) is then added to \( \sigma_{pc,dl} \). The resulting random variable is the total uplink power control error. Therefore, the closer in time the uplink and downlink transmission are (\( \alpha \) close to 1), the better the power control (small \( \sigma_{pc,ul} \)).

4.8 Exit Condition

As the load in the network increases, it is obvious that the frequency of blocked and dropped events increases up to a point where it can be considered that no new subscriber should be accepted. The network reaches the sought saturation point.

Unfortunately, it is not straightforward to determine exactly when this threshold is crossed in the course of a trial. One approach could be to stop the trial when more than a certain fraction \( t \) of the last \( 4n \) events are fail events (blocked or dropped). This fraction should be chosen large enough to ensure that a trial is not stopped prematurely, but small enough to avoid spoiling computation time. It has been found that a good trade-off is to set the value \( t \) to 0.35. The condition is checked after every power control loop.

4.9 Other Assumptions - Signaling

Not all timeslots have signaling traffic. The Synchronization CHannel (SCH) is considered to be present on timeslot 0 and timeslot 7 because the two SCH need to be separated by exactly 8 timeslots [43]. Each SCH uses a spreading factor of 16 thus using 1 channelization code. Also observe that the Random Access CHannel (RACH) is mapped on timeslot 8 and uses a spreading factor of 8. All other timeslots have 16 codes available for traffic data. Figure 4.5 shows the signaling channels in the radio frame.
4.10 Comparison with Analytical Model

The principal difference between the analytical model of Chapter 3 and the simulator of this chapter is that the latter considers both transmission links while the former only considers downlink transmission.

There are several other distinctions between the model and the simulator. They are summarized in tabular form in Table 4.3.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Analytical Model</th>
<th>Simulation Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity Considerations</td>
<td>Computed for one cell.</td>
<td>Computed for the entire network.</td>
</tr>
<tr>
<td>Power Control</td>
<td>Perfect.</td>
<td>Imperfect.</td>
</tr>
<tr>
<td>Link Gain(^2)</td>
<td>Shadowing, building penetration, and fading inversely proportional to 4(^{th}) power of the distance.</td>
<td>Shadowing, building penetration, fading given in equation 4.1, cable/body loss, and antenna gain.</td>
</tr>
<tr>
<td>Interference</td>
<td>Approximation of the sum of lognormal random variables.</td>
<td>Explicitly computed when establishing the transmit power requirements(^3).</td>
</tr>
<tr>
<td>Cell Shape</td>
<td>Varies from scenario to scenario. 4 cases.</td>
<td>Not completely defined. Can vary within the network.</td>
</tr>
<tr>
<td>Drop Calls</td>
<td>Impossible.</td>
<td>Must be minimized.</td>
</tr>
<tr>
<td>Traffic Channels Fraction (\psi)</td>
<td>The value is 0.987.</td>
<td>Hard to evaluate.</td>
</tr>
<tr>
<td>Distances between MS and BS</td>
<td>Ratio of distances.</td>
<td>Absolute values.</td>
</tr>
</tbody>
</table>

\(^2\)In most of the considered cell models and separations, the difference is less than 3 dB.

\(^3\)Using the realizations of the power control random variables.
Chapter 5

Results

The present chapter shows the principal results that were obtained during the course of this study. The results presented aim at fulfilling the objective of the project, namely to assess the capacity of a UMTS TDD CDMA cellular system.

The first section presents the results in approximating the sum of lognormal components. This approximation is required for the evaluation of the capacity with the analytical model presented in Chapter 3. The second section states the various traffic scenarios considered in this study. Resulting capacity are then displayed based on the different traffic scenarios. That section also shows interesting results of capacity-affecting considerations, such as base station separation, multicode interference, and multiuser detection efficiency.

5.1 Sum of Lognormal Components

This section presents the results for the approximation of the sums of lognormal components. Estimating the parameters of the distribution of the sum of lognormal random variables plays an important role in the analytical model presented in Chapter 3.

The approximations are two-folds: (1) the estimation of the parameters of the users’ power proportion of the total power transmitted by the BS used for the required service, and (2) the estimation of the cumulative density function (c.d.f.) of the sum of the users’ power proportions.

In both cases, the summation of lognormally distributed random variables is approximated by another lognormal random variable [63, 64, 73–75].
5.1.1 Results for the Users’ Power Proportion $\phi_n$

The general form of the users’ power proportion of equation 3.13 is:

$$
\phi_n^{(c)} = \frac{nc}{\psi} \cdot \frac{E_b^{(c)}}{N_0} \cdot \frac{I_{OC}}{S_0} + \theta_e
+ \frac{E_b^{(c)}}{N_0} \cdot \frac{PG^{(c)}}{\theta_e} , \quad (5.1)
$$

Of these terms, only $I_{OC}/S_0$ is a random variable. It is the parameters of this random variable, namely the mean $\mu_{is}$ and the standard deviation $\sigma_{is}$, that need to be estimated.

**Derivation technique for interference to received signal ratio $I_{OC}/S_0$**

The interference to received signal ratio is expressed as (see equation 3.17):

$$
\frac{I_{OC}}{S_0} = \sum_{k=1}^{K} \Theta_k \left( \frac{D_k}{D_0} \right)^{-\frac{1}{\zeta_k}} \cdot \frac{\zeta_k}{\zeta_0} , \quad (5.2)
$$

Computing the $I_{OC}/S_0$ comes down to adding statistically independent lognormally distributed random variables. Since the sum of lognormal random variables can be approximated as a lognormal random variable [63], the $I_{OC}/S_0$ will be approximated as a lognormal random variable. Appendix B gives a review of some commonly used techniques for this approximation.

According to [63] and [73], Schwartz and Yeh’s method, presented in [63] and reproduced in Section B.3, is well suited for estimating the parameters of a sum of lognormal variables. It was shown in [64] that Schwartz and Yeh’s method yields good approximations in almost all cases of mean and standard deviation for less than 18 components in the sum. However, as shown in Figures 3.3, 3.4, 3.5, and 3.6, the analytical model considers the sum of 24 components. Therefore, only the most significant 18 cells of the original 24 cells will be considered in estimating the parameters of $I_{OC}/S_0$. The most significant cells are the ones with the smallest distance ratio $D_k/D_0$.

Schwartz and Yeh’s method will be used to get the parameters of the random variable associated with the summation of the $\Theta_k \cdot (D_k/D_0)^{-\frac{1}{\zeta_k}} \cdot \zeta_k$ terms, say mean $\mu_{sk}$ and standard deviation $\sigma_{sk}$, both in dB.

The parameters of $\zeta_k$ in equation 5.2 depend on the environment in which the mobile
is evolving. Remember that $\zeta_k = \chi_k \cdot \xi_k$, where $\chi_k$ is due to shadowing and $\xi_k$ is due to building penetration losses. The parameters of these random variables were originally given in Tables 2.6 and 2.7 but are summarized in Table 5.1. The columns representing $\zeta_k$ are obtained by using equation A.7.

Table 5.1 Parameters of $\chi_k$, $\xi_k$, and $\zeta_k$ based on environment

<table>
<thead>
<tr>
<th>Environment</th>
<th>$\mu_{\chi_k}$ (dB)</th>
<th>$\sigma_{\chi_k}$ (dB)</th>
<th>$\mu_{\xi_k}$ (dB)</th>
<th>$\sigma_{\xi_k}$ (dB)</th>
<th>$\mu_{\zeta_k}$ (dB)</th>
<th>$\sigma_{\zeta_k}$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor</td>
<td>0</td>
<td>12</td>
<td>12</td>
<td>8</td>
<td>12</td>
<td>$\sqrt{208}$</td>
</tr>
<tr>
<td>Outdoors</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
</tbody>
</table>

The $\zeta_k$ of equation 3.17 are multiplied by a constant $\Theta_k \cdot (D_k/D_0)^{-l}$. As shown in equation A.7, the mean of the new random variable will be

$$\mu_{sk} = \mu_{\zeta_k} - l \cdot 10 \log_{10} (D_k/D_0) + 10 \log_{10} \Theta_k$$

while the standard deviation will remain the same. The mean $\mu_{sk}$ and standard deviation $\sigma_{sk}$ of the summation can now be estimated.

Once these are computed, the $1/\zeta_0$ term is taken into account to get the parameters of $I_{OC}/S_0$. Denote the parameters of $\zeta_0$ as $\mu_0$ and $\sigma_0$ for mean and standard deviation dB values, respectively. Using equation A.7, the resulting mean dB value is $\mu_{is} = \mu_{sk} - \mu_0$, and the resulting standard deviation dB value is $\sigma_{is} = \sqrt{\sigma_{sk}^2 + \sigma_0^2}$.

Results for interference to received signal ratio $I_{OC}/S_0$

The estimated parameters are summarized in Table 5.2 for the four cell shape cases considered in section 3.4.1. Since Schwartz and Yeh’s method is recursive, the term order in the summation of the $\zeta_k$’s has an influence on the resulting approximation. This does not have a significant influence on the standard deviation. However, the mean value can vary by as much as 1.8 dB (based on observed data). Many permutation scenarios were tried and the results shown in Table 5.2 are the average values of these scenarios.

Closer inspection of Table 5.2 and all the subsequent tables reveals that the interference levels are very dissimilar with respect to the network cell shape model. It can be inferred from the data that the distance ratio $D_k/D_0$ for the closest interferer strongly influences
the resulting interference power. For example, in Case 1, the smallest distance ratio is 0.5 (taken from Table 3.1) and results in a 24.8 dB mean (with $\theta_e = 0.4$). The distance ratio increases to 0.65 in Case 2 with $p_{cov} = 1.00$ and the resulting mean decreases to 21.7 dB. The smallest distance ratio is maximum in Case 4 with $p_{cov} = 0.90$. It is also for this case that the mean of $I_{OC}/S_0$ is minimum.

The effect of the orthogonality factor $\theta_e$ can clearly be seen in Table 5.2. When the orthogonality factor is closer to 0 (perfect orthogonality between OVSF codes), the interference level is lowered. It can be observed that variations in the mean can reach 0.7 dB when $\theta_e$ goes from 0.4 to 0.1. This can be interpreted as follows: the interfering intracell sources are effectively further away from the mobile of interest. If $\theta_e$ is 0, the distance between the interfering base station and the mobile is infinite hence the mobile does not suffer from intracell interference. Observe that the effect of $\theta_e$ is strongest when the closest intercell interferer is further away (i.e. lower $p_{cov}$ and Case 3).

For the indoor environment, the parameters of $I_{OC}/S_0$ are also given in Table 5.2. It can be noted that the means and the standard deviations of the interference to received signal ratio for indoor environment are higher by around 2.5 dB each. This behavior could have been predicted since the indoor environment is subject to more severe transmission conditions (i.e. building penetration losses).

Table 5.2  Summary of parameters for $I_{OC}/S_0$ using Schwartz and Yeh’s method

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Outdoors</th>
<th></th>
<th></th>
<th>Indoor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\theta_e = 0.4$</td>
<td>$\theta_e = 0.1$</td>
<td>$\theta_e = 0.1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1</td>
<td>$\mu_{IS}$</td>
<td>$\sigma_{IS}$</td>
<td>$\mu_{IS}$</td>
<td>$\sigma_{IS}$</td>
<td>$\mu_{IS}$</td>
</tr>
<tr>
<td>Case 2</td>
<td>24.8</td>
<td>11.4</td>
<td>24.6</td>
<td>11.4</td>
<td>27.3</td>
</tr>
<tr>
<td>Case 3</td>
<td>$p_{cov} = 1.00$</td>
<td>21.7</td>
<td>11.2</td>
<td>21.2</td>
<td>11.3</td>
</tr>
<tr>
<td></td>
<td>$p_{cov} = 0.95$</td>
<td>21.0</td>
<td>11.2</td>
<td>20.3</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>$p_{cov} = 0.90$</td>
<td>20.1</td>
<td>11.1</td>
<td>19.4</td>
<td>11.2</td>
</tr>
<tr>
<td>Case 4</td>
<td>16.1</td>
<td>10.9</td>
<td>15.5</td>
<td>11.0</td>
<td>18.7</td>
</tr>
<tr>
<td>Case 4</td>
<td>$p_{cov} = 1.00$</td>
<td>17.0</td>
<td>10.9</td>
<td>16.5</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td>$p_{cov} = 0.95$</td>
<td>16.5</td>
<td>10.9</td>
<td>16.1</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td>$p_{cov} = 0.90$</td>
<td>15.7</td>
<td>10.9</td>
<td>15.1</td>
<td>11.0</td>
</tr>
</tbody>
</table>

For comparison purposes, the parameters of $I_{OC}/S_0$ were also estimated using Wilkin-
son’s method (presented in [74] and reproduced in Appendix B.2) and using Choi and Kim’s approach (presented in [14] and reproduced in Appendix B.4). The results are exposed in Table 5.3. In all cell shape cases, the resulting standard deviations are similar, independently of the method used.

In Choi and Kim’s approach, the resulting $\sigma_{IS}$ are closer to the results from Schwartz and Yeh’s method (within 1.1 dB). As for the mean, Choi and Kim’s approach is, again, close to Schwartz and Yeh’s method, expect for Case 1 (close to 6 dB difference!). This could be due to the strong influence of the nearby interferers. This interference is lowered in the other cases by distancing the cell of interest’s boundary from the closest interferers.

As for the results of Wilkinson’s approach, they tend to underestimate the resulting means and overestimate the resulting standard deviations, as stated in [63, 64, 73]. The heretic behavior of the mean $\mu_{IS}$ is due to this significative imprecision in the method’s parameter approximation.

Note that only outdoor environments were considered for this comparison.

**Table 5.3** Summary of parameters for $I_{OC}/S_0$ using Wilkinson’s method and Choi and Kim’s approach

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Wilkinson</th>
<th>Choi and Kim</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\theta_e = 0.4$</td>
<td>$\theta_e = 0.4$</td>
</tr>
<tr>
<td></td>
<td>$\mu_{IS}$</td>
<td>$\sigma_{IS}$</td>
</tr>
<tr>
<td>Case 1</td>
<td>19.7</td>
<td>13.3</td>
</tr>
<tr>
<td>Case 2</td>
<td>15.8</td>
<td>13.2</td>
</tr>
<tr>
<td>$p_{cov} = 1.00$</td>
<td>14.9</td>
<td>13.2</td>
</tr>
<tr>
<td>$p_{cov} = 0.95$</td>
<td>14.0</td>
<td>13.1</td>
</tr>
<tr>
<td>$p_{cov} = 0.90$</td>
<td>10.6</td>
<td>12.9</td>
</tr>
<tr>
<td>Case 3</td>
<td>11.6</td>
<td>13.0</td>
</tr>
<tr>
<td>$p_{cov} = 1.00$</td>
<td>11.0</td>
<td>12.9</td>
</tr>
<tr>
<td>$p_{cov} = 0.95$</td>
<td>10.5</td>
<td>12.9</td>
</tr>
</tbody>
</table>

Moreover, the consideration of 24 cells, as was originally intended, was studied. All three methods showed similar behavioral results. The resulting means are higher, suggesting that the interference is more severe. Schwartz and Yeh’s, and Choi and Kim’s methods hinted a raise of less than 0.5 dB. Wilkinson’s method resulted in an increase of the mean in the neighborhood of 1.5 dB. On the other hand, the standard deviation is slightly lower (less
than 0.2 dB difference for Schwartz and Yeh’s, and for Choi and Kim’s methods and around 0.3 dB for Wilkinson’s method). These results hint that adding more far-away components only slightly increases the interference level and removes a very small parcel of uncertainty regarding the actual value of the interference. This suggests that the effect of the far-away cells could be neglected without great consequences. The interference from the closer cells overshadows the interference from farther away cells.

The users’ power proportion $\phi_n$

The parameters of the interference to received power ratio $I_{OC}/S_0$ are now estimated. More steps are required to compute the users’s power proportion $\phi_n$. Based on equation 5.1, it can be seen that the lognormal random variable $I_{OC}/S_0$ is multiplied by a service-dependent constant and gets a small quantity added (i.e. $\theta_e$). In more general terms, equation 5.1 becomes:

$$\phi^{(\cdot)} = K^{(\cdot)} \cdot \left( \frac{I_{OC}}{S_0} + \theta_e \right),$$

(5.4)

where

$$K^{(\cdot)} = \frac{nc}{\psi} \cdot \frac{E_{b}^{(\cdot)}}{N_0} \cdot \frac{1}{PG^{(\cdot)} + \frac{E_{b}^{(\cdot)}}{N_0} \theta_e}.$$  

(5.5)

Closer inspection of equation 5.4 with special interest to the lognormal random variable $I_{OC}/S_0$ reveals a fascinating characteristic: $\phi^{(\cdot)}$ is a so-called three-parameter lognormal random variable [62]. It can be represented as $\phi^{(\cdot)} \sim \Lambda(K\theta_e, \ln K + \lambda\mu_{is}, \lambda^2\sigma_{is}^2)$. $\lambda$ is equal to $(\ln 10)/10$ and is the transformation of $\mu_{is}$ and $\sigma_{is}$ from dB to natural base as explained in Appendix B.1.

Adding a constant to a lognormal variable merely shifts it, or thresholds it. However, estimating the parameters of its associated Gaussian random variable is not straightforward. Notwithstanding, $\theta_e$ is quite small compared to $I_{OC}/S_0$. As shown in [62] and here in equation A.10 of Appendix A.3, thresholding $I_{OC}/S_0$ by $\theta_e$ does not change the variance of $I_{OC}/S_0$. Moreover, using equation A.9 and the values considered in this study, the contribution of $\theta_e$ to the mean of $I_{OC}/S_0 + \theta_e$ is seen to be less than 0.1% of the total

---

1This type of random variable is introduced in Appendix A.3 for the benefit of the reader.
value. The deviation of the mean with and without $\theta_e$ is negligible. $\theta_e$ can therefore be disregarded. Hence, computing $\phi_n^{(c)}$ comes down to evaluating the parameters of

$$
\phi_n^{(c)} = K^{(c)} \frac{I_{OC}}{S_0},
$$

(5.6)

Again, denote the mean dB value and standard deviation dB value of $I_{OC}/S_0$ as $\mu_{IS}$ and $\sigma_{IS}$, respectively. Based on this notation, $\phi_n^{(c)}$ follows a lognormal distribution with mean and standard deviation

$$
\mu_\phi = \mu_{IS} + 10 \log_{10} K^{(c)}, \\
\sigma_\phi = \sigma_{IS}.
$$

(5.7a) (5.7b)

Again, the $\phi_n^{(c)}$ is service- and environment-dependent.

5.1.2 Results for the Probability of Blocking $P_{out}$

Once the users’ power proportions $\phi_n^{(c)}$ are assessed, the probability of blocking $P_{out}$ can be calculated. $P_{out}$ is expressed as (see equation 3.16):

$$
P_{out} = \Pr \left[ \eta \left( \sum_{n=1}^{N_v} \rho^{(v)} \phi_n^{(v)} + \sum_{n=1}^{N_{d1}} \rho^{(d_1)} \phi_n^{(d_1)} + \ldots + \sum_{n=1}^{N_{dM-1}} \rho^{(d_{M-1})} \phi_n^{(d_{M-1})} \right) \geq 1 \right].
$$

(5.8)

where the parameters of $\phi_n^{(c)}$ can be computed using equations 5.7 and the activity factor is equal to 1 for all services except the voice service where it is 0.375. The number of subscribers per service is known a priori based on the traffic scenario.

The goal here is to draw conclusion on the maximum number of subscribers per service that can successfully connect to the network for a certain outage probability. Hence, the varying parameter will be $N_{(i)}$. For a given traffic scenario of $N_{(i)}$, $P_{out}$ can be computed by evaluating the distribution of the sum of lognormal random variables $\phi_n^{(c)}$.

Consider the following equation:
\[ X = \psi \left( \sum_{n=1}^{N_v} \rho^{(v)} \phi_n^{(v)} + \sum_{n=1}^{N_{d_1}} \rho^{(d_1)} \phi_n^{(d_1)} + \ldots + \sum_{n=1}^{N_{d_{M-1}}} \rho^{(d_{M-1})} \phi_n^{(d_{M-1})} \right). \] (5.9)

The characteristics of \( X \) vary as a function of the number of subscribers on the network.

Since the sought result is a probability event, the interest of \( X \) does not directly lie in its parameters as was the case for \( I_{OC}/S_0 \) but in its cumulative density function (c.d.f.). Moreover, only values of under \( 10^{-1} \) are truly interesting. No system will run with a probability of blocking higher than 10%! It can be seen in [73] that Wilkinson’s method, presented in [74] and reproduced in Appendix B.2, is well suited for such considerations. Therefore, Schwartz and Yeh’s method will be used to approximate the parameters of \( I_{OC}/S_0 \) while Wilkinson’s method will be employed to approximate the c.d.f. of \( P_{out} \).

Once \( X \) is characterized, finding \( P_{out} \) comes down to computing

\[ P_{out} = \Pr \left[ X \geq \frac{\psi}{\eta} \right] \]
\[ = \Pr \left[ e^Z \geq \frac{\psi}{\eta} \right], \] (5.10) (5.11)

where \( Z \) is the Gaussian random variable associate with \( X \). \( Z \) is characterized by mean \( m_Z \) and standard deviation \( \sigma_z \) in natural base. Note that \( Z \) is characterized, from \( X \), using Wilkinson’s method. Continuing the development yields

\[ P_{out} = \Pr \left[ Z \geq \ln \left( \frac{\psi}{\eta} \right) \right] \]
\[ = Q \left( \frac{\ln \left( \frac{\psi}{\eta} \right) - m_z}{\sigma_z} \right), \] (5.12) (5.13)

where \( Q(x) \) is the \( Q \)-function, also known as the probability of the tail, which is defined as [76]

\[ Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-t^2/2} dt. \] (5.14)

\( P_{out} \) can now be estimated based on the approximation of \( m_z \) and \( \sigma_z \) and a given number of subscribers. The passage from decibels to natural base is simply for notational
convenience and to be in accordance with the methods presented in the literature.

The total number of subscribers $N$ is defined for one timeslot in one cell. Considering 14 traffic timeslots and symmetric traffic, 7 timeslots are used for downlink transmissions. Hence, to get the total number of subscribers in a cell, $N$ is multiplied by 7 since no inter-slot interference is present in this TD-CDMA study\(^2\). Moreover, to consider the total number of subscribers in the 25 sites network, the total number of subscribers per cell is multiplied by 75 (number of sectors).

It is important to note that the maximum number of components considered in the sum of lognormal random variables $X$ is 16 since there is a theoretical maximum of 16 codes available per timeslot and a voice service uses one code.

The resulting curves for $P_{out}$ are given along side the simulations curves in the following sections. Not all traffic scenarios considered in the simulation procedure were analyzed analytically. The reasons for omitting some cases are given in due time.

### 5.2 Traffic Scenarios Considered

The capacity of the system will depend on the type of service required by the subscribers as well as on the environment in which they evolve. The combination of service and environment proportions is called a traffic scenario. Computing the capacity for several traffic scenarios is relevant since the behavior of the subscribers will vary from network to network. It could also vary within a network. Moreover, some traffic scenarios can be used to compare the assessed capacity to the one evaluated in previous studies. They are also helpful in studying different capacity influencing factors, such as BS separation.

The traffic scenarios are summarized in Table 5.4. This table gives the basic parameters of each traffic scenario, nominally the proportions of subscribers per service and per environment. Justification and further details on these scenarios are offered in the following sections.

**Important Note:** It will be assumed that the orthogonality factor $\theta_e$ for all environments will be equal to 0.4 instead of being equal to 0.1 for pedestrian environments. The rationale behind this assumption is that the LCD144 service is only offered in the vehicular environment. It was deemed that using a much better orthogonality factor for pedestrian environments was over-discriminating towards the LCD144 service. This resulted in curves\(^2\)

\(^2\)Considering a uniform load on all timeslots
that seemed queer at first glance since service LCD384 allowed a higher number of users on the network than service LCD144 for the same $P_{out}$.

### 5.3 Model and Simulation Results

This section shows the results for the analytical model and the simulation tool considered in this study. The limitations of the analytical model are exposed right away. They are followed by a battery of analyses concerning different considerations affecting the capacity of the system. Firstly, the effect on capacity of cell shape in the analytical model is discussed. Secondly, the results for strictly voice services are compared. The attention then shifts towards data traffic. Along with the total capacity of the system, the principal topics presented are the effect on capacity of (1) the distance between base stations, of (2) the multicode transmission interference, of (3) the multiuser detection mechanism, and of (4) the dynamic channel allocation scheme.

The simulation curves are generated by averaging the results of multiple simulation trials. The exact number of trials varies from one traffic scenario to the next. In general, anywhere between 80 and 200 trials are executed in order to produce a graph.
5.3.1 On the Limitations of the Analytical Model

The analytical model proposed in Chapter 3 was seen to have important limitations. For instance, since the outage probability $P_{out}$ is computed with summations of an integer number of users on the network (refer to equation 3.16), not many possibilities are offered. Remember that the maximum number of LCD144 or LCD384 per timeslot is 1 since they each use 9 out of 16 codes. Moreover, it was seen in previous studies [18, 20, 58, 61] that the maximum number of users per timeslot is close to 8. Hence, not many points have significant contribution to the curves, even in strictly voice service scenarios.

In mixed traffic and/or mixed environments, the proportion of users of each service/environment combination on the network is seldom the one required. For example, consider that the sought proportions are $P_{voice} = 50\%$, $P_{LCD64} = 50\%$, $P_{ped} = 50\%$, and $P_{veh} = 50\%$. With an integer number of users in the model, there needs to be one pedestrian voice user, one vehicular voice user, one pedestrian LCD64 user, and one vehicular LCD64 user to respect the sought proportions. This means that 10 out of the 16 codes are used on one timeslot, which is a lot. The outage probability will be high, and this is the first point that has valid proportions! Considering the same example, the second point is found when all four service/environment combinations have 2 users each, which is impossible since 20 codes would be required! Thus it can be seen that the model is not well adapted for TD-CDMA in most mixed traffic scenarios.

The preceding example considers that all timeslots on the network have an identical service/environment distribution. In a real network, this is hardly the case. It should be observed that if it is almost impossible to get the sought proportions in one timeslot, it is easier to get them in 7 timeslots. Considering the example from the previous paragraph, timeslot 0 could have one pedestrian LCD64 user and one vehicular voice user while timeslot 1 would serve one vehicular LCD64 user and one pedestrian voice user, and so forth. This would considerably reduce the outage probability on one timeslot. Moreover, it would offer greater flexibility.

The cost of such an approach is a considerable increase in complexity. One needs to consider an important number of permutations of resources assignment in order to validate the results. Moreover, the resulting outage probability would give indication on whether or not a given service/environment combination is possible. The interest of this study is related to the outage probability of each service in a given traffic scenario (i.e. if two
services are present on the network, two $P_{out}$ curves are produced). The proposed approach would fall short in assessing such values. The approach is, however, suitable in a single service, mixed environment scenario since only one outage probability curve is generated.

Another limitation relates to the precision of the parameter estimations. It was observed that a difference of 0.5 dB in the mean of $I_{OC}/S_0$ can result in a capacity variation of over 15%. Thus the parameter approximation must be acute to yield meaningful results.

It should be noticed that a $P_{out}$ of zero is impossible with the analytical model. The reason is that even a single voice user in a timeslot has a small probability of being rejected due to the interference of neighboring cells. Remember that these cells transmit at $P_{max}$! This phenomenon is not present in the simulation tool where a 0% outage probability is possible. The nature of the network where some cells will not interfere at all with each other is partly responsible for this observation. Another part is attributable to the way the $P_{out}$ curves are built and smoothened from raw data based on successful, blocked or dropped events and their relative occurrences. No blocking or dropping ever occurs when the load on the network is relatively small.

5.3.2 Analysis of Cell Shape Considerations in Analytical Model

In a real world network, the shape of a cell will vary over time since the propagation environment is time-variant [46]. Hence the exact shape is hardly modeled. However, this study proposed several cell shapes in Section 3.4.1 to investigate different possibilities and scenarios. The present section compares the four cell shape cases in terms of capacity.

As can be seen in Figure 5.1, the effect of the cell shape on the analytical model is severe. The capacity of the most pessimistic case is only around 10% of the capacity of the most optimistic case for a 10% outage probability (i.e. Case 1 and Case 4 with $p_{con} = 0.90$, respectively).

The results from Figure 5.1 could have been predicted by looking closely at Tables 3.1 and 3.2. Indeed, it can be seen that the order in which the curves appear is the same as the order of the distance ratios of the closest intercell interferers $D_3/D_0$. This indicates that the closest intercell interferers are the most important source of interference on the downlink (i.e. more important than the intracell interference).

Special attention should be given to Case 3 and Case 4 as they seem to give results that most closely match the simulation results, as shown later. This is not surprising since the
simulator will assign the subscriber to the base station with the lowest path loss. The cell will then resemble the cell considered in Case 4 and, sometimes, in Case 3.

The following deduction results: when a mobile is at the boundary of a cell, the path loss between itself and the serving BS or the “BS-to-serve” should be the factor determining whether a hand-over should occur. The determining factor in the hand-over should not be the shape of the cell, which, in most theoretical studies, is hexagonal in nature. In the case where the $D_k/D_0$ is smaller than 1, it is very likely that a hand-over would be performed in a real-world system hence the more realistic results of Case 3 and Case 4.

This suggests that the usual tri-sector hexagonal cell shape model is unrealistic. As such, a mobile at the cell’s edge in this model would most likely perform a handover procedure to obtain services from another base station. Therefore, the most credible cell shapes would be the one represented in Case 3 and Case 4.

### 5.3.3 Voice Services

Solely voice service scenarios are considered in this section. The only variance between the different scenarios is the environment in which the subscribers are evolving. As such,
the first scenario (Voice 1) looks at an even number of subscribers being in an outdoor pedestrian and vehicular environment. This is more typical of an urban to sub-urban milieu. All subscribers are outdoors pedestrians in the second scenario (Voice 2). This case presents optimistic results that are easily comparable with the analytical model’s results. Voice 3 considers a more urban milieu with slightly more subscribers inside buildings than on the streets or in cars.

Figure 5.2 shows the capacity for Voice 1 obtained using both the analytical model and the simulation tool. Only the analytical curves close to the simulation curve are shown. It can be seen that the curves of Case 4 with $p_{cov} = 0.95$ and $p_{cov} = 1.00$ are relatively close to the simulation curve for outage probabilities between 0.5% and 5%. Note that this outage interval will be referred to as the *region of interest*. The best approximation of the cell shape for this scenario lies somewhere within $0.95 < p_{cov} < 1.00$ for Case 4.

![Fig. 5.2 Capacity for a 75 cells network: Voice 1 traffic](image)

In this environment, the capacity of the system for a 2% outage probability is close to 51 voice users per sector, or a capacity of around 405 kbps per sector.

The results for the second scenario are presented in Figure 5.3. Again, only the most significant analytical curves are shown. The simulation and the analytical curves are close
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to one another. The cell shape that most closely fits the simulated curve in the region of interest is the Case 4 shape with $p_{cov}$ between 0.95 and 1.00.

Observe that the deviation from the simulated curve to the model curves is slightly different than the one from the previous traffic scenario. This is due, in part, to the parameter estimation of the service and environment dependent users power proportions $\phi_n^{(i)}$. The precision for pedestrian and vehicular environment will most likely be different. Moreover, remember that the model’s results for *Voice 1* traffic scenario contains half of the points contained in the *Voice 2* scenario’s results. This is due to the model’s limitation when facing mix services or environments. As indicated previously, this restriction could be somewhat lifted by considering that the 7 downlink timeslots could have different proportions of users in each service/environment combination.

**Fig. 5.3** Capacity of a 75 cells network: *Voice 2* traffic

Around 52.4 voice users per sector are supported for an outage probability of 2% in this scenario. The capacity in **kbps** is close to 420 kbps in this environment. This is higher than the capacity observed for the previous scenario.

The analytical model’s results for the third scenario were obtained by considering different users’ proportions in each service/environment combination per timeslot. The global
proportions on the network were respected. The results can be viewed in Figure 5.4 for both the analytical model and the simulator.

It can be seen that the cell shapes that more closely fit the simulation results in the region of interest are the Case 3 and Case 4 with $p_{\text{cov}}$ somewhere between 0.90 and 0.95. This is different from the previous two scenarios. This difference could be due to the fact that there exists many permutations of the users’ proportions per service/environment combination per timeslot. Other permutations could yield curves that are closer to say Case 4 with $p_{\text{cov}} = 1.00$. Another explanation is related to the parameter estimation of $I_{OC}/S_0$ in indoor environment. The estimated mean could be slightly overestimated, hence resulting in a more pessimistic capacity.

![Graph](image)

**Fig. 5.4** Capacity of a 75 cells network: Voice 3 traffic

In this particular traffic scenario, 45.3 voice users per sector can be on the network for an outage probability of 2%. This results in a capacity of close to 363 kbps. This is lower than the previous two scenarios.

From the previous results, it can be inferred that the environment plays a relatively important role in the capacity of the system. As such, the outdoors pedestrian environment is the easiest environment in which mobiles evolve. This conclusion comes from observing
that the maximum capacity is offered with the Voice 2 scenario. The toughest environment seems to be the indoor environment since the resulting capacity for Voice 3 is less important than for the other two scenarios. The building penetration losses seem to be more important than the loss due to the Doppler shift (important in fast-moving environments [46]).

It should be noted that the maximum number of codes used per timeslot hovers around 8 for the previously studied traffic cases. This is fully coherent with precedent studies in the literature [18, 20, 58, 61]. This observation tends to validate the results given by the analytical model and the simulation tool.

Important aspects of the analytical model can be interpreted from the previous curves in Figures 5.2 and 5.3. The analytical curves are much smoother than the simulated curves. That is imputable, in part, to the fact that less points are computed in the analytical approach. Intermediate values are simply interpolated to complete the graph.

On the other hand, the simulated curves are rougher. They are built from raw data and the resulting curves are constructed using a common curve smoothing technique that preserves the essentials of the behavior of the users on the network. Adding a user to the network does not necessarily increase the outage probability. Remember that users that are far away from one another do not interfere with one another. Hence they may not cause each other to be denied services. This leads to small plateaus in the curves, as can be observed throughout this chapter.

Moreover, the sometimes abrupt increase in $P_{\text{out}}$ seem to indicate that the simulator is more susceptible to detecting subscribers that cause a sudden increase in interference (e.g. subscribers requesting LCD384 data service at the cell border).

It should also be noted that the simulated $P_{\text{out}}$ curves have a relatively high slope. This indicates that the network reaches a saturation point. Once this saturation point is reached, postulant users will be denied service in an almost systematic fashion. This is reminiscent of the hard capacity limit of previous personal communication system standards. The difference is that, here, the saturation point is not reached because of a lack of resources but because of the total interference on the network (i.e. soft capacity limit). It will be observed that not all traffic scenarios give rise to this phenomenon, especially mixed service scenarios.

Note that all simulated voice scenario results shown within this section have a base station separation of 400m.
5.3.4 Data Transmission Capacity

In this section, the focus shifts from a strictly voice network to a more diverse mixture of services: data traffic is introduced alongside. The choice of traffic mixes is arbitrary since no consistent models of expected subscriber’s behavior are available. The goal is to show different amalgamations in order to compare them with one another without over-emphasizing the performance of one over the other.

As explained in Section 5.3.1, traffic mixtures tend to yield insignificant results with the analytical model. They will thus be ignored in this section, except for the all LCD64 service scenario. Otherwise, only simulation results are shown. Results shown are with a BS separation of between 400m and 600m.

The simplest scenario in data transmission is the \textit{LCD64} scenario. Only LCD64 users are present on the network. Figure 5.5 presents the analytical and simulated results. The analytical curve was taken with Case 4 $p_{cov} = 0.90$ as the cell shape. It can be seen that the difference between the two curves is relatively small (i.e. around 15% in the region of interest), with the analytical curve yielding slightly better performance for outage probabilities above 0.7%. One of the reasons for this result could be the consideration of a perfect power control in the analytical model.

Using the simulation tool, the capacity of the system for this scenario is 426 kbps per sector for an outage probability of 2% ($\approx 500$ users on network $\times 64$ kbps / 75 sectors).

Figure 5.6 shows the capacity for the first mixed scenario, namely \textit{mix phase 1}. Observe that the curves for services LCD144 and LCD384 are close to one another. The proximity of the curves highlights the fact that service LCD144 is considered to be solely provided in a vehicular environment while service LCD384 is solely available in a pedestrian environment. Both services have similar power requirements. They use the same amount of OVSF codes per timeslot. The difference in outage between these two services is mostly attributable to the fact that service LCD384 uses three timeslots.

Another noteworthy point in Figure 5.6 is the gap between service LCD64 and LCD144. The important difference between the performance of these two services is due, in part, to the environment restriction on service LCD144. Another part of the gap is imputable to the \textit{dropping} phenomenon. As the traffic load increases, the subscribers using high-rate services are more likely dropped from the network than low-rate users since their average transmission powers are higher. The power control loop might bring the transmission power
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Fig. 5.5 Capacity of a 75 cells network: \textit{LCD64} traffic

requirement above the allowed threshold, hence needing to drop the high-rate subscriber. The dropped users will likely be replaced by less power-demanding users (low-rate services). This will have the effect of lowering the outage probability of these low-rate users. The global effect will be a decrease in the capacity of the system. Note that the dropping probability is relatively high in this scenario: in average 16\% of the failures are drop events.

The resulting capacity in kbps in the region of interest is effectively lowered compared to scenarios where the dropping rate is smaller. At 2\% outage, the capacity is only of around 282 kbps per sector. Roughly, this figure is computed by doing the following: (440 voice users \times 8 \text{kbps} \times 0.2 + 393 LCD64 users \times 64 \text{kbps} \times 0.5 + 135 LCD144 users \times 144 \text{kbps} \times 0.2 + 103 \times 388.9 \text{kbps} \times 0.1) / 75 sector on the network.

The results for the \textit{mix phase 2} scenario can be seen in Figure 5.7. This scenario is interesting as it shows similar behavioral results to the first scenario. The gap between service LCD64 and LCD144 is tighten, in part because the dropping probability is lowered: around 12\% of failures are drop events. Moreover, the total capacity in kbps is slightly lower to the ones from previous simulations (e.g. \textit{Voice} scenarios and \textit{LCD64}), the difference being imputable, again, to the drops. For a 2\% outage probability, about 315 kbps
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Fig. 5.6  Capacity of a 75 cells network: mix phase 1 traffic

per sector are supported.

Figure 5.8 displays the results for the mix phase 3 traffic scenario. The total capacity in terms of kbps is in the vicinity of other traffic mixes. The dropping rate is relatively low at around 5% of the failure events. As mentioned above, this behavior suggests that high rate users are more susceptible to dropping since the highest rate per user available in this scenario is 64 kbps. The resulting capacity for an outage probability of 2% is around 380 kbps per sector.

The effect of the indoor environment can partly be seen in Figure 5.9 where the mix phase 5 scenario’s results are shown. This scenario will be particularly helpful in studying the capacity impact of several considerations in upcoming sections. Observe that the capacity of system is, again, in the neighborhood of previous results. It is also noted that the dropping rate is similar to the one observed for the mix phase 3 scenario. Here, a capacity of close to 375 kbps per sector is supported with an outage probability of 2%.

5.3.5 On the Effect of Distance between Sites

This section investigates the capacity impact of the distances between sites. Five traffic scenarios were considered: (1) LCD64, (2) mix phase 2, (3) mix phase 3, (4) mix phase 4,
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Fig. 5.7 Capacity of a 75 cells network: mix phase 2 traffic

and (5) mix phase 5. These scenarios will allow a more thorough study of the influence of the environment and of the type of services on the network’s capacity. For all of these scenarios, the normalized capacities of the system with an outage probability of around 1% are compared for distances varying between 100m and 3000m.

Figure 5.10 presents the normalized capacity of the system in terms of the total transmission rate of the network as a function of the BS separation. All marked points in the graph are simulated values. The shown curves are formed by fitting polynomials of different orders to the simulated values.

In Figure 5.10, it can be observed that the distance between sites has an influence on the capacity of the system. All traffic scenarios perform well when the separation is small. However, it can be seen that traffic scenarios where many users are indoors (i.e. mix phase 4 and mix phase 5) suffer sharp capacity degradation when the separation increases. Moreover, it can be seen that traffic scenarios with high-rate users are also more affected by base station separation than low-rate scenarios (e.g. mix phase 2 vs. mix phase 3). It can also be observed that the difference between the mix phase 3 and LCD64 is quite small, hinting that an all-outdoors pedestrian environment is less affected by distance than an outdoors pedestrian-vehicular mix (based on the previous observation that high rate users
These results are in accordance with the generally accepted theory that TD-CDMA should be used in pico- and micro-cellular environment [6, 41]. The reason for such a limiting factor is that signals in TD-CDMA require higher transmit powers than their W-CDMA counterparts. This is attributable to the relatively low spreading factors used in TD-CDMA. Therefore, this study also advocates a BS separation of less than 1500m to assure good performance in several realistic traffic scenarios.

Observe that Figure 5.10 could be used for network design purposes. The network deployment planning could be done as a function of the environment in which the users are forecasted to evolve for a particular area.

This investigation is possible since the capacity is interference-limited in TD-CDMA. As the BS separation increases, so does the path loss. This results in an heightened power requirement, and therefore, in a higher interference level. Higher interference leads to fewer possible users on the network, or in other words, in a higher outage probability.

This study is impossible with the analytical model since it does not consider absolute distances but distance ratios between interfering cells.
5.3.6 On the Effect of Multicode Transmission Interference

The effect of multicode interference was expressed in close form in equation 2.17. The influence of this multicode transmission interference on the capacity of the system is investigated in this section. This constitutes an original contribution to the capacity study of a TD-CDMA system.

To evaluate the impact of multicode interference on the capacity of the system, the total capacity with and without the multicode factor will be compared.

The influence of multicode transmission interference will be inspected, in part, with the help of the analytical model. The model does need minor changes. The intracell interference $I_{IC}$ must be redefined as $I_{ICOM}$ instead of the form proposed in equation 3.6. This means that the multicode interference $I_{ICMC}$ is 0. Thus

$$I_{IC} = (1 - \psi \cdot \phi_n) \cdot \theta_c \cdot P_0 \cdot L_0.$$  \hspace{1cm} (5.15)

Using a similar development to the one presented in Section 3.3, the users’ power proportion can now be expressed as
Fig. 5.10 Influence of the BS separation on the capacity

\[ \phi_n^{(\cdot)} = \frac{nc}{\psi} \cdot \frac{E_b^{(\cdot)}}{S_0} + \theta_e \cdot \frac{I_{OC}}{PG^{(\cdot)} + nc \cdot \frac{E_b^{(\cdot)}}{N_0}} \cdot \theta_e^\cdot \]

(5.16)

where the difference with the previous expression of Chapter 3 resides in the denominator. Observe that the number of transmitted codes \( nc \) is now present in the denominator. This reduces the power proportion used by user \( n \) hence increasing the capacity of the system. Figure 5.11 presents the results when considering \( P_{LCD64} = 1.00 \) and \( P_{ped} = 1.00 \). The dashed curve indicates the results excluding multicode interference while the solid curve includes the multicode interference. For a \( P_{out} \) of 2%, the capacity degradation in terms of transmission rate is around 3%. This capacity degradation is imputable to the fact that more transmit power is required if the multicode interference is considered.

The effect of multicode interference is also studied with the simulator in Figures 5.12 and 5.13. The first scenario considered is the same as the one suggested for the analytical model, namely \( LCD64 \). It can be seen that the results in terms of capacity degradation are similar to the ones presented in Figure 5.11. Again, the degradation is only of about 3%
The next graph shows the capacity degradation of the system in terms of the transmission rate with respect to the outage probability for several traffic scenarios. The considered scenarios are (1) *mix phase 2*, and (2) *mix phase 3*. Results can be viewed in Figure 5.13. Here, the capacity degradation depends on the scenario but seems to be relatively constant within a given scenario. Note that the aforementioned figure also displays the degradation for both *LCD64* scenario analysis.

For the *mix phase 2* scenario, the capacity degradation varies around 13.5%. This increase in the capacity degradation (meaning that more capacity is lost due to the multicode interference) is attributable to the presence of service LCD144 users. This service is the most affected by multicode interference. It is intuitive to think that a service with more codes is more affected by multicode interference. Moreover, it will be even more affected if each code requires high transmit power to attain an acceptable quality of service. Since the LCD144 service requires 9 OVSF codes and is only available in an outdoors vehicular environment, it will strongly be influenced by multicode interference, as can be seen in Figure 5.13.
The *mix phase 3* is also affected by the multicode interference. Note that the voice users are not subject to such a phenomenon since they only use one OVSF code. However, in terms of *kbps*, 8 voice users are needed as an equivalent to a single LCD64 user. This results in a greater capacity degradation for this particular traffic mix. As can be seen in Figure 5.13, the capacity degradation hovers around 6.5%. This is slightly higher than the strictly LCD64 scenario.

It should be concluded that the influence of multicode transmission interference was often neglected erroneously in previous TD-CDMA studies. This is especially true if the orthogonality factor is close to 1 and/or if high-rate users employ many OVSF codes.

Note that this study of the impact of multicode transmission interference on the capacity of the system is only valid if the system is interference-limited on the downlink since multicode transmission is the preferred transmission scheme on that link.
5.3.7 On the Effect of Multiuser Detection Efficiency

It was seen that the capacity is downlink-limited. The multiuser detection scheme is responsible in part for this characteristic since it removes an important amount of interference on the uplink. Is the capacity still downlink-limited if the efficiency of the multiuser detection scheme decreases? This section aims to answer that question. It also aims to know the importance of the efficiency of the MUD on the capacity of the considered system. Several traffic scenarios are considered in order to study these aspects. Each traffic scenario is studied with different levels of multiuser detection efficiencies.

Figure 5.14 gives the normalized capacity in terms of the total transmission rate of traffic on the network as a function of the multiuser detection scheme efficiency $\beta$. Note that the maximum capacity is reached with a $\beta$ of around 35% for most traffic scenarios.

It was observed that most traffic scenarios are insensitive to the MUD efficiency in terms of capacity. Only the scenarios where a notable deviation was noticed are presented in Figure 5.14. Note that the capacity impact for the shown traffic scenarios is not critical. This is different from the observations made earlier for the base station separation. The worst case observed in this study is when the capacity of scenario *mix phase 4* reaches around 80% of its maximum capacity. This occurs when $\beta$ is 0% (i.e. when no MUD
scheme is used). Remember that this traffic mix is very demanding on the system as all
users transmit at high rates and are indoors. Thus the observed degradation does not
suggest terrible consequences.

Figure 5.14 also suggests that the main factor influencing the capacity of the system as
a function of the MUD scheme efficiency is the presence of high-rate users. Traffic scenarios
where only voice and/or LCD64 users are on the network did not suffer from a poor MUD
scheme efficiency in terms of capacity.

In Figure 5.14, the simulated points are marked and the shown curves are taken from
polynomial interpolations of different orders.

![Normalized capacity vs. MUD efficiency](image)

**Fig. 5.14** Influence of the multiuser detection efficiency on the capacity

Earlier, it was observed that the closest intercell interferer seems to contribute more
to the total interference than the intracell interference. This observation could also be
used here to explain why the capacity impact of the MUD mechanism is not noticeably
important.

All of this hints that if the signal on the uplink can maintain some orthogonality, as
assumed in this study, the performance of the multiuser detection scheme can be consider-
ably relaxed. It also confirms the hypothesis that the system’s capacity is downlink-limited
and helps justify the use of a simple MUD model.
This investigation also hints that the efficiency of the multiuser detection mechanism might have an important influence on the capacity of the TD-CDMA cellular system if code orthogonality cannot be preserved (e.g. due to synchronization issues). It also suggests that, depending on $\beta$, the uplink can sometimes be the mild capacity-limiting link. This implies that the analytical model would only be valid if $\beta$ is high enough to assure that the downlink is the capacity-limiting link. Otherwise, the estimated capacity should be deemed optimistic.

5.3.8 On the Effect of Dynamic Channel Allocation Scheme

The management of radio resources plays an important role in the deployment of a cellular system. In TD-CDMA, the resource allocations are two-folds: (1) time, and (2) OVSF code. This yields great flexibility and complexity. It was suggested in [32] that the DCA plays but a small role when it comes to symmetric services. This section aims to verify that statement. As such, it presents the effect of using different DCA schemes for timeslot selection.

Three different DCA algorithms are compared. The first one is the least-interfered channel (LIC) approach. The second one is the pseudo-random approach. The third one is the channel segregation (SEG) approach. All three algorithms were summarily presented in Section 4.6.

Figure 5.15 presents the capacity analysis as a function of the DCA scheme implemented. This figure shows the comparison between the least-interfered and the pseudo-random approaches for several traffic scenarios. The figure represents the capacity degradation of one approach versus the other as a function of the outage probability.

It can be seen that the difference in terms of capacity between the two schemes is not very significant, as expected. A factor other than the symmetric nature of the traffic plays a role in reaching that conclusion. Since the simulation tool will try to reallocate different resources to users that would have dropped from the network, the load on each timeslot will even out over time, no matter what type of initial timeslot selection is used. Therefore, in this study, the initial timeslot selection process does not significantly influence the capacity of the system, as exposed in [32].

Note that a negative deviation indicates that the pseudo-random algorithm yields a better capacity than the LIC algorithm. It should be observed, however, that the deviation
is almost null.

A comparison of the least-interfered channel and channel segregation approaches is displayed in Figure 5.16. Again, the capacity deviation is not very severe (under 5% deviation). The deviation is only slightly traffic scenario dependent but no clear conclusion on its influence can be inferred from the presented data.

From the previous two analyses, the LIC approach yields slightly better results than the other two algorithms. This is due to the fact that LIC is a devised method that adapts well to the instantaneous load on the network. On the other hand, the SEG method is better suited if the time-variant aspects of the subscribers are modeled [33]. As for the pseudo-random method, it is, on average, suitable for most applications.

From Figures 5.15 and 5.16, it can be inferred that the capacity degradation between the pseudo-random and channel segregation approaches can also be neglected. They are very close to one another in most traffic scenarios.

Note that if other considerations were taken into account, like processing time or signaling needs, the conclusions might be different. For instance, the LIC algorithm does need more computation than the pseudo-random approach. The SEG scheme requires some
information storage space for its priority values, *et cetera*. However, in a pure capacity performance optic, there is no significant difference between all three DCA methods for the system considered in this study.
Chapter 6

Conclusion

In the rapidly converging world of high-speed information, the symbiosis between accessibility, efficiency and reliability is highly sought. The studied technology could well be the solution that network operators will employ to solve this tremendous problem.

The present study investigated the capacity of a UMTS TDD CDMA system at peak usage. It was interested in the probability of blocking a service request as a function of the instantaneous load on the network.

6.1 Summary of the Work

This capacity was investigated with the help of a system-level approach. Two methods were used: (1) an analytical model, and (2) a simulation tool.

The proposed analytical model was never used per se to investigate the capacity of a TD-CDMA system. The model had the advantage of considering only one transmission link, nominally the downlink. The reasons for such a consideration are: (1) the presence of a multiuser detection scheme on the uplink, (2) the Internet traffic distribution, and (3) the use of antenna diversity on the uplink for voice services. Using the simulation tool, this hypothesis was validated in most traffic scenarios with a modest multiuser detection scheme efficiency. The analytical model also allowed the study of the effect on the capacity of the cell’s geometrical shape.

However, the analytical model was seen to have important limitations. For instances, it does not allow a comprehensive study of traffic mixes with several different services and environment simultaneously. Moreover, the model is very sensitive to the accuracy of
several approximations. The resulting capacity can be significantly altered with a slight variation in the estimated parameters.

On the other hand, the simulation tool considered both transmission links and was better suited for most traffic mixes. It allowed for more realistic studies of capacity-impacting phenomena such as (1) base station separation, (2) multiuser detection scheme efficiency, (3) presence of multicode transmission interference, and (4) dynamic channel allocation algorithms. Moreover, the simulation tool included a model for the power control imperfections.

6.2 Gained Experience

Using these two approaches interchangeably, it was observed that the capacity is affected by the proportion of users per service since high-rate users are more prone to being blocked or dropped from the network. Dropped high-rate users will tend to be replaced by less power-demanding low-rate users. The dropping was considerably reduced by using resource reallocation schemes but could not be entirely prevented in the simulation tool since a TD-CDMA system advocates higher transmission powers than its W-CDMA counterpart.

It was also observed that the capacity depends on the environment in which the mobiles are evolving. Indoor environments tend to give poorer results. This indicates that the effect of the building penetration losses on the capacity are relatively severe with this wireless technology.

In general, it was noticed that around 400 kbps per sector can be supported in the considered network for an outage probability of around 2%. In almost all cases, the capacity is downlink interference-limited.

It was noticed that a maximum of around 7 to 9 orthogonal codes can be used per timeslot. This is fully coherent with what other studies suggested.

Using the BS separation study, it was concluded that a UMTS TDD CDMA system should be used in pico- and micro-cellular environments in order to support efficient data transmissions. This is consistent with the results stated in previous studies.

The study of the presence of multicode transmission interference indicated that this type of interference is often wrongfully neglected in capacity studies. The multicode interference was expressed in closed-form and can easily be included in most existing capacity studies without great restructuring. **These results and the closed-form expression of the**
multicode transmission interference are original contributions.

The dynamic channel allocation algorithms does not play an important role in the total capacity of the system. This result is due to the presence of symmetric services and to a resource reallocation scheme that effectively evens out the traffic load on each timeslot. This conclusion is similar to the ones found in the literature.

6.3 Future Work

Further investigation should be oriented towards evaluating the traffic asymmetry possibilities of TD-CDMA. As such, new asymmetric services should be defined. The role of the dynamic channel allocation algorithms would then become predominant in terms of the capacity of the network.

Furthermore, the introduction of packet switched services would provide insightful information on the potential of a TD-CDMA system. It could also prove interesting to investigate the actual movement of the subscribers, thus allowing the study of handover characteristics of the system.

In this study, it was decided to use a uniform code orthogonality factor $\theta_e$ of 0.4. This is a conservative consideration as this factor is much better in pedestrian environments where the Doppler spread is not as severe [50]. Moreover, considering the synchronous nature of the TD-CDMA, it might prove reasonable to lower $\theta_e$. Even so, the orthogonality factor for downlink transmissions could be different than the one for uplink transmissions. On a different topic, note that it is unclear whether the $\theta_e$ for multi-code transmission is the same as the $\theta_e$ for a user-to-user transmission. These aspects require further investigation.

Moreover, it might prove interesting to investigate the effect of having no code orthogonality on the uplink. This would emphasize the role played by the multiuser detection scheme on the capacity of the network.

Based on the observed results, the simulation tool is more adequate for the creation of a UMTS TDD CDMA network deployment/design tool. The proposed simulator would be a fundamental building block. This network design tool would be helpful in planning the roll-out of a 3G wireless network in terms of capacity and coverage estimation at the air interface layer.
Appendix A

Characteristics of Lognormal Distributions

This Appendix presents the fundamental characteristics of a lognormal random variable. Most of what is presented here can be found in the first chapter of [62].

A.1 Definition and Notation

Consider a random variable $X$. If $Y = \ln X$ is a Gaussian random variable with mean $\mu$ and variance $\sigma^2$, then $X$ is said to be lognormally distributed with parameters $\mu$ and $\sigma^2$. Denote the two-parameter lognormal distribution by $\mathcal{L}(\mu, \sigma^2)$ and the normal/Gaussian distribution by $N(\mu, \sigma^2)$.

The probability density function (p.d.f.) of $X \sim \mathcal{L}(\mu, \sigma^2)$ is

$$f_X(x) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma x} \exp \left\{ -\frac{(\ln x - \mu)^2}{2\sigma^2} \right\} & x > 0 \\ 0 & x \leq 0. \end{cases} \quad (A.1)$$

It can be shown that the $k^{th}$ moment of $X$ is

$$E[X^k] = \exp(k\mu + \frac{1}{2}k^2\sigma^2), \quad (A.2)$$

where $E[\cdot]$ is the expectation symbol. Therefore, the mean and variance of $X$ can respectively be expressed as
Consider \( Z = aX \), where \( X \sim \Lambda(\mu, \sigma^2) \) and \( a \) is a strictly positive constant. Since [76]

\[
f_Z(z) = \frac{1}{|a|} \cdot f_X\left(\frac{z}{a}\right),
\]

then, it can be seen that

\[
f_Z(z) = \begin{cases} \frac{a}{|a|\sqrt{2\pi}\sigma z} \exp\left\{-\frac{\ln z - \ln a - \mu}{2\sigma^2}\right\} & z > 0 \\ 0 & z \leq 0. \end{cases}
\]

Hence \( Z \sim \Lambda(\ln a + \mu, \sigma^2) \).

### A.2 Product of Lognormal Random Variables

Let \( X_1, \ldots, X_n \) be independent positive random variables where \( X_i \sim \Lambda(\mu_i, \sigma_i^2) \). Let \( c, b_1, \ldots, b_n \) be constants with \( c > 0 \), then [62]

\[
c \cdot \prod_{i=1}^{n} X_i^{b_i} \sim \Lambda(\ln c + \sum_{i=1}^{n} b_i\mu_i, \sum_{i=1}^{n} b_i^2\sigma_i^2).
\]

### A.3 Three-Parameter Lognormal Distribution

A random variable \( X \) that can only take values exceeding a certain value \( \alpha \) is said to be lognormally distributed with three parameters \( \alpha, \mu, \) and \( \sigma^2 \) if \( Y = \ln (X - \alpha) \) is normally distributed with parameters \( \mu \) and \( \sigma^2 \). These three-parameter lognormal distributions are denoted \( \Lambda(\alpha, \mu, \sigma^2) \). The \( \alpha \) parameter is called the threshold parameter (i.e. the lower limit). The p.d.f. of such a distribution can be expressed as

\[
f_X(x) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma(x - \alpha)} \exp\left\{-\frac{(\ln(x - \alpha) - \mu)^2}{2\sigma^2}\right\} & x > 0 \\ 0 & x \leq 0. \end{cases}
\]
Based on this observation, the mean and variance of $X$ can be represented by

$$E[X] = \alpha + \exp(\mu + \frac{1}{2}\sigma^2), \quad (A.9)$$

$$Var[X] = \exp(2\mu + \sigma^2) \left( \exp(\sigma^2) - 1 \right). \quad (A.10)$$

Note that the variance does not change and that the mean is "shifted" by the threshold parameter.
Appendix B

The Sum of Lognormally Distributed Random Variables

An expression for the sum of lognormal random variables cannot be expressed in closed form [63]. Many methods exist to approximate this sum. They all have their merits and flaws. Most methods approximate the sum as being another lognormally distributed random variable.

Beaulieu, Abu-Dayya and McLane [73] studied and compared different methods of computing the sum of lognormal random variables. Among the proposed methods, two are of particular interest in the present case, namely the Wilkinson method [74] & [63] and the Schwartz and Yeh method [63].

This Appendix presents these methods and others. It also introduces basic concepts required to successfully translate decibel values to natural base values.

B.1 From Decibels to Natural Base

This section offers rapid reference to convert mean and standard deviations in decibels (dB) to natural base units for computation simplicity. It also presents the notation used throughout this Appendix.

Consider $X_i$ as a lognormal random variable with known characteristics. The p.d.f. of $X_i$ is given in equation A.1. In communication applications, it is convenient to express the parameter of $X_i$ in terms of dB. This can be represented as
\[ P_i = 10 \cdot \log_{10} X_i. \] (B.1)

It implies that \( P_i \) is normally distributed with known mean \( m_p \) dB and standard deviation \( \sigma_p \) dB. For simplicity of manipulation, define \( Y_i \) as the natural logarithm of \( X_i \), i.e.

\[ Y_i = \ln X_i. \] (B.2)

\( Y_i \) is normally distributed with mean \( m_Y \) and standard deviation \( \sigma_Y \). Therefore, the relation between \( P_i \) and \( Y_i \) and their respective parameters can simply be expressed by

\[ Y_i = \lambda \cdot P_i, \]
\[ m_Y = \lambda \cdot m_p, \]
\[ \sigma_Y = \lambda \cdot \sigma_p. \] (B.3)

where \( \lambda = \ln 10 / 10 \).

Consider \( X \) the sum of \( K \) lognormal random variable.

\[ X = \sum_{i=1}^{K} X_i = \sum_{k=1}^{K} e^{Y_i} = e^Z, \] (B.4)

where \( Z \) is the normal random variable associated with \( X \). \( Z \) has a mean \( m_z \) and a standard deviation \( \sigma_z \). Remember that \( X \) is approximately lognormally distributed. The goal of the presented methods is to obtain these two parameters with accuracy.

**B.2 Wilkinson’s Method**

The Wilkinson method consists in matching the first two moments of \( X \) with the \( Y_i \)'s to obtain a set of two equations and two unknowns, namely \( m_z \) and \( \sigma_z \). For example [63], if \( K=2 \), and \( Y_1 \), and \( Y_2 \) are both represented by \( m_Y \) and \( \sigma_Y \), then using equation A.2, it can be established that
The Sum of Lognormally Distributed Random Variables

\[ E[X] = e^{(m_Z + \frac{1}{2} \sigma^2_Z)} = 2e^{(m_Y + \frac{1}{2} \sigma^2_Y)}, \]

\[ E[X^2] = e^{(2m_Y + 2 \sigma^2_Y)} = 2e^{(2m_Y + 2 \sigma^2_Y)} + 2(e^{(m_Y + \frac{1}{2} \sigma^2_Y)})^2. \]  

(B.5)

This follows from the fact that the \( Y_i \)'s are statistically independent and from the linearity of the expectation operation, i.e. the mean of the sum is the sum of the means. In a more general case [75], consider \( K \) terms in the sum \( X \) and denote the first and second moment of \( X \) by \( v_1 \) and \( v_2 \), respectively. Using equations B.4 & A.2 and matching the first moment results in [75]

\[ E[X] = E[e^Z] = E\left[ \sum_{i=1}^{K} e^{Y_i} \right] \]

\[ = e^{(m_Z + \frac{1}{2} \sigma^2_Z)} = \sum_{i=1}^{K} e^{(m_{Y_i} + \frac{1}{2} \sigma^2_{Y_i})} = v_1. \]  

(B.6)

Proceeding similarly for the second moment yields

\[ E[X^2] = E[e^{2Z}] = E\left[ \left( \sum_{i=1}^{K} e^{Y_i} \right)^2 \right] \]

\[ = e^{(2m_Y + 2 \sigma^2_Y)} = \sum_{i=1}^{K} E[e^{2Y_i}] + 2 \sum_{j=1}^{K-1} \sum_{i=1}^{K} E[e^{Y_i}e^{Y_j}] \]

\[ = \sum_{i=1}^{K} e^{(2m_{Y_i} + 2 \sigma^2_{Y_i})} + 2 \sum_{i=1}^{K-1} \sum_{j=i}^{K} e^{(m_{Y_i} + m_{Y_j})} e^{\frac{1}{2}(\sigma^2_{Y_i} + \sigma^2_{Y_j} + 2\rho_{ij}\sigma_{Y_i}\sigma_{Y_j})} = v_2. \]  

(B.7)

where \( \rho_{ij} \) is the cross-correlation between \( Y_i \) and \( Y_j \). When the variables are statistically independent, the cross-correlation is zero. Equations B.6 & B.7 contain two unknowns: \( m_Z \) and \( \sigma_Z \). Taking logarithms gives a set of linear equations. Solving these equations comes down to
Wilkinson’s method looses precision on parameter estimation when the standard deviation of the $Y_i$’s standard deviation gets higher, i.e. when $\sigma_p > 4 \text{ dB} [63]$. However, this does not imply that the method yields poor approximation of the cumulative density function (c.d.f.) of $X$. In fact, [75] states that the approximation is advantageously interesting in regions of $\sigma_p$ applicable to digital wireless telecommunication and in regions of the c.d.f. lower than $10^{-1}$. The advantages of this method with respect to Schwartz and Yeh’s method are found in simplicity and in accuracy of the c.d.f.

### B.3 Schwartz and Yeh’s Method

In [63], Schwartz and Yeh propose an algorithm to approximate the sum of lognormal random variables by another lognormal random variable.

The method consists in exactly expressing the moments of two lognormal variables. Assuming that the result is lognormally distributed, the moments are then used in a recursive fashion to obtain the moments of the desired sum. For example [63], consider the sum of three lognormal random variables

$$X = X_1 + X_2 + X_3 = e^Z \quad (B.9)$$

The exact first and second moments of $Z_2 = \ln (X_1 + X_2)$ can be computed. One can then take $Z_2$ and recursively find the moments of $Z$ by doing

$$Z = \ln X = \ln e^{Z_2} + X_3 \quad (B.10)$$

Thus, the results depend on the order in which the summation is approximated, i.e. $X_1 + X_2 + X_3$ could yield slightly different results than $X_2 + X_3 + X_1$. The severity of the difference varies according to the scenario. This effect is always ignored in the literature as of the writing of this document.

In general, consider $X$ of equation B.4. The normal random variables $Y_i$’s are uncor-
related with mean and variance given by \( m_{Y_i} \) and \( \sigma_{Y_i} \), respectively. Define \( \omega = Y_2 - Y_1 \) as a normal random variable.\(^1\) \( m_\omega \) and \( \sigma_\omega \) are the mean and standard deviation of \( \omega \), respectively. They can be compute as [76]

\[
\begin{align*}
m_\omega &= m_{Y_2} - m_{Y_1} & \quad \text{(B.11a)} \\
\sigma_\omega^2 &= \sigma_{Y_1}^2 + \sigma_{Y_2}^2 & \quad \text{(B.11b)}
\end{align*}
\]

The exact moments of \( Z_2 \) are given by

\[
\begin{align*}
m_{Z_2} &= m_{Y_1} + G_1(\sigma_\omega, m_\omega) & \quad \text{(B.12a)} \\
\sigma_{Z_2} &= \sigma_{Y_1} - G_1^2(\sigma_\omega, m_\omega) + 2\frac{\sigma_{Y_1}^2}{\sigma^2_\omega}G_3(\sigma_\omega, m_\omega) + G_2(\sigma_\omega, m_\omega) & \quad \text{(B.12b)}
\end{align*}
\]

where the functions \( G_1, G_2, \) and \( G_3 \) are functions defined in [63]. The procedure is repeated recursively until all of the variables in the summation are taken into account.

Schwartz and Yeh’s method shows high accuracy in estimating the characteristic of \( X \) when the spread is relatively high, i.e. \( \sigma_\rho > 2 \) dB [63], especially the mean of the resulting lognormal random variable. In particular, the mean of the summation of up to 30 components is accurate for \( 2 \leq \sigma_\rho \leq 14 \). The standard deviation estimation looses exactitude when more than eight equal components with \( \sigma_\rho < 10 \) are considered. The estimation of the c.d.f. is accurate in the 0.01 to 0.99 region.

### B.4 The Choi and Kim Technique

In [14], the authors use another computation technique to estimate the parameters of a summation of lognormal random variables. Consider

\[
S = c_1 \sum_{i=1}^{K_1} \chi_i + c_2 \sum_{i=1}^{K_2} \chi_i + \ldots + c_n \sum_{i=1}^{K_n} \chi_i \quad \text{(B.13)}
\]

\(^1\)The sum of two normal random variables is a normal random variable [76].
where \( \chi_i \) are lognormally distributed random variables with mean dB value and standard deviation dB value \( m_\chi \), and \( \sigma_\chi \), respectively, \( c_k \)'s and \( K_k \)'s are positive constants.

The mean and variance of \( S \) can be obtain as

\[
E[S] = K_1 \cdot f(m_\chi + \ln c_1, \sigma_\chi) + \ldots + K_n \cdot f(m_\chi + \ln c_n, \sigma_\chi) \quad \text{(B.14a)}
\]
\[
Var[S] = K_1 \cdot h(m_\chi + \ln c_1, \sigma_\chi) + \ldots + K_n \cdot h(m_\chi + \ln c_n, \sigma_\chi) \quad \text{(B.14b)}
\]

where

\[
f(a, b) = \exp(\lambda a + \frac{1}{2}(\lambda b)^2), \quad \text{(B.15)}
\]

and where

\[
h(a, b) = \exp(2\lambda a + (\lambda b)^2)(\exp((\lambda b)^2) - 1). \quad \text{(B.16)}
\]

To get the values of \( \tilde{S} = 10\log_{10} S \) in dB, the following manipulations are in order

\[
Var[\tilde{S}] = \sigma_{\tilde{S}}^2 = \frac{1}{\lambda^2} \ln \left( \frac{Var[S]}{E^2[S]} + 1 \right) \quad \text{(B.17a)}
\]
\[
E[\tilde{S}] = m_{\tilde{S}} = \frac{\ln(E[S])}{\lambda} - \frac{1}{2} \cdot \lambda \cdot \sigma_{\tilde{S}}^2 \quad \text{(B.17b)}
\]

The accuracy of this method was not found in the literature as of the writing of this document.
Appendix C

Distances between Base Stations and Mobile

This Appendix presents the distances between 9 base stations and a mobile station located within the cell of interest, as a function of its position.

C.1 Network Layout

The network is modeled as tri-sectored hexagonal cells. The base station of interest is labelled $BS_0$. The other base stations are labelled $BS_k$, where $k$ varies from 1 to 9. This is illustrated in Figure C.1.

C.2 Mobile Position

The mobile is positioned randomly. Its coordinates are given by two parameters, $r$ and $\theta$, the radius and the angle, respectively. The radius varies between 0 and $2D/3$, where $D$ denotes the distances between base stations. The angle $\theta$ varies between $0^\circ$ and $120^\circ$. This is presented in Figure C.1.

C.3 Distances

The distance between base station $k$ and the mobile is denoted as $d_k$ and can be computed using the following formulae.
\[d_1 = \frac{D - r \cos \theta}{\cos[\arctan \left( \frac{r \sin \theta}{D - r \cos \theta} \right)]}\]  
(C.1)\\
\[d_2 = \frac{D - r \cos (\theta - 60')}{\cos[\arctan \left( \frac{r \sin (\theta - 60')}{D - r \cos (\theta - 60')} \right)]}\]  
(C.2)\\
\[d_3 = \frac{D - r \cos (120' - \theta)}{\cos[\arctan \left( \frac{r \sin (120' - \theta)}{D - r \cos (120' - \theta)} \right)]}\]  
(C.3)\\
\[d_4 = \frac{D + r \cos \theta}{\cos[\arctan \left( \frac{r \sin \theta}{D + r \cos \theta} \right)]}\]  
(C.4)\\
\[d_5 = \frac{D + r \cos (\theta - 60')}{\cos[\arctan \left( \frac{r \sin (\theta - 60')}{D + r \cos (\theta - 60')} \right)]}\]  
(C.5)\\
\[d_6 = \frac{D + r \cos (120' - \theta)}{\cos[\arctan \left( \frac{r \sin (120' - \theta)}{D + r \cos (120' - \theta)} \right)]}\]  
(C.6)\\
\[d_7 = \frac{\sqrt{3}D - r \cos \theta - 30'}{\cos[\arctan \left( \frac{r \sin (\theta - 30')}{\sqrt{3}D - r \cos (\theta - 30')} \right)]}\]  
(C.7)\\
\[d_8 = \frac{2D - r \cos \theta - 60'}{\cos[\arctan \left( \frac{r \sin (\theta - 60')}{2D - r \cos (\theta - 60')} \right)]}\]  
(C.8)\\
\[d_9 = \frac{\sqrt{3}D - r \cos \theta - 90'}{\cos[\arctan \left( \frac{r \sin (\theta - 90')}{\sqrt{3}D - r \cos (\theta - 90')} \right)]}\]  
(C.9)
Appendix D

Antenna Gain and Cable/Body Losses

This Appendix reproduces the results shown in [7] concerning the antenna gain and cable/body losses considerations. The antenna gain factor can be decomposed into two parts,

\[ G_a = G_{\text{amax}} - L_a, \]  

(D.1)

where \( G_{\text{amax}} \) is the maximum antenna gain over all azimuths and \( L_a \) is the azimuth-dependent difference from the maximum. In other words, \( L_a \) contains the antenna pattern. As an omnidirectional antenna is assumed at the subscriber mobile station, \( L_a \) depends only on the azimuth of the subscriber mobile station as seen from the base station. The gain of the subscriber mobile station antenna can therefore be lumped into \( G_{\text{amax}} \). In the simulation tool, \( G_{\text{amax}} \) and the body loss \( L_b \) are lumped into a single parameter \( G_c (= G_{\text{amax}} - L_b) \) called combined gain of antenna gains, cable losses and body losses. The default value of this parameter is 12.5 dB, but can be changed by the user. The pattern \( L_a \) is typical of a 120-degrees sectorized antenna, as illustrated in Figure D.1. Note that only the “horizontal” (azimuth) pattern is used by the simulation tool. The main features of the default antenna are a gain of 17.5 dBm, and an attenuation between antenna and the transmitter of 5 dB.

In the current version of the simulation tool, it is not possible for the user to change the shape of the antenna pattern using the graphic interface. Note that parameters related to antenna gains, body losses and cable losses are independent of the environment.
Fig. D.1  Base station antenna pattern assumed in the simulation tool (the vertical pattern is ignored)
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