UMTS Cellular Network with Relaying Concept

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Abstract

Wideband Code Division Multiple Access (WCDMA) is one of the technologies for third generation systems. In a CDMA system, all users interfere with each others, therefore the CDMA system is interference limited. The users, who suffer from a strong shadow effect or that are far away from the BS, need more power to reach it. In this case, the users may transmit at their maximum allowed power without satisfying their Quality of Service. Therefore, this would leave some mobiles in outage and also create too much interference to the neighboring cells. One-way to counter this problem and therefore to improve the capacity is to increase the number of BSs. But this solution cannot be efficient as it significantly increases the network infrastructure cost. Alternative techniques that involve less planning and are quick to deploy appear to be more advantageous. Relaying is one of these techniques and is growing in importance for future wireless systems.

In this thesis, a new radio access network based on combinations of multi-hop and star-topology architectures is proposed. The main objective of this thesis is to demonstrate achievable capacity gains under various relaying criteria compared with no-relaying (conventional) cellular architecture. In this new architecture, some intermediate nodes (mobile or fixed) located between the originating terminal and the BSs are used for the purpose of retransmitting the original packets.

We show that under specific criteria and conditions the multihop concept indeed yields capacity gains. A number of different scenarios are defined and their relative performances are fully evaluated using an accurate dynamic system-level simulator. The capacity gains are compared to the case of no relaying/hopping. To demonstrate the achievable capacity gains, we use UMTS FDD and TDD modes. The proposed concepts and criteria for relaying are generic enough to be used with current and future radio access technologies. The results show that under certain conditions an uplink capacity gain of 30-40% is readily achievable with the multihop architecture.
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## Abbreviations

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<th>Description</th>
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<tbody>
<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
</tr>
<tr>
<td>BS</td>
<td>Base Station</td>
</tr>
<tr>
<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
</tr>
<tr>
<td>FRS</td>
<td>Fixed Relay Station</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communication</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial, Medical and Scientific</td>
</tr>
<tr>
<td>IRHO</td>
<td>Inter-Relay Handoff</td>
</tr>
<tr>
<td>LOS</td>
<td>Line of Sight</td>
</tr>
<tr>
<td>MAI</td>
<td>Multiple Access Interference</td>
</tr>
<tr>
<td>MAPL</td>
<td>Maximum Allowed Path Loss</td>
</tr>
<tr>
<td>MI</td>
<td>Mobile Intermediate</td>
</tr>
<tr>
<td>MO</td>
<td>Mobile Originator/Outage</td>
</tr>
<tr>
<td>MRS</td>
<td>Mobile Relay Station</td>
</tr>
<tr>
<td>MS</td>
<td>Mobile Station</td>
</tr>
<tr>
<td>NLOS</td>
<td>Non Line of Sight</td>
</tr>
<tr>
<td>ODMA</td>
<td>Opportunity Driven Multiple Access</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>PC</td>
<td>Power Control</td>
</tr>
<tr>
<td>PCS</td>
<td>Personal Communication System</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability Density Function</td>
</tr>
<tr>
<td>PL</td>
<td>Path Loss</td>
</tr>
<tr>
<td>RS</td>
<td>Relay Station</td>
</tr>
<tr>
<td>SAC</td>
<td>Shadowing Auto-Correlation</td>
</tr>
<tr>
<td>SCC</td>
<td>Shadowing Cross-Correlation</td>
</tr>
<tr>
<td>SIR</td>
<td>Signal-to-Interference Ratio</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TD-CDMA</td>
<td>Time Division – Code Division Multiple Access</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>UE</td>
<td>User’s Terminal</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
</tr>
<tr>
<td>UTRA</td>
<td>Universal Terrestrial Radio Access</td>
</tr>
<tr>
<td>UWC</td>
<td>Universal Wireless Communication</td>
</tr>
<tr>
<td>WCDMA</td>
<td>Wideband CDMA</td>
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Chapter 1

1 Introduction

1.1 Thesis Motivations

In a conventional cellular network (e.g. UMTS), a base station (BS) controls a number of mobile stations (MS) within its own coverage area and all the terminals communicate directly with the BS, Figure 1.1 (a). The capacity per cell represents the maximum amount of data, which is sent/received to/by the BS. However with an ever-increasing demand for mobile communications, we need to investigate new access schemes as well as novel system architectures to improve the offered cell capacities without increasing the required radio frequency spectrum. Hence the question of efficient use of limited available spectrum resources is becoming an important research issue particularly for systems beyond 3G where capacity (i.e. number of supported users) per cell of more than 100Mbps are targets. One of the main impediments to successful data transmission is errors due to fading and interference. In the current conventional cellular network, all MSs, even those far away from their BS have to communicate directly with the access point, requiring high levels of radiated powers. This high power causes considerable interference with other users within a cell as well as neighboring cells. Reducing required transmission power would result in an increased cell capacity or range. One solution would be to reduce cell size and thereby increase the number of base stations. In this way the majority of users will be closer to a base station and would create less interference to others cells. However, this solution is not very economical due to significant increase in network infrastructure costs and complicated planning procedures (obtaining permissions for base stations are becoming increasingly difficult) and network operations. Another possible solution to improve the capacity and coverage of cellular network is to use the concept of ad hoc networking in a cellular network. In a fully distributed or a pure ad hoc network there are no base stations to control the communications and the terminals themselves have to organize the communications in a distributed manner. A source node sends its data packets to a destination node by relaying the data packets using intermediate nodes; Figure 1.1 (b). A pure ad hoc network offers interesting features such as self-organizing, infrastructureless or possibility of dynamic adaptation to the environment [Toh02]. However there are still many challenges, such as routing protocols, radio link reliability, network connectivity, signaling overhead or terminal’s battery life, that are subject of intensive research world wide.
Chapter 1. Introduction

It is clear from the above discussions that the multihop architecture is a promising approach to the capacity and coverage improvement of a cellular network [Pab04]. However, there are many challenges in realizing multihop cellular network (discussed in section 1.3). One of the most important challenges is due to the radio resource management problem.

In a cellular network with relaying, the users transmit their traffic to the BS through relay stations. During the relaying process, the relay stations are active and hence contribute to the interference in the system. In fact, there are more users transmitting in a multihop cellular network than in a conventional cellular network. Even though in multihop cellular networks, the users are transmitting to a closer destination (RS or BS), it is still not clear which architecture provides less interference and consequently more capacity.

Another drawback of cellular networks employing relaying is the need for additional resources. Whenever relaying is performed another additional channel is required for the link between MSs and relay stations (RS). If the same frequency is used for the link MSs-RSs and RSs-BS, it might yield to excessive interference. If another frequency is used for the relaying channel then additional bandwidth is required. Therefore, multihop cellular networks have some advantages and disadvantages that need to be investigated before deciding its adoption.

1.2 History of Relaying Concept

In this section, we give a brief history of the relaying concept. A more detailed state of art is described in the next chapter.

The concept of relaying was first introduced and studied as a theoretical problem in the 1970's with the work of Van der meulen [Meu71]. Cover et al. [Cov78] also evaluated the capacity gains of simple relaying channels where three nodes were able to communicate with each others.

In the late 1980's, Quinn suggested the use of repeaters to enhance the coverage of the cellular network. A repeater is a device that is located between a BS and a user. It has two antennas, a donor antenna directed to the BS and a coverage antenna directed toward a service area. The goal of the repeaters is to amplify and retransmit received signals in both uplink and downlink [Dru88, Qui86, Lef88]. However the application of a repeater is limited because a repeater amplifies not only the useful received signal but also the noise.

In 1995, a patent called adaptive communication system was invented. From this patent, the concept of ODMA (Opportunity Driven Multiple access) came about. This concept is based upon the idea of using other existing terminals located between the originating terminal and the BS for the purpose of retransmitting the original packet. This concept was introduced into the UMTS 3GPP standard in 1997 [ETSI97]. However modifying the WCDMA standard to enable relaying
was not a trivial task and as a result the ODMA concept was left for further investigations.

Since the early 2000's, there has been great interest in the research of multihop cellular network in both academia and industry. First in 2001, two journal papers have created a lot of interest due to their originalities. Aggelou et al. [Agg01] proposed the Ad Hoc GSM cellular system. The A-GSM adds the relay capability to a second generation GSM network to enhance the system coverage. While Wu et al. [Wu01] proposed the iCAR (integrated cellular and ad-hoc relay) system as an efficient way of balancing traffic loads between cells with the help of fixed relay stations from a congested cell to cells with a lower traffic.

In industry, most manufacturers (such as Nokia, Ericksson, Motorola, Siemens, Fujitsu) and operators (Such as Vodafone, NTT Docomo) have shown interest in the concept of relaying and are currently doing research on its possible integration in the cellular network. Furthermore, several start-up companies have developed their own proprietary relay based solutions to provide high capacity and coverage; such as BelAir Network [Bel02] or MeshNetwork (Which has been recently acquired by Motorola) [Mesh02].

In the last few years, many projects that evaluate the relaying concept have started. One of the most important one is the WINNER project which aims to develop a ubiquitous radio system concept covering the full range of scenarios from short range to wide area network providing significant improvements compared to current systems in terms of performance, efficiency, and relay-based deployment concepts [Win01]. Others EU-IST projects such as Romantik [Rom01], Mobile VCE [MVCE06], Fireworks are also considering relaying as a possible part of beyond 3G network.
1.3 Relaying Concept Considerations

A thorough investigation of the concept of relaying is an enormously complex task due to the many parameters involved, including channel propagation, physical layer issues, multiple access schemes and resource management, signalling issues, and finally implementation-related issues. Therefore before integrating relaying into a cellular network, many issues need to be investigated. The reference [Yan02] gives an exhaustive list of issues. Here are some of the main issues which deserve rigorous investigation.

The main issue in a relaying system concerns the air interface and multiple access schemes used in multihop cellular network. Since the users communicate with the BS but also with the RS, another channel is required. Therefore two different options are possible. One suggests using the licensed band while others suggest the use of licensed-exempt bands for relaying. For the first choice, some portion of the spectrum can exclusively be dedicated for relaying channels. With this scheme, the interference between the two different links (MS-RS and MS/RS-BS) is avoided. However the portion of spectrum used for relaying is an extra cost to the network architecture deployment. In the second choice, the MS and the RS communicate within an unlicensed band. This is an interesting approach since no expensive licensed band will be needed for relaying. On the other hand, it is difficult for a service provider to control the level of interference of the system since the band used is unlicensed. The multiple access schemes considered in multihop cellular networks are also an important issue. It is still not clear which access scheme will be more suitable for relaying (TDMA, CDMA, OFDM or a new access scheme designed for relaying etc...).

Another issue concerns the type of relay station used in the multihop cellular network. The relay station can either be mobile or fixed. In the case of a mobile relay station, the users terminals, laptops or vehicles can act as a relay station. In such architecture no extra cost is required for the integration of relaying in the cellular network (except an additional cost to the terminals hardware and functionality). However, the service providers need to have a strong control of the density of the users to be candidate relay stations. On the other hand, the use of fixed relay stations allow better control of the coverage area but an extra cost for the planning and deployment of fixed relay station is needed.

Another important issue is related to the routing mechanism. When a user requires relaying assistance it has to select an appropriate relay station in order to transmit successfully its traffic to the BS. Therefore a suitable routing (also called “relay station selection” scheme) should be designed in order to obtain the optimal performance. This issue is even more crucial in the case of a mobile relay station, since there are many possible candidates’ relay stations.
The relaying system can also be classified as analog (also referred as “amplify and forward” or “non-regenerative” relaying) or digital (“decode and forward” or “regenerative” relaying). In the analog relaying, the relay stations just amplify and retransmit the signal received. Even though the analog relays could be less expensive to implement, during the relaying process the relay station amplify also the noise, which can have a negative effect on the system performance. On the other hand, in digital relaying, the relay stations detect and decode the received signal before re-encoding and retransmitting it. In that case, the noise is not amplified but the re-encoding might introduce some error in the retransmission.

In multihop cellular network, a signal from a source may reach its destination in multiple hops through the use of relay stations. However it is still not clear what is the maximum number of hops allowed in the system in order to achieve the best performance. With multiple hops (e.g. more than two hops), the path links along the multi-hop chains are smaller and therefore less power is required to reach the next node, which can lead to a better system performance. However, the complexity in terms of resource needed, routing, signalling and delay might be significantly increased. While limiting the number of hops to two, might have a lower performance but the system complexity might not be important.

In multihop cellular network, multiple copies of the same signal may reach the destination since the same signal is transmitted at least twice in the same route; utilizing this natural diversity may yield significant performance enhancements. Moreover it is also possible that two or more relays station actually cooperate among themselves at various degrees in order to enhance the quality of the delivered signal. This approach is known as “cooperative Relaying system” [Her04] and is opposed to the conventional relaying system.

At least but not last, the signalling involved in multihop cellular network need also investigations. Since new links are required for the communications between MS and RS, the level of signalling increases compare to the cellular network. Therefore, it is possible that the amount of signalling required to operate and control an efficient multihop cellular network may nullify the advantages gained. Therefore it is important to evaluate the signalling required and then propose new algorithm to minimize it.

1.4 Scope of the Thesis

The main goal of this thesis is to evaluate the performance of the cellular network with relaying. First, we need to assess if relaying improve the cellular network in terms of capacity and coverage. And then if there is improvement what are the capacity and coverage gain?

For this, two cellular system models; one without relaying and one with relaying, are designed.
Chapter 1. Introduction

The performances of both systems are evaluated and compared through a dynamic system level simulator. The analytical models of each system are also studied to complement the simulations.

Whilst in the literature, most of the works consider TDMA as the multiple access for the relaying system, we concentrate herein more on the performance evaluation of the multihop cellular network for the 3G network. Therefore, the performances of UMTS cellular networks without and with relaying are evaluated. Since another channel is required for the MS-RS link, we propose to use the CDMA air interface for both links. However with the current technology, wireless terminals cannot transmit and receive simultaneously in the same carrier frequency [Hol00]. Therefore we use two carrier frequencies; one carrier (F1) is used for the link between MS-BS and another carrier (F2) is used for the link between MS-RS. However we also evaluated the system performance of the relaying system where the TDD mode is used between MS and RS.

Different routing algorithms were proposed and their influence on the system performance was assessed with simulations. The relaying model is based on a two-hop cellular system which limits the system complexity.

Almost all the works in the literature that have studied the concept of relaying in cellular networks have considered relaying either with mobile relay station or fixed relay station. In this thesis we have considered both scenarios. Their performance has been evaluated and compared through the same dynamic system level simulator so as to make a fair comparison. In both models, the mobile or fixed relay stations are considered to be digital relays.

However the control signalling is not considered in this study and is left as future work.

1.5 Thesis Structure

Chapter 2 is divided into two sections. Since the system model is based on a UMTS cellular network, the first section of the chapter gives a description of the CDMA air interface. The second section gives a detailed overview of the recent works that have been published in the field of relaying.

Chapter 3 gives the analytical model of the relaying system capacity, considering the uplink scenario. The capacity in terms of number of users for a certain outage probability for the non-relay and relay model is calculated. The mathematical model is expanded to provide results for the case of relaying with two hops. Additionally, results are produced for the case where a relay station can relay more than one MS. Two different modes of division are considered, FDD for the direct transmission and TDD for the relaying transmission and the effective use of bandwidth is taken into account in deriving conclusions.

Chapter 4 is based mainly on two sections. The first section gives a detailed description of the
dynamic system level simulator used to assess the performance of the cellular network without relaying. After explaining the role of the system level simulator, the different elements of the radio resource management of the simulator are described in detail. In the second section, a new shadowing model is proposed and explained. This shadowing model considers the two-dimensional auto-correlation and can be applicable to any dynamic system level simulator.

Chapter 5 evaluates the capacity gain that relaying with a mobile relay station brings to the CDMA cellular network through dynamic simulator. The model considers a two-hop based cellular network for the uplink scenario. When relaying is performed through a mobile relay station, two issues should be considered: first, when should a MS be relayed and what criteria should be used in selecting a relaying node. For each issue, different algorithms have been proposed and assessed. For evaluation of capacity gains the UMTS FDD and TDD modes were used for the two hops. In the case where two carrier frequencies are used, different carrier frequency usages/patterns for the relaying channel are suggested and tested.

In chapter 6, we propose and evaluate the performance of a UMTS FDD cellular network employing fixed relay station. The aim of this chapter is first to properly qualify and quantify the capacity and coverage enhancement of the cellular network with a fixed relay station. Due to the specificities of the fixed relay station, the different factors that can affect the system performance are defined and evaluated.

Chapter 7 compares the performance of the relaying system with mobile and fixed relay stations. First, the different advantages and disadvantages of each type of relay station are defined and discussed. Then their performances are compared through the same dynamic simulator.

In this chapter, the inter-relay handoff is also studied. Due to the MS’s mobility, the relayed users would probably need to handover from one RS to another RS with better channel quality. This process, particular to the relaying system, is called the inter-relay handoff. Its impact on the relaying system performance is also evaluated through simulation.

Chapter 8 gives the conclusions, the achievements and proposes some future work in the fields of relaying.

The thesis structure is shown in the figure 1.3.
1.6 Definitions of Terms used

In this thesis, different terms have the same meaning. The terms "multihop cellular network", "cellular network with relaying" or "relaying system" are used interchangeably. The terms "Mobile Originator (MO)" or "relayed mobile station" are used for the mobile stations that need to be relayed or require relaying assistance.
Chapter 2

2 State of the art

2.1 CDMA background

2.1.1 UMTS

The cellular telephone success story prompts the wireless communications community to turn its attention to even more information services, many of them in the category of wireless data communications. The explosive growth of the Internet and the continued dramatic increase in demand for all types of wireless services (voice and data) are fuelling the demand for a large increase in capacity, data rates, and supported services (e.g., multimedia services). To bring high-speed data services to the mobile population, “third generation” transmission technology has been devised. This is characterised by user bit rates on the order of hundreds or thousands of kb/s, one or two orders of magnitude higher than the bit rates of current digital cellular systems. The main force that is driving higher data rates over wireless is “Universal Mobile Telecommunications System” (UMTS), which is the official name for 3rd Generation (3G) cellular systems.

The reason for the introduction of 3G is that due to the constantly increasing demand for mobile radio services, the existing second generation (2G) mobile radio systems could not meet the requirement for increased capacity. Moreover, all these advanced services, such as multimedia applications, require higher data rates and higher transmission quality than voice services currently offered by 2G mobile radio systems. This, as well as the requirement for flexibility, such as coexistence of voice and advanced services, could not be fulfilled by the existing 2G mobile radio systems [Hol00].

Therefore, in the last decade, worldwide research activities have been aimed at the design and standardisation of the 3G mobile radio system. In Europe the work towards the third generation standard UMTS was led by the “European Telecommunications Standards Institute” (ETSI). The objective is to fulfil the requirement for capacity and provide advanced services and flexibility concerning the data rates and the transmission quality and attain a more efficient bandwidth utilisation than in 2G mobile radio systems.
2.1.2 3GPPs

The third Generation Partnership Project (3GPP) was created by Standards Developing Organizations (SDOs) as a type of joint venture [3GPP03]. It is a collaborative agreement between SDOs and other related bodies for the production of a complete set of globally applicable technical specifications and reports for a 3G system evolved from the GSM core network and based on WCDMA, which includes Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes.

2.1.3 CDMA concepts

CDMA exhibits numerous unique features compared with other multiple access technologies such as TDMA and FDMA. Most of these features are advantageous whereas some such as the requirement for power control are not. The features are:

- **No need for frequency management**: Due to scarce available frequency spectrum, frequency management is an important task for TDMA and FDMA systems where carriers frequency are reused to enhance the spectrum efficiency. In order to reduce the other cell interference, cells using the same carrier frequencies have to be sufficiently separated. In the DS-CDMA system, however, this is not needed as all the cells use the same carrier frequency.

- **Interference rejection capability**: The narrow-band interference will, when despreading at receiver is performed for desired user, be spread, making it appear as background noise within the information bandwidth compared to the de-spread signal.

- **Low probability of interception**: Because of its low power density, the spread spectrum signal is difficult to detect and intercept by hostile listeners.

- **Privacy**: The transmitted signal, when detected, can only be de-spread and the data recovered if the code sequence is known to the receiver.

- **Soft capacity limit**: In a CDMA system, the maximum number of users supported in a cell is decided by the total interference level, rather than the fixed number of carrier frequencies or timeslots respectively as in FDMA and TDMA systems. As all users use the same frequency to communicate and form multiple access interference to others, the interference level will
increase with number of users. However, the system can degrade the performance of all users when users increase and improve the performance when users decrease. In other words, there is no hard limit to users supported in a cell, which normally is referred to as soft capacity.

- Rake receiver provides multipath gain: In a radio channel, there exist multiple propagation paths between a receiver and transmitter due to reflections and refractions. They are all copies of the same transmitted signal with different amplitudes, phases and delays. If the paths arrive more than one chip apart from each other, the receiver can resolve them using a rake receiver that consists of a number of fingers. Each finger is actually a correlator and deals with one multipath component. The multipath components are then de-spread and combined using, for example, maximum ratio combining (MRC). By so doing, a diversity gain is provided to the signal performance.

- Fast power control to counter the near-far problem: The requirement for fast power control in the uplink (UL, from user to base station direction) is the most serious negative aspect of CDMA system. Due to the propagation mechanism, the signal received by the base station (BS) will be stronger from a close mobile station, resulting in increased interference to other users, in particular, the ones near to the cell boundaries. Hence, the distant users will be dominated by the close users in terms of signal quality. This problem is well known as the "near-far effect". Fast power control is one of the solutions to this problem. Fast power control tries to control the transmission power of each user such that all the users will be received at the required signal to interference ratio or average power at base station receiver, no matter where the users are located. This power control operation is normally performed periodically on a short-term basis, for instance 0.6667 ms in UMTS.

- Exploitation of soft handover: In a cellular system, when a user travels from one cell to another during the communication, a handover is needed to change its access point to the network. This is normally referred to as handover. The same frequencies reuse and rake receiver enable soft handover in UMTS, where a user can connect to two or more BSs before it completes the handover procedure. This feature eliminates the short interruption to the communications when a normal handover is applied. More importantly, it provides signal diversities in both uplink and downlink.

- Exploitation of sectored antennas: is one of the most effective techniques to reduce interference in UMTS and to improve the capacity in both uplink and downlink.
2.1.4 Constraints of CDMA

The obvious weakness of CDMA systems is the capacity is limited by multiple access interference (MAI) [Vit95]. MAI stems from signals from other users, who are active in the same frequency band and at the same time. In addition, CDMA systems have a frequency reuse factor of one, which means that they reuse the frequency in every cell. This implies that CDMA systems must contend with not only MAI from within the cell but also from users in neighboring cells.

Ideally, if the spreading codes are perfectly orthogonal, other users signals are perfectly time-aligned, and all signals have the same received power, then the despreading process can completely remove MAI. In real systems, however, the chips and codes are not perfectly synchronised, and are neither perfectly time-aligned nor all signals have the same power at the receiver. Thus real CDMA systems are all affected by MAI.

2.2 Background to Relaying

In this section we give a detailed description of the most relevant works that have been performed on relaying in the last few years. We classify them mainly in two parts. The first part considers the use of unlicensed bands for the relaying channel (link between MS-RS) while the second part considers the use of licensed band with different multiple access schemes.

2.2.1 Relaying in the unlicensed band

[Wu01] built up a new system concept called iCAR: Integrated Cellular and Ad-Hoc Relaying Systems. This system is based on the integration of cellular and modern ad hoc relaying technologies. It addresses the congestion problem due to unbalanced traffic in a cellular system and provides interoperability for heterogeneous networks. The iCAR system can efficiently balance traffic loads between cells by using ad hoc relaying stations (ARS) to dynamically relay traffic from one cell to another. When a mobile is involved in a new call, but is in a congested cell, it can switch over to communicate with an ARS in another cell. In this paper, mobile relay stations are not used. The ARS are fixed and have the same functionality as a simple BS with two radio interfaces. One interface for the link with the BS, which operates at or around 1900 MHz (PCS), and the other interface for the link with the MS uses an unlicensed band at 2.4 GHz (the ISM band). A three tier subsystem (25 cells) is considered, with 25000 users randomly distributed and 56 ARS placed at the boundaries of the cells. They have shown that iCAR, with only a limited number of ARSs placed using the seed-growing approach [Lai02], can dynamically balance the traffic amongst cells, reduce the call blocking/dropping probability (thus increase
system capacity), and improve the system throughput cost effectively.

A two-hop-relay architecture that enhances the system capacity of existing Wireless Wide Area Network (WWAN) was proposed in [Wei04]. The WWAN network encourages mobile terminals that have a good channel quality state to become intermediate relay gateways to assist those mobile terminals with a poor channel quality state to achieve better overall system performance. In this paper, a mobile terminal connects to a relay node using the WLAN radio interface (unlicensed band) and the relay node communicates with the base station with a WWAN radio interface (licensed band). Due to practical reasons, the number of hops is limited to two. The two-hop relay approach reduces the system complexity, avoids inefficient mobile ad hoc routing, reduces the impact of inefficient random medium access protocols and alleviates the congestion bottleneck at the internet gateway nodes.

The results showed that the capacity gain is dependent on the WLAN range of the relay node and the node density. Therefore the capacity of the cellular network is enhanced by between 15% and 45% in the uplink scenario.

The technique of augmenting cellular networks with multihop relays has been applied to different types of cellular network. In terms of the practical benefits of using a wireless ad hoc relay subnet to improve cellular coverage in the second-generation (2G) cellular systems, Aggelou et al. extended the GSM standard with relay capability in an ad hoc GSM (A-GSM) scheme [Agg01] to improve receiving signal strength and eliminate dead spots. A separate MANET interface was used for A-GSM in the dual mode GSM/A-GSM handset. The A-GSM protocol stack as well as handoff decision algorithm and handoff signaling flow are discussed in [Agg01]. A-GSM can typically reduces 8-17% of the dead spots in the GSM network.

### 2.2.2 Relaying in the licensed band

#### 2.2.2.1 Relaying in TDMA

A lot of work on relaying for TDMA cellular networks has been done at Carleton University (Canada). Yanikomeroglu et al. have studied the coverage improvement of TDMA cellular networks [Yan06]. They believe that TDMA will assume an important part of the 4G network and this is the reason that they have based their study on TDMA.

Since a new channel is needed between the users and the relay stations, a reuse channel scheme from a further adjacent cell is proposed instead, in order to avoid allocating a new frequency which costs in extra bandwidth.
The system level aspects for TDMA network with mobile relay station capability are investigated in [Sre02], [Sre03]. For both papers, a decode and forward relaying strategy for the relay nodes is considered. The relaying model is tested for the downlink scenario simulator in an environment consisting of several square cells. In [Sre03], different relay station selection schemes were proposed and evaluated through a static system level. The results showed that better performance is obtained when the relay node is selected based on minimum path loss than distance.

The coverage enhancement with relaying has been studied in [Hu03]. It has been proposed to use digital fixed relays (decode and forward relay) to extend the high data rate coverage of cellular networks. In particular, they consider the downlink of the TDMA cellular network where 6 fixed relays are placed around each BS. The results showed that the area that a single BS can provide high data rate coverage can significantly be increased by the employment of digital fixed relays without any penalty in capacity. In fact, they have shown that the cell area increases by a factor of 4, i.e a region which will necessitate 4 BSs can be covered with only one BS and 6 FRS.

Mengesha et al. have also investigated the capacity improvement of TDMA cellular networks through analysis [Men01], [Men03]. A simple scenario of two cells is considered; formulas for SINR, packet error rate, and throughput are derived and numerically evaluated for both the standard direct communication case and the use of relaying terminals. The path loss coefficient and the physical location of terminals are the most important parameters and for realistic scenarios, relaying is shown to improve the total throughput of a cell by over 40% [Men03].

2.2.2.2 Relaying in CDMA

In 1997, [ETSI97] proposed Opportunity Driven Multiple Access (ODMA), which is an intelligent protocol that sits upon a radio sub-system that support relaying, as one of strong candidates for UMTS. In ODMA, one node relays its packets through others nodes and a node closer to the BS relays the packet. In this way, ODMA can extend the range of the high data rate services and can be used to provide coverage in dead spots. ODMA breaks difficult radio paths that enable:

- Avoiding shadowing
- Decreasing path loss
- Lower transmit power (and so less interference, more capacity)

However, the ODMA functionality is mainly situated in the network and medium access control layer (MAC). In principle, ODMA is a mechanism for maximizing the potential for effective communication. In practice, ODMA is an intelligent protocol that sits upon a radio sub-system
that supports relaying. The goal of the protocol is to choose the least cost route through the relaying system when the relays are moving and the radio paths are dynamically changing. One node relays its packets through others nodes by using ODMA and a separate unpaired spectrum band (TDD) and the node closer to the BS sends the packet by using the TD/CDMA-FDD or TDD mode.

Another paper that used ODMA as a support for relaying to show the improvement of the system is [Wil01]. In this paper, existing terminals located between the originating terminal and the BS are used as relay stations. They summarize how the ODMA protocol finds the route between the mobile originator and the BS. The aim of the simulation was to achieve results indicating the potential for capacity gain. The model is performed at system level in a macrocell environment. The work is based on a central cell, which is surrounded by two tiers of cells, with each cell containing 24 user’s terminals (UE). The simulation model is implemented with signal-to-interference ratio (SIR) based closed loop and open loop power control algorithms. Uplink and downlink are simulated with the FDD mode between the UE and the BS and the TDD mode between the UEs. They have simulated the model with and without slow fading. The result shows ODMA is able to improve the capacity compared to UMTS in an environment where slow fading is substantial and, as explained above, only to the amount set by SIR at node B. With Slow fading, ODMA improves UMTS by a ratio of 4 in uplink and 3 in downlink. But without slow fading, the capacity of UMTS is better when ODMA is not integrated.

In [Rou01] and [Rou02], the capacity and coverage of the cells with ODMA is investigated. However in their model, all the nodes transmit in the UTRA TDD mode. In [Rou01], the optimal routing is calculated using intelligence in the MS and BS achieves the minimum total path loss for the transmission. Whereas in [Rou02], the best path is based on minimizing interference in order to avoid hot spots in the cell. The study has been done for the vehicular and indoor models. For the former, they calculate the average number of supported calls for 5% outage as a function of the cell size. The results show that until the cell size reaches 30m the conventional TDD system achieves greater capacity. But for greater radius than 30m the UTRA TDD using ODMA increases the capacity. This is due to the greater path loss value, for the signal to achieve the required SIR at the BS.

In [Daw03] a multihop based cellular network design is proposed to enhance the uplink performance. Each cell is divided into two regions, where users that belong in the inner region directly communicate with the base station (one hop) whilst users in the outer region
communicate with the base station via a mobile relay station (two hops). Perfect power based control is assumed and also that there is no shadowing in the whole environment. Each of the two regions is allocated a separate frequency channel to enable practical implementation and reduce interference. Base stations suffer interference from the one hop mobiles and from relay stations whilst relay stations suffer interference from the mobiles that lie in the outer region. In both cases the interference comes from the same cell and from neighboring cells. The maximum range of the cell, $R_{\text{max}}$, is determined by the maximum range in each of the two regions, $R_{\text{B, max}}$ and $R_{\text{R, max}}$ for the inner and outer region, respectively: $R_{\text{max}} = R_{\text{B, max}} + R_{\text{R, max}}$. Pole capacity, defined as the maximum number of users that can be supported per cell as the coverage shrinks to zero, is calculated as $K_{\text{pole}} = \min\{K_{\text{B, pole}}, K_{\text{R, pole}}\}$, where $K_{\text{B, pole}}$ and $K_{\text{R, pole}}$ are the maximum number of users that can be accommodated by the base station and each relay station respectively. It is shown by analysis that the multihop based design outperforms the conventional design in terms of coverage for low to moderate user loads and that at high cell range a gain in user capacity is achieved.

In [Her03] it is shown that the overall performance of the relay system depends on the node density and the relative load. The case of an isolated cell is studied, meaning that intercell interference is neglected. The transmit powers are expressed by two factors that reflect the path-loss dependency and the load-dependency of the transmit powers. For a fixed number of users and low data rates (large processing gains) it is stated that the transmit powers are path loss-determined, whilst for higher rates (greater load) the transmit powers become load-determined. By introducing relay hops (inner tier of mobiles) in the cell, the path loss reduces at the cost of an increased total data rate as relay stations retransmit information that has already been emitted by the base station or target stations. Because relay stations transmit their own data in addition to the relayed information, the link between the base station and the relay stations carry the total data rate of the cell. In order to be able to transport this increased rate the processing gain (spreading factor) of these links needs to be appropriately reduced. It depends on the load of the system whether relaying yields transmit power savings with respect to the direct case. There is a break-even load above which relaying becomes less attractive than the direct case as relaying requires stronger transmit powers than the conventional direct communication. Simulation results support the conclusions derived by analysis.

Yamamoto et al. have also evaluated the performance of CDMA cellular networks with relaying through others mobiles terminals [Yam02], [Tak03], [Fuj02].

In [Yam02], the same frequency band is allocated to the two hop communications. They compare the model without and with two hop through simulation for the macrocell environment. The
routing is based on minimum total transmit power along the paths. The results show that the average transmit power of the MS decrease by 7 dB in the case of the two hop model. However, no study has been done on the corresponding capacity enhancement.

[Tak03] and [Fuj02] evaluated the capacity and coverage of a two hop model using the TDD mode of transmission. The routing proposed here is based on the maximum SINR along the two hops. Even though they showed that the coverage is improved without capacity penalty, they did not succeed to find the capacity improvement with relaying. However, the algorithms, they propose for deciding when a MS should be relayed and which MS should be used as relay station, are not the optimal one. Therefore the interference in the system is not significantly decreased due to the inter-hop interference and hence the maximum capacity gain is not achieved in their model.
CHAPTER 3

3 Analytic Capacity Evaluation of UMTS Cellular Network with Relaying

3.1 Introduction

The aim of this chapter is to provide the analytical expression that describes the probability of a mobile to be in outage in a UMTS cellular network with and without relaying. From the analytic expression of the outage probability, the capacity of both systems can be found and compared. Since the case of the uplink is investigated, this outage probability corresponds to the event that a mobile cannot communicate with the base station and the call has to be dropped. This probability is at first presented for the case where no relay occurs and then the calculations are expanded to include the case where two-hop relaying occurs. In this chapter, the MSs communicate with their relay station in the TDD mode (first hop) and the relay stations communicate with the BS in the FDD mode (second hop). Also the different parameters, such as standard deviation of shadowing, path loss exponent, that affect the outage probability are investigated. An attempt to prove analytically that relaying can indeed improve the performance of the system is made. The calculations of the various parameters and of the outage probability as well as the graphical illustration of all the results are implemented in the MATLAB 6.5 environment.

Section 3.2 presents the derivation of the analytical expressions for the probability of a mobile to be in outage in a UMTS cellular network. Section 3.3 presents the derivation of the analytical expressions for the outage probability in a UMTS cellular network with relaying. Section 3.4 gives the output of the calculations presented in the section 3.3 and discusses the various results. Section 3.5 presents the conclusions of the chapter.
3.2 Analysis of UMTS cellular network without relaying

3.2.1 Outage Probability

In this section the expression for the outage probability in the case where no relay occurs is presented.

The analysis is based on the cellular model that is illustrated in Figure 3.1. The cellular layout consists of 19 cells of radius R. These cells are distributed in two tiers of surrounding cells with centrally located base stations. In the first tier belong the cells with numbers from 1 to 6, lying in a distance $D_0 = \sqrt{3} R$ from the base station of the central cell. In the second tier belong the cells 7 to 18; the odd-numbered cells of the second tier are at a distance $D_{21} = 3R$ while the even-numbered cells lie at a distance $D_{22} = 2D_0 = 2\sqrt{3} R$.

In each cell there are $N$ users assumed to be all active and uniformly distributed. The path loss between the mobile user and the cell site is a product of two parameters that represent the losses due to the distance between them and due to shadowing:

$$\text{Path Loss} = 10^{\mu r^\mu}$$

$r$ is the distance from subscriber to cell site (BS) with path loss exponent $\mu$ and the shadowing $\xi$. 
Chapter 3. Analytical Evaluation of the CDMA Cellular Network Capacity with Relaying

represented by a Gaussian random variable with zero mean on the logarithmic scale and a standard deviation \( \sigma \). Fast fading that arises due to the constructive and destructive interference between multiple waves that reach the base station is assumed not to affect the average power level.

In the case that no relay occurs, all mobile stations intend to directly communicate with the base station and the mode assumed to be used by the mobile stations to reach the base station is FDD. All the mobiles use the 5MHz bandwidth of the uplink and will interfere with the signal from the desired user at the base station.

Let a mobile be in a random position in a cell, called home cell, at a distance \( r_m \) from its base station, as illustrated in Figure 3.2. If \( D \) is the distance of the home cell (BS1) from the central base station (BS0), taking the values \( D_0, D_2, 2D_0 \), then the distance of the mobile from the central cell can be expressed as:

\[
r_o = \sqrt{D^2 + r_m^2 - 2r_m D \cos \theta}.
\]

![Figure 3.2: Capacity calculation geometrics](image)

Perfect power based power control is assumed. Each user is controlled by the BS with whom it experiences the maximum pilot signal power, i.e. from the BS that experiences the minimum path loss. The signals from all the users controlled by the same base station will arrive at this base station with the same power \( H_{ms} \).

Apart from the desired user’s signal, all the other signals that arrive at the base station of the home cell from the remaining (N-1) users in the same cell are ‘seen’ as interference at the base station. This interference is called intracell interference, is denoted as \( I_{intra} \) and is equal to:

\[
I_{intra} = (N-1)H_{ms}
\]

The users that belong to the cells in the two tiers are controlled by other base stations but also create interference to the base station of the central cell, called intercell interference. If M is the desired user, then because it is power controlled by BS1, the power that BS1 receives from M is
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Therefore $M$ transmits $H_m = \frac{r_m^{\mu}}{10^{\xi_m/10}}$ and $BS_o$ receives as interference from the desired user power:

$$I(r_m, r_o) = H_m = \frac{r_m^{\mu}}{10^{\xi_m/10}} \cdot 10^{-\xi_o/10}$$

The interference received at the $BS_o$ over the transmit power from the desired user can be rewritten as a ratio in the following form:

$$\frac{I(r_o, r_m)}{H_m} = \frac{10^{\xi_o/10} r_o^{-\mu}}{10^{\xi_m/10} r_m^{-\mu}} \Rightarrow \frac{I(r_o, r_m)}{H_m} = \left( \frac{r_m}{r_o} \right)^{\mu} \cdot 10^{(\xi_o - \xi_m)/10} \quad (3.1)$$

where $\xi_m$ and $\xi_o$ represent the shadowing component in the paths $r_m$ and $r_o$ respectively.

Since $\xi_m$ and $\xi_o$ follow Gaussian distributions with zero mean and variance $\sigma^2$ their difference can be expressed with a new variable $\chi$ that also follows a Gaussian distribution with zero mean and variance $2\sigma^2$, see Appendix A.

The density of the users is:

$$\rho = \frac{N}{cell \ area} = \frac{2N}{3\sqrt{3}R^2}$$

To calculate the total interference that is caused at the central base station by all the users that belong to a cell at a distance $D$ from the central cell, the ratio in (3.1) must be integrated over the whole area of the home cell. The integration is applied for $r_m$ varying from 0 to $R$, assuming that the user is moving in a circular cell of radius $R$. Hence the ratio of the intercell interference caused from the home cell by the power $H_m$ is given by the integral:

$$\frac{I}{H_m} = \int \int \left( \frac{r_m}{r_o} \right)^{\mu} \cdot 10^{\chi/10} \delta(\chi, r_o/r_m) \cdot \rho dA , dA = r_m dr_m d\theta$$

where $dA$ represents the integration in the whole cell area and $\delta$ denotes that the mobile is controlled by the cell site for which: $r_m^{\mu} 10^{-\xi_m/10} = \min (r_k^{\mu} 10^{-\xi_k/10})$, $k \neq 0$ where $k$ represents the user's index and is expressed by:
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\[ \phi = \begin{cases} 
1, & \left( \frac{r_m}{r_o} \right)^\mu \cdot 10^{x/10} \leq 1 \Rightarrow x \leq 10\mu \log \left( \frac{r_o}{r_m} \right) \Rightarrow \frac{I}{H_{ms}} \leq 1 \\
0, & \text{otherwise} 
\end{cases} \]

The ratio (3.1) is less than one because otherwise \( I > H_{ms} \). This would mean that the receiving signal at the central cell would be greater than the one received at the controlling base station and hence the user should be controlled by \( BS_o \).

If the mobile is assumed to be power controlled by the nearest cell site, then the results for \( I \) only slightly increase and therefore \( I/H_{ms} \) becomes upper bounded [Has01]:

\[ \frac{I}{H_{ms}} \leq \int_0^{2\pi} \int_0^R \left( \frac{r_m}{r_o} \right)^\mu \cdot 10^{x/10} \phi(\chi, r_o / r_m) \cdot \rho r_m d\theta d\phi \]

(3.2)

It is obvious that the ratio \( I/H_{ms} \) is a random variable. In [Gil91] it is stated that this random variable can be well modelled as a Gaussian random variable. In the following section the mean value and variance of this random variable will be calculated. Based on (3.2) these values are respectively:

\[ \mathbb{E}\left[ \frac{I}{H_{ms}} \right] \leq \int_0^{2\pi} \int_0^R \left( \frac{r_m}{r_o} \right)^\mu \mathbb{E}\left[ 10^{x/10} \phi(\chi, r_o / r_m) \right] \cdot \rho r_m d\theta d\phi \]

\[ \text{var}\left[ \frac{I}{H_{ms}} \right] \leq \int_0^{2\pi} \int_0^R \text{var}\left[ \left( \frac{r_m}{r_o} \right)^\mu \cdot 10^{x/10} \phi(\chi, r_o / r_m) \right] \cdot \rho r_m d\theta d\phi \]

From this point the inequality will be substituted with equality for simplicity. For the calculation of the mean value the term \( \mathbb{E}[10^{x/10} \phi(\chi r_o/r_m)] \) needs to be evaluated.

\[ \mathbb{E}[10^{x/10} \phi(\chi, r_o / r_m)] = \left\{ \begin{array}{ll} 
\mathbb{E}[10^{x/10}], & x \leq 10\mu \log \left( \frac{r_o}{r_m} \right) \\
0, & \text{otherwise} 
\end{array} \right. \]

(3.3)

\( \chi \) follows \( \mathcal{N}(0, 2 \sigma^2) \) and hence its pdf is:
Chapter 3. Analytical Evaluation of the CDMA Cellular Network Capacity with Relaying

\[ \text{pdf}(\chi) = \frac{1}{\sqrt{2\pi}\sqrt{2\sigma^2}} e^{-\frac{\chi^2}{2\sigma^2}} = \frac{1}{\sqrt{4\pi\sigma^2}} e^{-\frac{\chi^2}{4\sigma^2}} \]  

(3.4)

Substituting (3.4) into (3.3), function \( f \) can be written as:

\[
f\left(\frac{r_m}{r_o}\right) = \int_{-\infty}^{0} e^{\chi} d\chi = \int_{-\infty}^{0} e^{2\chi/10} \frac{1}{\sqrt{2\pi}\sqrt{2\sigma^2}} e^{-\frac{\chi^2}{4\sigma^2}} d\chi = e^{(\sigma/10)^2} \int_{-\infty}^{0} e^{\chi} e^{-\chi^2/20} d\chi = e^{(\sigma/10)^2} \int_{-\infty}^{0} e^{-\chi^2/20} d\chi \]

By modifying the integral of (3.5) and combining it with the Q-function in the following way:

\[
Q(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-y^2/2} dy
\]

For \( y = \frac{\chi}{\sqrt{2\sigma^2}} = \sqrt{2\sigma^2} (\ln 10)/10 \Rightarrow dy = \frac{d\chi}{\sqrt{2\sigma^2}}, \)

\( \chi = -\infty \rightarrow y = -\infty \)

\( \chi = 10\mu \log(r_o/r_m) \rightarrow y = \frac{10\mu \log(r_o/r_m)}{\sqrt{2\sigma^2}} - \sqrt{2\sigma^2} (ln 10)/10 \)

The function \( f \) can be rewritten as:

\[
f\left(\frac{r_m}{r_o}\right) = e^{(\sigma/10)^2} \left\{ 1 - Q\left[ \frac{10\mu \log(r_o/r_m)}{\sqrt{2\sigma^2}} - \sqrt{2\sigma^2} (ln 10)/10 \right] \right\} \]

(3.6)

Finally \( E\left[\frac{1}{H_{ms}}\right] \) is given by:

\[
E\left[\frac{1}{H_{ms}}\right] = e^{(\sigma/10)^2} \int_{0}^{2\pi} \int_{0}^{R} \frac{r_m}{r_o} d\theta \left\{ 1 - Q\left[ \frac{10\mu \log(r_o/r_m)}{\sqrt{2\sigma^2}} - \sqrt{2\sigma^2} (ln 10)/10 \right] \right\} \rho_m dr_m d\theta
\]

(3.7)
The variance of $I/H_{\text{ms}}$ is calculated as follows:

$$\text{var}\left[\frac{I}{H_{\text{ms}}}\right] = \int_0^{2\pi} \int_0^R \frac{r_m}{r_0}^{2\mu} \text{var}\left[10^{x/10} \Phi(x, r_0 / r_m)\right] \cdot \rho r_m dr_m d\theta$$

$$\text{var}[10^{x/10} \Phi(x, r_0 / r_m)] = E[10^{x/10} \Phi^2(x, r_0 / r_m)] - E^2[10^{x/10} \Phi(x, r_0 / r_m)] =$$

$$= E[10^{x/15} \Phi^2(x, r_0 / r_m)] - f\left(\frac{r_m}{r_0}\right)$$

$$E[10^{x/15} \Phi^2(x, r_0 / r_m)] = E[e^{x(\ln 10)/5}] \Phi^2(x, r_0 / r_m) =$$

$$g\left(\frac{r_m}{r_0}\right) = \begin{cases} E[e^{x(\ln 10)/5}], & x \leq 10 \mu \log\left(\frac{r_0}{r_m}\right) \\ 0, & \text{otherwise} \end{cases}$$

$$g\left(\frac{r_m}{r_0}\right) = e^{(\sigma(\ln 10)/5)^2} \left[1 - Q\left(\frac{10 \mu \log(r_0 / r_m)}{\sqrt{2\sigma^2}} - \sqrt{2\sigma^2 (\ln 10) / 5}\right)\right]$$

(3.8)

$$\text{var}\left[\frac{I}{H_{\text{ms}}}\right] = \int_0^{2\pi} \int_0^R \frac{r_m}{r_0}^{2\mu} g\left(\frac{r_m}{r_0}\right) - f^2\left(\frac{r_m}{r_0}\right) \cdot \rho r_m dr_m d\theta$$

(3.9)

where $f\left(\frac{r_m}{r_0}\right)$ and $g\left(\frac{r_m}{r_0}\right)$ are given by (3.6) and (3.8) respectively.

The SNR is represented as:

$$\frac{S}{N_0} = \frac{H_{\text{ms}}}{N_0} = \frac{R E_b}{W N_0} = \frac{E_b}{N_0} \cdot \frac{1}{W} \Rightarrow$$

(3.10)

where $S=H_{\text{ms}}$ is the received power at the base station of the home cell, $N_0$ is the total noise power- including the total interference ($I_{\text{tot}}$) and the background noise ($\eta$), $W$ is the bandwidth and $R$ is the bit rate.

$$\frac{E_b}{N_0} = \frac{W}{R} \cdot H_{\text{ms}}$$

$$\frac{E_{\eta}}{N_0} = \frac{W}{R} \cdot \frac{H_{\text{ms}}}{I_{\text{tot}} + \eta}$$

(3.11)

Where $\eta$ represents the background noise.
The total interference is divided into intracell and intercell interference:

\[ I_{\text{tot}} = I_{\text{intra}} + I_{\text{inter}} \]  
(3.12)

\[ I_{\text{intra}} = \sum_{i=1}^{N-1} H_{ms} = (N-1)H_{ms} \]  
(3.13)

Intercell interference is a summation of 18 random variables that are grouped in three sets. Each of these sets includes 6 random variables with the same mean and variance. The first set represents the interference coming from the first tier following \( \mathcal{N}(m_{1\text{tier}}, \sigma^2_{1\text{tier}}) \), the second the interference coming from the cells of the second tier that have distance 2D_o from the central cell following \( \mathcal{N}(m_{2\text{tier}/2D_o}, \sigma^2_{2\text{tier}/2D_o}) \) and the third represents the interference coming from the cells of the second tier that have distance 3R from the central cell following \( \mathcal{N}(m_{2\text{tier}/3R}, \sigma^2_{2\text{tier}/3R}) \).

The mean and standard deviation of the total intercell interference to \( H_{ms} \) ratio is given by:

\[ m = 6 \cdot m_{1\text{tier}} + 6 \cdot m_{2\text{tier}/2D_o} + 6 \cdot m_{2\text{tier}/3R} \]

\[ \sigma = \sqrt{6 \cdot \sigma^2_{1\text{tier}} + 6 \cdot \sigma^2_{2\text{tier}/2D_o} + 6 \cdot \sigma^2_{2\text{tier}/3R}} \]

Hence the ratio \( \frac{I_{\text{inter}}}{H_{ms}} \) follows \( \mathcal{N}(m, \sigma^2) \). The values \( m_{1\text{tier}}, m_{2\text{tier}/2D_o}, m_{2\text{tier}/3R} \) and \( \sigma^2_{1\text{tier}}, \sigma^2_{2\text{tier}/2D_o}, \sigma^2_{2\text{tier}/3R} \) are calculated from (3.7) and (3.9) respectively for the corresponding distances of D.

Substituting (3.12) and (3.13) in (3.11):

\[ \frac{E_b}{N_o} = \frac{(W/R) \cdot H_{ms}}{(N-1) \cdot H_{ms} + I_{\text{inter}}^\text{tot} + \eta} = \frac{W/R}{(N-1) + \frac{I_{\text{inter}}^\text{tot}}{H_{ms}} + \frac{\eta}{H_{ms}}} \]
A mobile will be in outage if the ratio $E_b/N_o$ of the receiving signal at the base station cannot reach the required value $(E_b/N_o)_{req}$:

$$P_{\text{outage}} = \Pr \left( \frac{E_b}{N_o} < \frac{E_b}{N_o}_{\text{req}} \right)$$

$$\frac{E_b}{N_o} < \frac{E_b}{N_o}_{\text{req}} \Rightarrow \frac{W}{R} < \frac{N_{\text{req}} + \frac{\eta}{H_{ms}}}{E_b/N_o}_{\text{req}} \Rightarrow (N - 1) + \frac{I_{\text{int,er}}}{H_{ms}} > \delta, \quad \delta = \frac{W}{R} - \frac{\eta}{(E_b/N_o)_{\text{req}}}$$

$$P_{\text{outage}} = \Pr \left( \frac{E_b}{N_o} < \frac{E_b}{N_o}_{\text{req}} \right) = \Pr \left( (N - 1) + \frac{I_{\text{int,er}}}{H_{ms}} > \delta \right) = \Pr \left( \frac{I_{\text{int,er}}}{H_{ms}} > \delta - (N - 1) \right)$$

When background noise power $\eta$ is considered negligible: $\delta = \frac{W}{R} - \frac{\eta}{(E_b/N_o)_{\text{req}}}$. Therefore the outage probability can be calculated as:

$$P_{\text{outage}} = Q \left( \frac{\delta - (N - 1) - m}{\sigma} \right) \quad \text{(3.14)}$$

### 3.2.2 Results

In the following section, the result that has been derived from the analysis discussed is presented. The cellular environment considered is described in section 3.2.1 and the radius of the cell is 2km.
Table 3.1 shows the system parameters that are used unless otherwise stated.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>W</strong></td>
<td>3.84 MHz</td>
</tr>
<tr>
<td><strong>R</strong></td>
<td>12.2 kbps</td>
</tr>
<tr>
<td><strong>η</strong></td>
<td>-103 dBm</td>
</tr>
<tr>
<td><strong>Eb/N₀</strong></td>
<td>5 dB</td>
</tr>
<tr>
<td><strong>μ</strong></td>
<td>3.76</td>
</tr>
<tr>
<td><strong>σ</strong></td>
<td>7 dB</td>
</tr>
</tbody>
</table>

**Table 3.1: System Parameters**

W is the spread bandwidth, R is the bit rate, η is the noise power, Eb/N₀ is the energy per bit to noise power spectral density ratio, μ is the path loss exponent and σ is the standard deviation of shadowing.

Figure 3.3 shows the probability of a mobile to be in outage when no relay occurs, but all mobiles intend to directly communicate with the base station of their home cell. The outage probability is plotted based on (3.14) for the parameters stated above. The voice activity factor is assumed to be one; hence all the mobile stations are active. This line will be shown in most of the figures that follow for comparison reasons.

![Figure 3.3: Outage Probability when no relay occurs.](image-url)
For outage probability 1% the figure 3.3 shows that approximately 50 users can be accommodated in the cell when no relay occurs.

In order to verify if the plot is correct, the result has been compared with the one found in the reference [Gil91]. And indeed, the same result is obtained when the same parameters values are used.

### 3.3 Analysis of UMTS cellular network with relaying

In the following section, the mathematical model for the calculation of the outage probability when relay occurs is described. Two-hop relay is mathematically examined. The cellular model on which the analysis is based is the same with the one presented in 3.2 (Figure 3.1).

For the two-hop relay scenario the relay stations lie on a circle of radius $rR$ inside the cell. The cell is thus divided into two regions, an inner circle of radius $rR$ and a ring of width $(1-r)R$ (Figure 3.4).

![Figure 3.4: Inner circle-ring (a), 4 relay stations/cell (b), 6 relay stations/cell (c), 8 relay stations/cell (d), 12 relay stations/cell (e)](image-url)

The case of four, six, eight and twelve relay stations is examined. When the relay stations are fixed, it is assumed that they are located in constellations, at positions where shadowing can be neglected (LOS with the home BS). This assumption is based on the fact that the fixed relay stations can indeed be placed at specific positions so that LOS communication with the base station is possible.

Also the case of moving relay stations, where shadowing is taken into account (NLOS with the
home BS), is examined.

The users that do not relay are randomly selected from the area of the whole cell. For the relaying users two different cases are examined. The first is when they are randomly selected from the whole cell and the second when they are selected only from the ring. For the second case the outage probability is also evaluated when more than one mobile relays to a relaying station.

### 3.3.1 Frequency Bandwidth

For third generation wireless systems a number of new multiple access schemes have been proposed. The air interface technologies selected for 3G systems are WCDMA schemes, UWC-136 TDMA-based scheme and TD-CDMA. For the scenarios tested, the WCDMA air interface is used. WCDMA has a bandwidth of 5MHz or more. The nominal bandwidth for all third generation proposals is 5MHz [Oja98].

In the two-hop relay case the mobiles that relay, communicate with the relay stations in TDD mode (first hop), while the non relayed mobiles and the relay stations use FDD to communicate with the base station (second hop). The use of two different duplex division schemes between the two hops is necessary as it would be impossible to use FDD for both hops. In FDD there are two different frequency band and hence two different carrier frequencies, one for uplink ($f_1$) and one for downlink ($f_2$). If FDD was used in both hops then the relay stations would receive the signal from the relayed mobile at $f_1$ (uplink for the link: relaying MS-RS) and the signal from the base station at $f_2$ (downlink for the link: BS-RS). But the relay station can only receive at $f_2$, which is the carrier frequency for the downlink. Hence TDD is used for the first hop and FDD for the second hop, as illustrated in Figure 3.5.

![Figure 3.5: Modes of transmission for each hop](image)

Because of the way the modes of transmission are used, the relayed mobiles will interfere at the relay stations and all the non relayed mobiles and the relay stations will interfere at the base
station. The sources of interference in the two-hop relay case are shown in Figure 3.6.

![Figure 3.6: Two-hop relay-sources of interference](image-url)

Actually in the TDD mode, only the relayed mobiles that use the same time slot interfere with each other but in the analysis that follows, the calculation of interference at the base station is done for the worst case, where all the relayed mobiles interfere at the relay stations.

The non relayed mobiles, similarly to the case where no relay occurs, will use the total 5MHz bandwidth of the FDD uplink. The TDD bandwidth of 5MHz, is divided into 15 timeslots and is designed to accommodate the relayed mobiles. In each timeslot, 16 different users can transmit their signal, as it is assumed that 16 codes are used for the spreading procedure for the voices services. When the relaying users in one cell are less or equal to 16 then only one time slot from the TDD bandwidth is going to be used. This is the case when only one mobile is relaying per relay station for all sets of relay stations (4, 6, 8, 12 RS). Figure 3.7 shows how the 15 timeslots and the 16 codes are distributed in the TDD bandwidth.
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When more than 16 users are relaying, the relayed mobiles are accommodated by two or more timeslots depending on how many spreading codes need to be used. This is the case when more than one mobile are relaying to a relay station and the dependent on the number of relayed mobiles to a single relay station.

For example if 6 users are relaying in the cell, the total bandwidth used by all the users in the cell will be \((5+5 \cdot \frac{1}{15})\) MHz because the 6 relaying users can be accommodated by one TDD timeslot which occupies \(\frac{1}{15}\) of the 5MHz TDD bandwidth and the rest of the non relaying users will use the 5MHz FDD uplink bandwidth. If 6 relay stations are used with 2 mobiles per relay station, then there will be 2\( \cdot 6=12\) coding sequences needed, that can be accommodated in one timeslot and the total bandwidth used will again be: \((5+5 \cdot \frac{1}{15})\) MHz. If 8 relay stations are used with 3 mobiles per relay station, then 3\( \cdot 8=24\) coding sequences will be needed. Therefore not all 24 relayed mobiles can use the same time slot. Instead, 16 relayed mobiles will use the same time slot and the rest, 24-16=8, will use another one. The total bandwidth used in this case is: \((5+5 \cdot \frac{2}{15})\) MHz.

3.3.2 Fixed Relay Station

The users are uniformly distributed inside the whole cell. This means that inside the inner circle there will be \(N_1=\tau^2N\) users and inside the ring \(N_2=N-N_1=(1-\tau^2)N\) users. If \(j\) is the number of relay stations

![Figure 3.7: TDD timeslot and code distribution](image)

When more than 16 users are relaying, the relayed mobiles are accommodated by two or more timeslots depending on how many spreading codes need to be used. This is the case when more than one mobile are relaying to a relay station and the dependent on the number of relayed mobiles to a single relay station.

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stations inside the cell, then when the relayed users comes from the whole cell the probability that a user is relaying is:

\[ P_{\text{relay}} = \frac{j}{N} \quad (3.15) \]

and obviously the probability that a user is not relaying is:

\[ P_{\text{no relay}} = 1 - \frac{j}{N} = \frac{N - j}{N} \quad (3.16) \]

The equations (3.15) and (3.16) are valid for one user per relay station.

When the relaying user comes only from the ring then the \( P_{\text{relay}} \) can be calculated as follows:

\[ p(\text{relay}|\text{user in the ring}) = \frac{p(\text{user in the ring}, \text{relay})}{p(\text{user in the ring})} \Rightarrow p(\text{user in the ring}, \text{relay}) = p(\text{user in the ring}) \cdot p(\text{relay}|\text{user in the ring}) \quad (3.17) \]

\[ p(\text{user in the ring}|\text{relay}) = 1 \Rightarrow \frac{p(\text{user in the ring}, \text{relay})}{p(\text{relay})} = 1 \Rightarrow \]

\[ p_{\text{relay}} = p(\text{relay}) = p(\text{user in the ring}, \text{relay}) \quad (3.18) \]

Equation (3.17), because of (3.18) transforms to:

\[ p_{\text{relay}} = p(\text{relay}|\text{user in the ring}) \cdot p(\text{user in the ring}) \quad (3.19) \]

\[ p(\text{relay}|\text{user in the ring}) = \frac{j}{N} \]

\[ p(\text{user in the ring}) = \frac{N_2}{N} \]

Substituting the above two equations into (3.19), \( P_{\text{relay}} \) and \( P_{\text{no relay}} \) — for relaying users only from the ring — become:
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\[ P_{\text{relay\_ring}} = \frac{j}{N_2} \cdot \frac{N}{N} = \frac{j}{N} \]  
(3.20)

\[ P_{\text{norelay\_ring}} = 1 - \frac{j}{N} = \frac{N - j}{N} \]  
(3.21)

If \( u \) users instead of one are communicating with the relay station then in the equations (3.15), (3.16) and (3.20), (3.21) the factor \( j \) is substituted by \( u \cdot j \).

For the two-hop relay the total interference received at the BS is also a summation of two factors, the intracell and intercell interference. The intracell interference is caused by the mobiles that do not relay and by the relay stations that are in the home cell. The intercell interference is caused by the non relayed mobiles (\( I_{\text{intray}}^{\text{tot}} \)) and the relay stations that belong in the cells of the two tiers (\( I_{\text{relay}}^{\text{tot}} \)) transmitting in FDD mode. The intercell interference caused by relay station \( n \) in the cell \( k \) is symbolized as \( I_{\text{RS\_n\_k}}^{\text{cell\_k}} \):

\[ I_{\text{tot}} = I_{\text{intray}}^{\text{tot}} + I_{\text{inter}}^{\text{tot}} \]  
(3.12)

\[ I_{\text{inter}}^{\text{tot}} = I_{\text{norelay}}^{\text{tot}} + I_{\text{relay}}^{\text{tot}} \]

\[ I_{\text{relay}}^{\text{tot}} = I_{\text{cell\_1}}^{\text{tot}} + I_{\text{cell\_2}}^{\text{tot}} + \ldots + I_{\text{cell\_18}}^{\text{tot}} \]

\[ I_{\text{cell\_k}}^{\text{tot}} = I_{\text{RS\_1\_k}}^{\text{RS\_1\_k}} + I_{\text{RS\_2\_k}}^{\text{RS\_2\_k}} + \ldots + I_{\text{RS\_j\_k}}^{\text{RS\_j\_k}}, \]  
\( k=1,\ldots,18 \) and \( j=4, 6, 8, 12 \)

Let \( H_{\text{RS}} \) and \( H_{\text{RS}} \) be the received power from the non relayed mobiles and the relay stations respectively. For fixed relay stations, \( I_{\text{RS\_n\_0}}^{\text{cell\_k}} \) and hence \( I_{\text{relay}}^{\text{tot}} \) are calculated, similarly to (3.1), by:

\[ I_{\text{RS\_n\_k}}^{\text{RS\_n\_k}} = H_{\text{RS}} \cdot 10^{\frac{x_{\text{kn}}}{10}} \left( \frac{\tau R}{x_{\text{kn}}} \right)^{\mu} \]  
\( n=1,\ldots,j \)

\[ I_{\text{relay}}^{\text{tot}} = H_{\text{RS}} \sum_{k=1}^{18} \sum_{n=1}^{j} 10^{\frac{x_{\text{kn}}}{10}} \left( \frac{\tau R}{x_{\text{kn}}} \right)^{\mu} = \beta \cdot H_{\text{RS}}, \]  
(3.22)

Where \( x_{\text{kn}} \) represents the distance between the relay station \( n \) in the cell \( k \) with the BS.

In Figure 3.8 the case of six fixed relay stations per cell is illustrated and the calculation of \( x_{\text{kn}} \) is
shown analytically.

Figure 3.8: 6RS/cell geometrical layout

\[ x_{11}^2 = x_{10}^2 = D_o^2 + (\tau R)^2 - 2D_o(\tau R) \cos 30^\circ = D_o^2 + (\tau R)^2 - \sqrt{3} D_o(\tau R) \quad \text{with } 1 \leq k \leq 6 \]

\[ x_{12}^2 = x_{13}^2 = D_o^2 + (\tau R)^2 - 2D_o(\tau R) \cos 90^\circ = D_o^2 + (\tau R)^2 \quad \text{with } 1 \leq k \leq 6 \]

\[ x_{14}^2 = x_{14}^2 = D_o^2 + (\tau R)^2 - 2D_o(\tau R) \cos 150^\circ = D_o^2 + (\tau R)^2 + \sqrt{3} D_o(\tau R) \quad \text{with } 1 \leq k \leq 6 \]

\[ x_7^2 = x_{12}^2 = (2D_o)^2 + (\tau R)^2 - 2D_o(\tau R) \cos 30^\circ = 4D_o^2 + (\tau R)^2 - 2\sqrt{3} D_o(\tau R) \quad \text{with } k = \{8, 10, 12, 14, 16, 18\} \]

\[ x_{18}^2 = x_{11}^2 = (2D_o)^2 + (\tau R)^2 - 2D_o(\tau R) \cos 90^\circ = 4D_o^2 + (\tau R)^2 \quad \text{with } k = \{8, 10, 12, 14, 16, 18\} \]

\[ x_{18}^2 = x_{18}^2 = (2D_o)^2 + (\tau R)^2 - 2D_o(\tau R) \cos 150^\circ = 4D_o^2 + (\tau R)^2 + 2\sqrt{3} D_o(\tau R) \quad \text{with } k = \{8, 10, 12, 14, 16, 18\} \]

\[ x_{13}^2 = x_{17}^2 = (3R)^2 + (\tau R)^2 - 3R(\tau R) \cos 60^\circ = 9R^2 + (\tau R)^2 - 3R(\tau R) \quad \text{with } k = \{7, 9, 11, 13, 15, 17\} \]

\[ x_{14}^2 = x_{16}^2 = (3R)^2 + (\tau R)^2 - 3R(\tau R) \cos 120^\circ = 9R^2 + (\tau R)^2 + 3R(\tau R) \quad \text{with } k = \{7, 9, 11, 13, 15, 17\} \]

\[ x_{15} = 3R + \tau R = (3 + \tau)R \quad \text{with } k = \{7, 9, 11, 13, 15, 17\} \]

\[ x_{18} = 3R - \tau R = (3 - \tau)R \quad \text{with } k = \{7, 9, 11, 13, 15, 17\} \]
Chapter 3. Analytical Evaluation of the CDMA Cellular Network Capacity with Relaying

The Eb/No and the total interference are calculated by:

\[
\frac{E_b}{N_0} = \frac{W}{R} \cdot \frac{H_{ms}}{I_{tot} + \eta} \tag{3.11}
\]

\[
I_{tot} = I_{tot}^{intra} + I_{tot}^{inter} \tag{3.12}
\]

When the desired user is not relaying the outage probability represents the case that the mobile cannot reach the base station. The intra cell interference is:

\[
I_{tot}^{intra} = \sum_{i=1}^{N-j-1} H_{ms} + jH_{RS} = (N-j-1)H_{ms} + jH_{RS} \tag{3.23}
\]

If u users are relaying to a relay station then (3.23) becomes:

\[
I_{tot}^{intra} = \sum_{i=1}^{N-uj-1} H_{ms} + jH_{RS} = (N-uj-1)H_{ms} + jH_{RS} \tag{3.24}
\]

The total intercell interference can be calculated by:

\[
I_{tot}^{inter} = I_{tot}^{norelay} + \beta H_{RS} \tag{3.25}
\]

The total interference received at the central BSo from the users in the different tiers (first and second tiers) with different distances (Do, 2Do, 3R) are calculated by:

\[
I_{tot}^{norelay} = I_{1}^{tier} + I_{2}^{tier} + I_{3}^{tier} + I_{4}^{tier} + I_{5}^{tier} + I_{6}^{tier} + I_{7}^{tier} + 2Do + I_{10}^{tier} + I_{12}^{tier} + I_{14}^{tier} + I_{16}^{tier} + I_{18}^{tier} + I_{2}^{tier} + 2R + I_{11}^{tier} + I_{13}^{tier} + I_{15}^{tier} + I_{17}^{tier} \tag{3.26}
\]

Where \( I_{i}^{tier} \) represents the interference received at the BSo from the users in the cell i in the first tier.

The intercell interference from non-relayed mobiles to \( H_{ms} \) ratio, coming from the cells that belong to 1tier, 2tier/2Do and 2tier/3R are random variable that are normally distributed and each set has the same mean and variance: \( m_{1tier}, m_{2tier/2Do}, m_{2tier/3R} \) and \( \sigma^{2}_{1tier}, \sigma^{2}_{2tier/2Do}, \sigma^{2}_{2tier/3R} \) respectively. The mean and variance of the total intercell interference from non-relayed
Chapter 3. Analytical Evaluation of the CDMA Cellular Network Capacity with Relaying

Mobiles to \( H_m \) ratio \( \frac{r_{\text{tot}}}{H_m} \) are given by:

\[
m' = 6 \cdot m_{\text{tier}} + 6 \cdot m_{2\text{tier}/2D_0} + 6 \cdot m_{2\text{tier}/3R}
\]

\[
\sigma' = \sqrt{6 \cdot \sigma_{\text{tier}}^2 + 6 \cdot \sigma_{2\text{tier}/2D_0}^2 + 6 \cdot \sigma_{2\text{tier}/3R}^2}
\]

This means that the ratio \( \frac{r_{\text{tot}}}{H_m} \) follows \( \mathcal{N}(m', \sigma'^2) \).

(a) Relaying users selected from the whole cell

If the relayed users can be anywhere in the cell then the values of \( m_{\text{tier}}, m_{2\text{tier}/2D_0}, m_{2\text{tier}/3R} \) and \( \sigma_{\text{tier}}^2, \sigma_{2\text{tier}/2D_0}^2, \sigma_{2\text{tier}/3R}^2 \) are calculated by (3.7) and (3.9) respectively for the corresponding distances of \( D \), but the density of the users is now given by: \( \rho = \frac{2(N-j)}{3\sqrt{3R^2}} \).

If \( u \) users are relaying to a relay station then \( j \) is substituted by \( u-j \).

(b) Relaying users selected from the ring

If the relayed users are selected only from the ring, then the calculation of \( m_{\text{tier}}, m_{2\text{tier}/2D_0}, m_{2\text{tier}/3R} \) and \( \sigma_{\text{tier}}^2, \sigma_{2\text{tier}/2D_0}^2, \sigma_{2\text{tier}/3R}^2 \) slightly changes and \( m_0, \sigma_0^2 \) are the new mean and the variance of \( \frac{r_{\text{tot}}}{H_m} \). The hexagonal cell is approximated by a circle of the same radius \( R \). For any cell, in any tier at a distance \( D \) from BS_0:

\[
m_0 = \int_0^{2\pi} \int_0^R \left( \frac{r_m}{r_0} \right)^{2\mu} \frac{N}{\pi R^2} r_m dr_m d\theta - \int_0^{2\pi} \int_0^R \left( \frac{r_m}{r_0} \right)^{2\mu} \frac{j}{(1-\tau^2)\pi R^2} r_m dr_m d\theta
\]

\[
\sigma_0^2 = \int_0^{2\pi} \int_0^R \left( \frac{r_m}{r_0} \right)^{2\mu} \left[ g \left( \frac{r_m}{r_0} \right) - f^2 \left( \frac{r_m}{r_0} \right) \right] \frac{N}{\pi R^2} r_m dr_m d\theta - \int_0^{2\pi} \int_0^R \left( \frac{r_m}{r_0} \right)^{2\mu} \left[ g \left( \frac{r_m}{r_0} \right) - f^2 \left( \frac{r_m}{r_0} \right) \right] \frac{j}{(1-\tau^2)\pi R^2} r_m dr_m d\theta
\]

Again if \( u \) users are relaying to a relay station then \( j \) is substituted by \( u-j \).
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Substituting (3.23) and (3.24) in (3.11):

\[
\frac{E_b}{N_0} \cdot \frac{\left(\frac{W}{R}\right) \cdot H_{ms}}{\left[(N - j - 1) \cdot H_{ms} + jH_{RS} + (I_{\text{tot}}^{\text{relay}} + \beta \cdot H_{RS}) + \eta\right] + \left(\frac{W}{R}\right)}
\]

Where \( \beta = \sum_{k=ln}^{j} 10^{2ln/10} \left( \frac{\tau R}{\xi ln} \right)^{\mu} \), defined in (3.22).

A mobile that is not relaying suffer from the interference received from the RS and others non-relayed mobile at its serving BS. Therefore the probability a mobile that is not relaying to be in outage is expressed as:

\[
P_{\text{outage, no relay}} = \Pr\left( \frac{E_b}{N_0} \left(\frac{E_b}{N_0}\right)_{\text{req}} \right)
\]

\[
\frac{E_b}{N_0} < \left(\frac{E_b}{N_0}\right)_{\text{req}} \Rightarrow \frac{W}{R} \left[\left(\frac{N - j - 1} + j \cdot H_{RS} + \frac{I_{\text{tot}}^{\text{relay}}}{H_{ms}} + \beta \cdot H_{RS} + \frac{\eta}{H_{ms}}\right) + \frac{\eta}{H_{ms}}\right] < \left(\frac{E_b}{N_0}\right)_{\text{req}} \Rightarrow \lambda,
\]

\[
\lambda = \frac{W}{R} \left(\frac{E_b}{N_0}\right)_{\text{req}} \left[\left(\frac{N - j - 1} + j \beta \cdot H_{RS} + \frac{\eta}{H_{ms}}\right) + \frac{\eta}{H_{ms}}\right]
\]

\[
P_{\text{outage, no relay}} = \Pr\left( \frac{I_{\text{tot}}^{\text{relay}}}{H_{ms}} > \lambda \right) = Q\left[\frac{\lambda - m'}{\sigma'}\right]
\]

When the desired user is relaying the outage probability represents the case that the relay station cannot reach the base station.

\[
I_{\text{init}} = \sum_{i=1}^{N-j} H_{ms} + (j-1)H_{RS} = (N-j)H_{ms} + (j-1)H_{RS}
\]  

(3.25)
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If \( u \) users are relaying to a relay station then (3.25) becomes:

\[
I_{\text{intra}}^{\text{tot}} = \sum_{i=1}^{N-u} H_{\text{ms}} + (j-1)H_{\text{RS}} = (N-u)H_{\text{ms}} + (j-1)H_{\text{RS}}
\]  

(3.26)

The intercell interference is given again by:

\[
I_{\text{inter}}^{\text{tot}} = I_{\text{norelay}}^{\text{tot}} + \beta H_{\text{RS}}
\]  

(3.24)

The analysis of the intercell interference statistics, stated previously for the case of the non-relaying desired user is still valid. Hence the ratio \( \frac{I_{\text{norelay}}^{\text{tot}}}{H_{\text{ms}}} \) follows \( \mathcal{N}(\mu', \sigma^2) \).

Substituting (3.25) and (3.24) into (3.11); we can write:

\[
E_b \quad N_o \quad \frac{(W/R) \cdot H_{\text{RS}}}{[ (N-j) \cdot H_{\text{ms}} + (j-1) \cdot H_{\text{RS}} ] + \left( I_{\text{norelay}}^{\text{tot}} + \beta H_{\text{RS}} \right) + \eta} = \\
W / R \quad \frac{\left[ (N-j) \cdot \frac{H_{\text{ms}}}{H_{\text{RS}}}(j-1) \right] + \left[ I_{\text{norelay}}^{\text{tot}} + \beta H_{\text{RS}} \right] + \eta}{H_{\text{RS}}}
\]

The probability of a mobile that is relaying to be in outage is expressed as:

\[
P_{\text{outage relay}} = P_{\text{outage RS}} = \text{Pr} \left( \frac{E_b}{N_o} < \left( \frac{E_b}{N_o} \right)_{\text{req}} \right) \\
\frac{E_b}{N_o} < \left( \frac{E_b}{N_o} \right)_{\text{req}} \Rightarrow \\
\frac{W/R}{\left[ (N-j) \cdot \frac{H_{\text{ms}}}{H_{\text{RS}}} + (j-1) \right] + \left[ I_{\text{norelay}}^{\text{tot}} + \beta \right] + \eta} < \left( \frac{E_b}{N_o} \right)_{\text{req}} \Rightarrow 
\]

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\[
\frac{W/R}{(E_b/N_0)_{\text{req}}} - \left[ (N - j) \cdot \frac{H_{\text{ms}}}{H_{\text{RS}}} + (j - 1 + \beta) + \frac{\eta}{H_{\text{RS}}} \right] < \frac{I_{\text{total}}^{\text{norelay}}}{H_{\text{RS}}} \Rightarrow \frac{I_{\text{total}}^{\text{norelay}}}{H_{\text{RS}}} > \lambda' \Rightarrow
\]

\[
\frac{I_{\text{total}}^{\text{norelay}}}{H_{\text{ms}}} > \lambda' \Rightarrow \frac{I_{\text{total}}^{\text{norelay}}}{H_{\text{ms}}} > \lambda' \cdot \frac{H_{\text{RS}}}{H_{\text{ms}}},
\]

\[
\lambda' = \frac{W/R}{(E_b/N_0)_{\text{req}}} - \left[ (N - j) \cdot \frac{H_{\text{ms}}}{H_{\text{RS}}} + (j - 1 + \beta) + \frac{\eta}{H_{\text{RS}}} \right]
\]

\[
P_{\text{outage relay}} = \text{Pr} \left( \frac{I_{\text{total}}^{\text{norelay}}}{H_{\text{ms}}} > \lambda' \cdot \frac{H_{\text{RS}}}{H_{\text{ms}}} \right) = Q \left[ \frac{\lambda' \cdot (H_{\text{RS}}/H_{\text{ms}}) - m'}{\sigma'} \right] \quad (3.27)
\]

For relaying users selected only from the ring the mean and variance of \( \frac{I_{\text{total}}^{\text{norelay}}}{H_{\text{ms}}} \) is \( m_d \) and \( \sigma_d^2 \) as explained in the previous section and thus (3.27) is appropriately modified.

The probability of any mobile in the central cell to be in outage is expressed as:

\[
P_{\text{outage}} = P_{\text{no relay}} P_{\text{outage no relay}} + P_{\text{relay}} P_{\text{outage relay}} = \]

\[
P_{\text{no relay}} \cdot Q \left[ \frac{\lambda - m'}{\sigma'} \right] + P_{\text{relay}} \cdot Q \left[ \frac{\lambda' \cdot (H_{\text{RS}}/H_{\text{ms}}) - m'}{\sigma'} \right] \quad (3.28)
\]

Perfect power based power control is assumed. Hence, the powers received at the base station from the mobiles directly communicating with the base station and from the relay stations are assumed to be equal, therefore: \( H_{\text{RS}}/H_{\text{ms}} = 1 \). Additionally, when background noise power \( \eta \) is considered negligible: \( \lambda = \lambda' \) and because \( P_{\text{no relay}} + P_{\text{relay}} = 1 \), it is clear that:

\[
P_{\text{outage}} = Q \left[ \frac{\lambda - m'}{\sigma'} \right]
\]

### 3.3.3 Calculation of the interference at the relay station

The results for the outage probability are more accurate if an additional term that represents the case that the relayed mobile cannot reach the relay station is also considered in the final formula. Then (3.28) would be modified as follows:

\[
P_{\text{outage}} = P_{\text{no relay}} P_{\text{outage no relay}} + P_{\text{relay}} P_{\text{outage relay}} =
\]
The analysis that follows is for the case of fixed relay stations.

$P_{\text{outage}} = P_{\text{outage, no relay}} + P_{\text{relay}} \left( P_{\text{outage, MS} \rightarrow \text{RS}} + P_{\text{outage, RS} \rightarrow \text{BS}} \left( 1 - P_{\text{outage, MS} \rightarrow \text{RS}} \right) \right)$ (3.29)

$P_{\text{outage, MS} \rightarrow \text{RS}}$ expresses this additional term whose existence is due to the interference of all the relayed mobiles in all the cells to a relay station of the central cell. For the calculation of this outage probability a relay station in the central cell is chosen and the distances of all the base stations in the two tiers from this relay station must be calculated. It is assumed that these distances do not significantly vary when the number of relay stations and consequently their location changes. It is also assumed, for simplicity in the calculations that the relayed mobiles lie on the line that unites the base station with the relay station. Figure 3.9 illustrates the geometrical layout of the cellular model for the calculation of the interference at the relay station. Only the case where the relayed mobiles are found in the ring is investigated.

$\rho_0 = (\tau R)^2 + r_m^2 - 2r_m \tau R \cos \theta$ and $\rho_1 = \sqrt{x_1^2 + r_m^2 - 2r_m x_1 \cos \theta}$,

where $x_i$ represents the distance of the relay station from the cell with number $i$:

$x_1^2 = x_6^2 = (\tau R)^2 + (D_o)^2 - 2(\tau R)(D_o)\cos(150^\circ)$

Figure 3.9: Geometrical layout of the cellular model for the calculation of the interference at the relay station.
\[ x_2 = x_5 = (\tau R)^2 + (D_0)^2 - 2(\tau R)(D_0)\cos(90^\circ) \]
\[ x_3 = x_4 = (\tau R)^2 + (D_0)^2 - 2(\tau R)(D_0)\cos(30^\circ) \]
\[ x_7 = (3+\tau)R \]
\[ x_8 = x_{18} = (\tau R)^2 + (2D_0)^2 - 2(\tau R)(2D_0)\cos(150^\circ) \]
\[ x_9 = x_{17} = (\tau R)^2 + (3R)^2 - 2(\tau R)(3R)\cos(120^\circ) \]
\[ x_{10} = x_{19} = (\tau R)^2 + (2D_0)^2 - 2(\tau R)(2D_0)\cos(90^\circ) \]
\[ x_{11} = x_{15} = (\tau R)^2 + (3R)^2 - 2(\tau R)(3R)\cos(60^\circ) \]
\[ x_{12} = x_{14} = (\tau R)^2 + (2D_0)^2 - 2(\tau R)(2D_0)\cos(30^\circ) \]
\[ x_{13} = (3-\tau)R \]

The total interference at the relay station \( I_{tot}^{RS} \) is a summation of two factors that represent the interference coming from relayed mobiles in the central cell \( I_{int ra}^{RS} \) and from relayed mobiles in all the rings of the two tiers \( I_{inter}^{RS} \): 

\[ I_{tot}^{RS} = I_{int ra}^{RS} + I_{inter}^{RS} \]

Perfect power based power control is also assumed at the relay stations. Each relay station receives the signal of the mobile that relays to it with power \( H_{ms}^{RS} \). Similarly to (3.1) the ratio of the interference that comes from a relayed mobile inside the central ring to the received power \( H_{ms}^{RS} \) is:

\[ \frac{I_{int}^{RS}}{H_{ms}^{RS}} = \left( \frac{r_m - \tau R}{r_o} \right)^\mu \cdot 10^{(\xi_0 - \xi_{int}^{RS})/10} \]

\( \xi_0 \) represents the shadowing component between the interfering mobile M and the relay station RS. The ratio \( \frac{I_{int}^{RS}}{H_{ms}^{RS}} \) follows \( \mathcal{N}(m_{int}, \sigma_{int}^{RS}) \). Similarly to (3.7) and (3.9) the mean and variance of the ratio of intracell interference are:
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\[ m_{\text{intra}} = E \left[ \frac{\Gamma_{\text{LS}}}{H_{\text{ms}}} \right] = \frac{2\pi R}{\tau R} \sum_{j=1}^{j-1} \frac{r_m - \tau R}{r_0'} \left( \frac{r_m}{r_0'} \right)^{\mu} \left[ 1 - \left( 1 - \frac{r_m}{r_0'} \right)^{\tau R} \right] \frac{1}{(1 - \tau^2)\pi R^2} r_m \text{d}r_m \text{d}\theta \]  

(3.30)

\[ \sigma^2_{\text{intra}} = \text{var} \left[ \frac{\Gamma_{\text{LS}}}{H_{\text{ms}}} \right] = \frac{2\pi R}{\tau R} \sum_{j=1}^{j-1} \frac{r_m - \tau R}{r_0'} \left( \frac{r_m}{r_0'} \right)^{2\mu} \left[ 1 - \left( 1 - \frac{r_m}{r_0'} \right)^{\tau R} \right] \frac{1}{(1 - \tau^2)\pi R^2} r_m \text{d}r_m \text{d}\theta \]  

(3.31)

If \( u \) users are relaying to each relay station then the relay station examined suffers intracell interference from the \( (u-j-u) \) mobiles that relay to the \( j-1 \) relay stations in the same cell and also from the \( (u-1) \) mobiles that relay to the specific relay station. Hence, (3.30) and (3.31) become:

\[ m_{\text{intra}} = E \left[ \frac{\Gamma_{\text{LS}}}{H_{\text{ms}}} \right] = \frac{2\pi R}{\tau R} \sum_{j=1}^{j-1} \frac{r_m - \tau R}{r_0'} \left( \frac{r_m}{r_0'} \right)^{\mu} \left[ 1 - \left( 1 - \frac{r_m}{r_0'} \right)^{\tau R} \right] \frac{u(j-1)}{(1 - \tau^2)\pi R^2} r_m \text{d}r_m \text{d}\theta + (u-1) \]

\[ \sigma^2_{\text{intra}} = \text{var} \left[ \frac{\Gamma_{\text{LS}}}{H_{\text{ms}}} \right] = \frac{2\pi R}{\tau R} \sum_{j=1}^{j-1} \frac{r_m - \tau R}{r_0'} \left( \frac{r_m}{r_0'} \right)^{2\mu} \left[ 1 - \left( 1 - \frac{r_m}{r_0'} \right)^{\tau R} \right] \frac{u(j-1)}{(1 - \tau^2)\pi R^2} r_m \text{d}r_m \text{d}\theta \]

The total intercell interference to \( H_{\text{ms}} \) ratio can be modeled by a random variable that follows Gaussian distribution and is expressed as a summation of Gaussian random variables that represent the intercell interference to \( H_{\text{ms}} \) ratio coming from the \( i \)-th cell:

\[ \frac{\Gamma_{\text{int err}}}{H_{\text{ms}}}^R = \sum_{i=1}^{18} \frac{\Gamma_{\text{int err}}}{H_{\text{ms}}}^R \]

The mean and variance of the total intercell interference to \( H_{\text{ms}} \) ratio are:

\[ m_{\text{intererr}} = \sum_{i=1}^{18} \left[ m_{i1} + m_{i2} + m_{i3} + m_{i4} + m_{i5} + m_{i6} + m_{i7} + m_{i8} + m_{i9} + m_{i10} + m_{i11} + m_{i12} + m_{i13} + m_{i14} + m_{i15} + m_{i16} + m_{i17} + m_{i18} \right] \]

\[ = 2m_{i1} + 2m_{i2} + 2m_{i3} + 2m_{i4} + 2m_{i5} + 2m_{i6} + 2m_{i7} + 2m_{i8} + 2m_{i9} + 2m_{i10} + 2m_{i11} + 2m_{i12} + 2m_{i13} \]
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\[ \sigma_{\text{int}}^2 = \sum_{i=1}^{18} \sigma_i^2 = \sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4^2 + \sigma_5^2 + \sigma_6^2 + \sigma_7^2 + \sigma_8^2 + \sigma_9^2 + \sigma_{10}^2 + \sigma_{11}^2 + \sigma_{12}^2 + \sigma_{13}^2 + \sigma_{14}^2 + \sigma_{15}^2 + \sigma_{16}^2 + \sigma_{17}^2 + \sigma_{18}^2 \]

\[ = 2 \sigma_1^2 + 2 \sigma_2^2 + 2 \sigma_3^2 + 2 \sigma_4^2 + 2 \sigma_5^2 + 2 \sigma_6^2 + 2 \sigma_7^2 + 2 \sigma_8^2 + 2 \sigma_9^2 + 2 \sigma_{10}^2 + 2 \sigma_{11}^2 + 2 \sigma_{12}^2 + \sigma_{13}^2 + \sigma_{14}^2 + \sigma_{15}^2 + \sigma_{16}^2 + \sigma_{17}^2 + \sigma_{18}^2 \]

where \( m_i \) and \( \sigma_i \) represent respectively the mean and standard deviation of the intercell interference to \( H_{\text{ms}}^{RS} \) ratio coming from \( i \)-th cell and symmetry is taken into account (Figure 3.9). \( m_i \) and \( \sigma_i \) are calculated similarly to (3.30) and (3.31) by:

\[ m_i = \int \int_{0 \leq r \leq R} \left( \frac{r_m - \tau R}{r_0''} \right)^4 f \left( \frac{r_m}{r_0''} \right) \cdot \frac{j}{(1 - \tau^2)\pi R^2} r_m \, ds \, d\theta \]  

(3.32)

\[ \sigma_i^2 = \int \int_{0 \leq r \leq R} \left( \frac{r_m - \tau R}{r_0''} \right)^{2\mu} \left[ g \left( \frac{r_m}{r_0''} \right) - f^2 \left( \frac{r_m}{r_0''} \right) \right] \cdot \frac{j}{(1 - \tau^2)\pi R^2} r_m \, ds \, d\theta \]  

(3.33)

If \( u \) users are relaying to each relay station then \( j \) in (3.32) and (3.33) is substituted by \( u-j \).

The total interference at the relay station is a summation of two independent random variables \( I_{\text{int}}^{RS}/H_{\text{ms}}^{RS} \) that follow Gaussian distribution with mean and variance \( (m_{\text{int}}, \sigma_{\text{int}}^2) \) and \( (m_{\text{int}}, \sigma_{\text{int}}^2) \) respectively. Hence, \( I_{\text{tot}}^{RS}/H_{\text{ms}}^{RS} \) follows Gaussian distribution with mean and variance \( (m^-, \sigma^-) \), where \( m^- = m_{\text{int}} + m_{\text{int}} \) and \( \sigma^- = \sigma_{\text{int}}^2 + \sigma_{\text{int}}^2 \).

The case for which the relayed mobile cannot reach the relay station is investigated. Therefore:

\[ P_{\text{outage,MS}} = \Pr \left( \frac{E_b}{N_o} \leq \frac{E_b}{N_o} \right) \]

\[ \frac{E_b}{N_o} = W \cdot \frac{H_{\text{ms}}^{RS}}{I_{\text{tot}}^{RS} + \eta} \Rightarrow \frac{E_b}{N_o} = \frac{W}{R} \cdot \frac{H_{\text{ms}}^{RS}}{I_{\text{tot}}^{RS} + \eta} \Rightarrow \frac{E_b}{N_o} = \frac{W}{R} \cdot \frac{I_{\text{tot}}^{RS}}{H_{\text{ms}}^{RS}} + \frac{\eta}{H_{\text{ms}}^{RS}} \]

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\[ \frac{E_b}{N_o} < \left( \frac{E_b}{N_o} \right)_{req} \Rightarrow \]

\[ \frac{W/R}{I_{int,n}^{RS} + I_{int,er}^{RS} + \eta} < \left( \frac{E_b}{N_o} \right)_{req} \Rightarrow \frac{W/R}{\eta} \frac{H_{ms}^{RS}}{H_{ms}^{RS}} > \frac{W/R}{\eta} \frac{H_{ms}^{RS}}{H_{ms}^{RS}} > \delta', \]

where

\[ \delta' = \frac{W/R}{(E_b/N_o)_{req}} - \frac{\eta}{H_{ms}^{RS}} \]

\[ P_{outage, MS\rightarrow RS} = Pr \left( \frac{E_b}{N_o} < \left( \frac{E_b}{N_o} \right)_{req} \right) = Pr \left( \frac{I_{tot}^{RS}}{H_{ms}^{RS}} > \delta' \right) \]

The probability that a relayed mobile cannot reach the relay station is:

\[ P_{outage, MS\rightarrow RS} = Q \left( \frac{\delta' - \mu}{\sigma} \right) \]  \hspace{1cm} (3.34)

When background noise \( \eta \) is considered negligible, then \( \delta' = \delta = \frac{W/R}{(E_b/N_o)_{req}} \).

Equation (3.34) is substituted into (3.29) for the final calculation of the total outage probability. (and \( P_{outage, RS\rightarrow BS} \) is computed in (3.27)).

3.4 Numerical Results

In the following section the results that have been derived from the analysis discussed in section 3.3 are presented. The cellular environment considered is described in section 3.2 and the different parameters are listed in Table 3.1.

3.4.1 Relaying users from the whole cell or from the ring

The relay stations are assumed to be fixed, placed at positions where LOS communication is possible with the base station, forming constellations as shown in Figure 3.4 and one mobile is relaying per relay station.

Two different scenarios are investigated: the first is when the mobiles that relay are chosen from the whole cell and the other is when the mobiles that relay are chosen only from the ring, defined by a circle of radius 0.5R as shown in Figure 3.12 (a) and (b) respectively.
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Figure 3.12: Selection area for relayed mobiles: whole cell (a), ring (b).

In Figure 3.13 the outage probability ($P_{out}$) is shown for the case of two-hop relay for the two different scenarios described above. The fixed relay stations are assumed to be placed on a circle of radius $0.5R \ (r=0.5)$. The results are illustrated for 4, 6, 8 and 12 relay stations.

Figure 3.13: Outage Probability for relayed mobiles from the whole cell and from the ring.

The results show that the outage probability decreases when relaying occurs. It is obvious that mobiles that would be in outage when no relay occurs, can with relaying reach the base station. Also the outage probability slightly decreases when the relayed mobiles are selected from the ring.
compared to the case where they are selected from the whole cell. For 1% outage probability and for relayed mobiles selected from the whole cell the capacity gain of relaying compared to the no relaying case is approximately 4% for 4 relay stations, 6% for 6 relay stations, 7% for 8 relay stations and 11% for 12 relay stations. For 1% outage probability and for relayed mobiles selected from the ring the improvement of relaying compared to the no relaying case is 5% for 4 relay stations, 7% for 6 relay stations, 9% for 8 relay stations and 13% for 12 relay stations. The fact that selection of the relayed mobiles from the ring gives better system performance than when selected from the whole cell is reasonable because the mobiles that are further away from the base station create more interference to the other cells (intercell interference). By choosing to relay the mobiles that are at the edge of the cell it means that they are substituted by relaying stations that are closer to the base station than themselves and hence they create less intercell interference than the substituting mobiles. Therefore the probability of a mobile being in outage decreases and the capacity of the system is enhanced. The rest of the scenarios examined consider that the relayed mobiles are chosen from the ring.

### 3.4.2 Different relay station positions

Figures 3.14 and 3.15 show the outage probability for 6 and 8 relay stations respectively for different radius $\tau R$ of the inner circle. The results for $\tau = 0.25, 0.5$ and 1 are illustrated.

![Figure 3.14: Outage Probability for 6 relay stations for different $\tau$.](image)
The figures show that the greatest number of mobiles accommodated in the cell occurs for \( \tau = 0.5 \), hence when the relay station lies on a circle that has half the radius of the original cell. When \( \tau \) is smaller than 0.5 the performance of the system is still better than the “no relay” case but worse than for \( \tau = 0.5 \). For \( \tau \) greater than 0.5 the results are even worse compared to the “no relay” case. The smaller the radius of the inner circle, the more the relay case approaches the no relay scenario as the ‘pool’ of relayed users increases and tends to become the whole cell. The results for \( \tau \) greater than 0.5 will be justified based also on Figure 3.17 that follows.

Figure 3.15: Outage Probability for 8 relay stations for different \( \tau \).
3.4.3 Different number of relay stations

Figure 3.16 illustrates the outage probability for different number of relay stations that lie on a circle of radius 0.5R.

The greater the number of relay stations the smaller the outage probability for a given number of users per cell. Obviously when the number of relay stations increases, the number of mobiles that are supported to reach the base station increases and the capacity is enhanced. For 1% outage probability the improvement of relaying with 12 relay stations is approximately 13% compared to the no relay case and 7% compared to the relay case with 6 relay stations.

Figure 3.17 shows the total intercell interference (I_{inter}) that 4, 6, 8 or 12 mobile stations cause when they are selected from the ring and the total intercell interference that 4, 6, 8 or 12 relay stations at radius \( \tau R \) cause, for different values of \( \tau \). The graph is calculated using the equation (3.22).
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Figure 3.17: Total intercell interference coming from mobile stations and equivalent relay stations

The intercell interference created by the RS when they are placed at a radius of the inner circle above 0.8R is greater than the intercell interference created by the mobiles they replace. This fact explains the results of Figures 3.14, 3.15 that when \( \tau \) is 1 the performance of the system degrades while for \( \tau = 0.25 \) and 0.5 the outage probability decreases.

Figure 3.18 shows the difference between the total intercell interference that the relayed mobiles and the relay stations create.

Figure 3.18: Difference between the total intercell interference of relayed mobiles and relay stations.
For a 0.5 radius of the inner circle this difference is at its maximum value, hence the system is most supported at $\tau=0.5$. This fact justifies the results illustrated in Figures 3.14 and 3.15, where it is shown that the best performance in terms of outage probability or capacity is when the relay stations lie on a circle of radius $0.5R$.

For reasons of annotation the first plot in Figure 3.19 reproduces the total intercell interference coming from 4, 6, 8 and 12 relay stations as shown in Figure 3.17. Also the mean intercell interference from the relay stations for each set of relay stations is illustrated. Until $\tau=0.5$ the mean intercell interference from the relay stations is very small for all sets (4, 6, 8 and 12 relay stations). Above $\tau=0.5$ the values increase exponentially. This increase in the intercell interference is due to the increase in the total transmit power of the relay stations as the radius of the inner circle rises. When the relay stations are closer to the edge of the cell they need to increase their transmit power so that their transmit signal can reach the base station. On the other hand the transmit power is proportional to the path loss expressed as $(r/R)^\alpha$, which justifies the exponential increase in the transmit power. The final plot in Figure 3.19 shows the mean transmit power from the relay stations for each set. Because the relay stations are fixed and do not experience shadowing effects the transmit power is the same for each of them, for any set of relay stations per cell.

![Figure 3.19: Total and mean intercell interference and transmit power from relay stations.](image-url)
The mean intercell interference coming from the non-relayed mobiles and the relay stations is shown in Figure 3.20 (a). The mean intercell interference for the no-relay case is also shown.

![Figure 3.20: Mean intercell and mean total intercell interference.](image)

The mean intercell interference is at its minimum value for $\tau=0.5$ (best performance as shown in Figures 3.14, 3.15), while for $\tau$ above 0.8 the mean intercell interference for the relay case is higher than the no-relay case. The last result justifies the fact that in Figures 3.14, 3.15 the outage probability for $\tau=1$ is worse even when compared to the no-relay case.

In the second plot of Figure 3.20 the mean total interference is shown. These results are derived from the previous section that describes the mean intercell interference, by adding the intracell interference. Because of the perfect power based power control assumed in the analysis, the intracell interference is a constant factor for each set of relay stations and therefore the results for the mean total interference have the same shape as the one for the mean intercell interference.

### 3.4.4 Users/Hz/cell instead of users/cell

In section 3.3.1 the effect of the duplex division schemes in the two-hop relay case is discussed. If the outage probability is investigated against the number of users/Hz/cell, then the fact that additional bandwidth is used in the TDD access scheme is taken into account. Under these terms the comparison between the different scenarios becomes fairer. Figure 3.21 shows the outage probability for the no-relay case and for different number of relay stations versus the number of users/Hz/cell. Figure 3.16 shows that the relaying leads to greater capacity for any number of relay stations, but Figure 3.21 shows that because of the occupation of additional bandwidth the relay does not improve the performance of the system compared to the no-relay case when 4 or 6
relay stations are used. This is due to the fact that the bandwidth is not efficiently used as one time slot from the uplink TDD bandwidth is occupied but not all codes are used. Therefore more than one mobile could relay to a relay station so that more mobiles that cannot directly reach the base station are supported by a relay station and also the bandwidth is more efficiently used.

Figure 3.21: Outage Probability for different relay stations at $\tau=0.5$ versus users/Hz/cell

For 1% outage probability, the improvement of relaying with 12 relay stations is approximately 6% compared to the no relay case when users/Hz/cell is considered, while this improvement is 13% when users/cell are considered (as seen in Figure 3.16).
3.4.5 Different number of relayed mobiles per relay station

Figure 3.22 shows the results for the outage probability against users/Hz/cell for 6 relay stations at $\tau=0.5$ and for different number of relayed mobiles.

![Figure 3.22: Outage probability for different number of relayed mobiles per relay station, 6 relay stations at $\tau=0.5$ versus users/Hz/cell](image)

The efficient use of the bandwidth improves the system compared to the no relay case (for outage probability of 1%) by 25% for 2 relayed mobiles per relay station and by 54% for 5 relayed mobiles per relay station. Figure 3.23 (a) shows that for 2 relayed mobiles per relay station one timeslot can accommodate all the relaying users since they are $2 \times 6 = 12$ and hence they can use 12 out of the 16 spreading codes of the first timeslot. Figure 3.23 (b) shows that for 5 users per relay station there are $5 \times 6 = 30$ relayed mobiles that can be accommodated in 2 timeslots using all the 16 codes from the first timeslot and $30 - 16 = 14$ codes from the second timeslot. The case of one relayed mobile per relay station (one timeslot) does not seem to give better results compared to the no relay case.
Figure 3.23: TDD timeslot and code allocation for 6 relay stations and 2 relayed mobiles per relay station (a) and 5 relayed mobiles per relay station (b).

Figure 3.24 shows the corresponding results for 8 relay stations and 1, 4 and 8 relayed mobiles per relay station. Here, relaying is shown to increase slightly the capacity of the system when only one mobile is relaying per relay station (one timeslot). The improvement for outage probability of 1% compared to the no relay case is 13% for one relay station (8 relayed users in one timeslot), 45% for 4 relay stations (4\cdot8=32 relaying users in two timeslots) and 87% for 8 relay stations (8\cdot8=64 relaying users in four timeslots).

Figure 3.24: Outage probability for different number of relayed mobiles per relay station, 8 relay stations at $\tau=0.5$ versus users/Hz/cell.
Figure 3.25 shows the outage probability against the number of users/Hz/cell when there are 12 relay stations at a radius of 0.5R and for different number of relayed mobiles per relay station.

![Figure 3.25](image)

**Figure 3.25: Outage probability for different number of relayed mobiles per relay station, 12 relay stations at \( r = 0.5 \) versus users/Hz/cell**

Compared to the no relay case the two-hop relaying introduces improvement in the performance of the system for outage probability of 1%, by 6% for one relayed mobile per relay station (1 timeslot), 32% for two relayed mobile per relay station (2 timeslots), 47% for three relayed mobiles per relay station (3 timeslots), 63% for four relayed mobiles per relay station (3 timeslots), and 96% for five relayed mobiles per relay station (4 timeslots).

### 3.4.6 Effect of standard deviation of shadowing

The effect of shadowing on the outage probability is illustrated in Figure 3.26.
Chapter 3. Analytical Evaluation of the CDMA Cellular Network Capacity with Relaying

Figure 3.26: Outage Probability for different standard deviation of shadowing for no relay and for 6 relay stations at $\tau=0.5$.

The case of no relay and of relaying with 6 relay stations and 5 mobiles per relay station are compared. It is shown that when the standard deviation of shadowing increases the outage probability for a given number of users increases for both cases. Larger values of shadowing standard deviation mean that the shadowing affects for a greater extent the transmitting signal. Therefore more non-relayed mobiles have difficulty in reaching the base station, and hence more mobiles are likely to be in outage. The improvement when relay is used compared to the no relay case is around 42% for standard deviation of shadowing $\sigma=4$dB and 59% for standard deviation of shadowing $\sigma=10$dB, for outage probability 1%. Hence the relaying method improves the performance of the system more significantly as the shadowing becomes more dominant.

Figure 3.27 presents the capacity of the system for different values of the standard deviation of shadowing for the no relay and for the relay case described above, for outage probability of 1%. As expected, increase in the standard deviation leads to a decrease in the capacity of the cell because the signal from the non-relayed mobiles is more attenuated until it reaches the base station and therefore it might not achieve the required signal.
Chapter 3. Analytical Evaluation of the CDMA Cellular Network Capacity with Relaying

3.4.7 Effect of path loss exponent

The same analysis is performed for different values of path loss exponent $\mu$. In Figure 3.28 the results show that when the path loss exponent increases the outage probability for a given number of users/Hz/cell decreases. While the path loss parameter increases, the received signal becomes more attenuated and the interference level to other neighboring base stations is reduced.

![Figure 3.27: System capacity for different values of shadowing standard deviation](image)

![Figure 3.28: Outage Probability for various path loss exponents for no relay and 6 relay stations at $\tau=0.5$.](image)
For outage probability 1%, the improvement when relay is used compared to the no relay case is around 100% for path loss exponent $\mu=1$ and 50% for path loss exponent $\mu=4$. Hence the relaying method improves the performance of the system more significantly for smaller values of the path loss exponent.

Figure 3.29 shows that the capacity of the system increases as the path loss exponent increases.

![Figure 3.29: System capacity for different values of path loss exponent.](image)

### 3.5 Conclusions

In this chapter we presented the analytical expression that describes the probability of a mobile in UMTS cellular network being in outage. The number of users supported in a cell for a particular outage probability represents the cell’s capacity. This probability is first presented for the case where no relaying occurs and then the calculations are expanded to the case of two-hop relaying. Several conclusions can be drawn from the various results obtained.

- The main achievement is that with respect to the number of users per cell, relaying can indeed decrease the intercell interference and therefore improve the performance of the system in terms of capacity.

- The FDD/TDD mode is used for the two hop model. The extra bandwidth used for relaying purposes is also taken into consideration in order to make a fair comparison. The result showed
that there is a capacity gain with relaying even if extra bandwidth is consumed between MSs and Relay Stations. However, it is worth noting that a time slot allocation strategy is employed in each cell. The strategy is based on allocating only a certain number of time slots for relaying purposes. If the relay mobiles use the TDD bandwidth in the most efficient way, then the improvement can be significant compared to the non relaying case.

- The results also showed that the improvement is greater when the mobiles that require relaying are located outside the circle where the relay stations lie (ring). In other words, there is a greater capacity gain when the users located at the edge of the cell are relayed. Therefore, all the results derived after this conclusion, are based on selection of the relayed mobiles being from the ring.

- In order to achieve sufficient capacity gain, several MSs should be relayed by the same relay stations. The intercell interference does not decrease significantly when only a few MSs are relayed (or one MS per fixed relay station).

- The relay stations are assumed to be fixed at a specific location. The best performance is obtained when the relay stations lie on a circle of radius 0.5R, which represents the half maximum distance from the BS.

- It was also shown that by increasing the number of fixed relay station, the capacity is significantly improved by relaying.

- The effect of different standard deviations of shadowing (σ) is also examined. The results show that when σ increases, the outage probability for a given number of users/Hz/cell also increases, or equivalently, the capacity of the system decreases. The opposite results are observed for different values of the path loss exponent μ. When μ increases the outage probability decreases for a given number of users/Hz/cell, or equivalently, the capacity of the system increases. Therefore, the two-hop relay system can achieve significant capacity gain over the conventional cellular system in an unstable radio environment.

In this chapter, we showed analytically that relaying can improve the capacity of the UMTS cellular network. However, due to the complexity of the system the analytical approach is limited to simplified models and several assumptions needed to be made. In order to confirm and quantify the capacity gain that relaying introduces to the conventional cellular networks, a simulation approach is adopted in subsequent chapters. The computer simulation allows more realistic and practical scenarios to be investigated.
Chapter 4

4 Dynamic System Level Simulator for UMTS Cellular Network

4.1 Introduction

In general, the performance of communication systems can be evaluated through analytical methods, computer simulation, and hardware prototyping [Gom03]. The analytical methods (adopted in chapter 3) use mathematical notation and equations to describe the system, and give clear insights into the relationships between the system parameters and performance. However, analytical approach may not be possible where the mathematics is intractable. Consequently, the analytical approach is limited to simplified models of the system; implying that analytical approach is useful in the early stages of system design for broadly exploring the design space.

Hardware prototyping involves building a hardware model of the system (test-bed), and evaluating the performance based on measurements obtained from the model. Although it is an accurate and more credible method, it is costly and time consuming. In addition, it is less flexible; as such, it is inappropriate at the early stage of system design when the number of validated design alternatives is large.

Computer simulation is the technique of designing a model of the actual or theoretical physical system, executing the model on a digital computer, and analyzing the results. Firstly, it acts as a communication vehicle that provides a description of the behavior of the system. Secondly, the simulation approach enables users to gain insight and an understanding of the behavior of the system. Thirdly, it enables development theories that account for the behavior of the system. Finally, it provides a means for analyzing and evaluating the system and predicting the system future behavior.

In the previous chapter, the analytical model of the cellular network without and with relaying was studied. Their performance in terms of capacity were evaluated and compared through mathematical equations. However, due to the complexity of the radio resource management (such as power control, handover and mobility behaviors) it becomes very difficult to carry out numerical analysis of a practical and more realistic model. Furthermore, since the study on
relaying systems is at its early stage, many issues need to be investigated before it is possible to analyze mathematically the performance of a more realistic relaying system. Therefore in order to complement the analysis study made in the previous realistic relaying chapter, we evaluate the performance of the cellular network without and with relaying through computer simulations. For this, a dynamic system level simulator for the relay and non-relay case was built. In this chapter, we concentrate on the description of the system level simulator for the UMTS cellular network without relaying (the system level simulator for the relaying system is explained in the following chapter).

This chapter is mainly based on two sections. The first section (4.2) gives a detailed description of the dynamic system level simulator. After explaining the role of a system level simulator, the different functionalities of the simulator are described in details. Then, the results obtained are shown at the end of this section.

In the second section (4.3), a new shadowing model is proposed and explained. This shadowing model considers the two-dimensional auto-correlation and can be applicable to any dynamic system level simulator.

4.2 System level simulator description for UMTS cellular network

4.2.1 Simulator description

Typically, radio network simulations can be classified as either link-level or system-level simulations. The link level simulator is needed for the system simulator to build a receiver model that can predict the receiver FER/BER performance, taking into account channel estimation, interleaving and decoding. In the link level, one single communication is modelled (between one user and one BS). It allows quality analysis of the binary digit flow transmitted between a mobile and a BS. This link level flow can result from the combination of different paths to or from various BS of the mobile active set in case of macrodiversity. For accurate receiver performance evaluation, a chip level or symbol-level simulation model is needed, typically with 3.84 Mcps time resolution [Hol00].

The system level simulator is needed to model a system with a large number of mobiles and base stations, and algorithms operating in such a system. System level simulations have the goal to model a network based on an existing or planned cell design, an estimated traffic distribution and a mix of services with multiple Quality of Services requirement. The different BS’s and traffic present in the zone interact with the various system algorithms and the propagation conditions. The simulation is rather complex as it requires additional inputs for: interference model, handover
usage, mobility, traffic load, power control, propagation model, etc...

A single simulator approach would be preferable to provide real-time processing of information bits to provide instantaneous block error rate readings; however this would be computationally excessive, and would result in large simulation times in multi-cell, multi-user environments [Rod04]. The required simulation resolutions and simulation times are far too high. Therefore, another approach where the link level and system level are separated is preferred. However, a method of interconnecting the two simulators has to be defined. Conventionally, the information obtained from the link level tool is linked to the system simulation by using a so-called average value interface that describes the BER/FER performance by average Eb/No requirements.

In this thesis, we mainly study the variation of the intercell interference due to relaying and therefore, we need to evaluate the intercell interference created by some relayed MS’s in the neighboring cell. In order to assess the interaction between users in different cells, we compare the performance of the non-relaying system with the relaying system using a system level simulator.

There are two approaches to design system-level simulators: the time based and the "Monte Carlo". The time-based approach provides dynamic capabilities, either algorithm time scheduling or measurement modelling or even motion features to analyse in detail a mobile change of active set. However, there is always a compromise to be made between the frequency of samples and the simulation duration. A more practical approach is a pure static snapshot requiring low computational capabilities. This approach is based on a discrete mobile placement in the network, followed by the determination of a stable state. A statistical analysis would require several samples with various mobile positions and activities to get significant results [Yan03].

Both approaches provide complementary cellular network results, but due to the complexity of time based system-level simulations, most of the simulators that are currently available use statistical methods. In order to analyze the handover in the non-relaying model and the connections between the MS and the relay nodes in the relaying model, we consider the time based system level simulator.

A system level simulator is basically a software tool modeling the system and the environment. In this chapter, a dynamic system level simulator is built for a wideband CDMA based mobile cellular radio network with FDD mode for the uplink scenario. In such a system, it is assumed that a single carrier frequencies is reused in all cells. A typical rural environment with vehicular users scattered is modeled. The simulation scenario is tested in a 91 Km² area with 19 cells of radius
2km deployed. At the beginning of the simulation, a predefined number of active users are uniformly distributed over the whole system. An active user is a user who transmits traffic on the data channel to its serving BS.

Then for each step, the position of the MS is updated following a mobility model (explained below). At this new position, the total path loss (including path loss and shadowing) between all MS and all BS are calculated and stored in a gain matrix. Based on the gain matrix and the handover mechanism, each MS selects the best BS as the serving BS. Once all the users know in which cell they belong, the (active) users transmit their data directly to their own BS. During the communication between the MS and the BS, the MS creates interference for other MS’s in the same cell (intracell interference) but also for MS’s in others cells (intercell interference). Therefore the Signal-to-Interference ratio (SIR) for each link MS-serving BS can be calculated. In order to combat the near-far effect and hence keep the level of interference low in the system, a distributed power control is implemented. The main goal of the distributed power control algorithm is to increase or decrease the transmitter power of each mobile terminal with respect to the transmitter power of other mobile terminals. This process is repeated several times within the same step (i.e. for the same MS locations). During this process (power control loop), the transmitter power of each user is stabilised to a required level in order to achieve the SIR target required. After the power control loop, the SIR of all MSs is calculated. The received Signal-to-Interference Ratio (SIR) of each active user is calculated at the BS and the number of users in outage in the system is found. A user is considered in outage if its received SIR is below the SIR target. This process is repeated for several steps. One step (or snapshot/iteration) represents one location for all users. If the received SIR is below the SIR target for a certain number of steps, the user is assumed to be unsatisfied. Figure 4.1 summarize the description of the system level simulator for one step.
Chapter 4 Dynamic System Level Simulator for CDMA based Mobile Systems

The simulations are run for 1000 steps. The simulation result is based on the percentage of non-satisfied user. A user is considered non-satisfied if its SIR is not above or equal to the SIR target -0.5 dB for a certain period of time (the period chosen is 5 consecutive seconds [ETSI98]). At the end of the simulation, the numbers of non-satisfied users in the central cell were calculated.

4.2.2 System Deployment model

4.2.2.1 Link budget

Before a service provider (i.e. operators) can install its sites in a certain area, it needs to do a planning (or dimensioning) exercise. The purpose of the dimensioning phase is to estimate: the approximate number of required sites, the base station configurations and the number of network elements, in order to forecast the projected costs and associated investments. Initial system dimensioning provides the first and most rapid evaluation of the network element count as well as the associated capacity of those elements. The target of the initial planning phase is to estimate the required site density and site configurations for the area of interest [Lai02].

One of the main activities of the dimensioning phase is the radio link budget. The link budget is the process of analyzing all major gains and losses in the uplink and downlink radio paths such as antenna gains, cable losses, fade margin, transmitter power, interference margin, (see Table 4.1)
The output of the link budget calculation is the maximum allowed propagation path loss (MAPL). This latter determines the cell range and thus the number of sites needed for a specific area. Since we do not simulate our model in a specific area and we already know the number of cells used (tree tiers cells), we calculate a link budget in order to find the appropriate cell’s radius.

Coverage design objectives are usually defined in terms of coverage probability. As an input of the link budget, the coverage probability is used to ensure that the received power within the cell is above the received power threshold. Therefore the cell’s range is calculated such that a predefined coverage probability is set. In practice, the particular clutter (buildings, trees, etc...) along a path at a given distance will be different for every path, causing variations with respect to the nominal value given by the path loss models. Some paths will suffer increased loss; while others will be less obstructed and have increased signal strength. This phenomenon is called shadowing or slow fading [Sau99]. It’s crucial to account for this in order to predict the reliability of coverage provided by any mobile cellular system.

In order to provide reliable communications at a given distance, therefore, an extra fade margin has to be added in to the link budget according to the reliability required from the system. A fade margin is a margin included to the link to take account of the signal’s fade. By adding a fade margin the coverage of the system is reduced but the reliability is greatly increased.

The coverage requirement of 90% sets the actual shadowing margin. If 90% coverage is to be achieved over the whole cell area and we know that we have shadowing with a standard deviation of 7 dB and path loss model with exponent 3.76, we get from [Jak74] that the coverage probability at the area boundary is 75%. To achieve this, we need a shadowing margin of approximately 7.3 dB.

Table 4.2 gives a link budget as in [Lai02] where all the parameters used in the simulator for the voice service users in the vehicular environment are listed.
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<th>Uplink</th>
<th>Downlink</th>
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<td></td>
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<tr>
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<td>j</td>
<td>-10.09</td>
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<td>139.83</td>
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</table>

Table 4.1 Link budget for voice service for macrocell
Once the maximum allowed propagation loss in a cell is known, it is easy to apply any known propagation model for the cell range estimation. The propagation model should be chosen so that it optimally describes the propagation conditions in the area. Therefore we use the path loss model from [ETSI98] applicable in the vehicular environment. Equation 4.1 gives the path loss model used with base station antenna height 15 m above average rooftop and carrier frequency of 2000 MHz:

$$L = 128.1 + 37.6 \times \log_{10}(D) \quad (dB)$$  \hspace{1cm} (4-1)$$

where $D$ is the separation distance between the base station and the mobile station in kilometres.

The cell’s range or radius is the distance from base station at which the path loss equals MAPL. Beyond this radius, the signal is too weak to be acceptable. Therefore the radius of the cell is found such as:

$$MAPL = 128.1 + 37.6 \times \log_{10}(R) \quad (dB)$$  \hspace{1cm} (4-2)$$

Where $R$ is the cell’s radius.

For a MAPL of 139.83 dB, the radius of the cell found is 2051m.

4.2.2.2 Cell deployment

The simulation scenario is set in a rural environment where the homogeneous area consists of 3 tiers of 19 hexagonal omni-directional cells of 2000m radius. In UMTS cellular systems, the link quality in one cell is affected by the interference from both its own cell and other surrounding cells. Hence, in the simulations, the data collected from the base stations close to the boundary of the simulation area is considered as inaccurate, as there is no interference from part of their surrounding cells. This is called the boundary effect. To eliminate such an effect, only quality statistics of users located in the centre cell are collected. The cells deployment in the simulation area are depicted in Figure 4.2
4.2.2.3 Mobility Model

In this dynamic simulator the users are moving within the simulation area according to a mobility model. The former for the Vehicular Test environment is a pseudo random mobility model with semi-directed trajectories. The mobile's position is updated according to the decorrelation length, and direction can be changed at each position update according to a given probability [ETSI98]. Direction can be changed within a given sector to simulate a semi-directed trajectory. The mobile's speed is constant and the mobility model is defined by the following parameters:

- Speed value: 120 km/h
- Probability to change direction at position update: 0.2
- Maximal angle for direction update: 45°
Mobiles are uniformly distributed on the map and their direction is randomly chosen at initialisation.

### 4.2.3 Propagation model

In mobile communication systems, the signal attenuation along the propagation path is normally modeled as the sum of three distinct components, namely the path loss, shadowing (or slow fading) and fast fading. The path loss is primarily a function of transmitter and receiver separation. The shadowing occurs due to the effects of buildings, small terrain features, trees, etc. The fast fading is caused by the wave interference between two or more multipath components that arrive at the receiver while the mobile travels in a short time or over a short distance. However in our simulation model, we consider only the path loss and the shadowing. We assume the fast fading to be averaged out.

#### 4.2.3.1 Path Loss

According to the ETSI document for evaluating selected test environments for UMTS [ETSI98], the following path loss model should be used in the vehicular environment where buildings are assumed to have uniform height:

\[
L = 40 \times (1 - 4 \times 10^3 \times \Delta h_b) \times \log_{10}(D) - 18 \times \log_{10}(\Delta h_b) + 21 \times \log_{10}(f) + 80 \text{ (dB)}
\]  

where \(D\) is the separation distance between the base station and the mobile station in kilometres, \(f\) is the carrier frequency of 2GHz and \(\Delta h_b\) is the base station antenna height in meters. Measured from the average rooftop level \(\Delta h_b = 15\text{m}\). Considering the given values, (4-3) can be simplified to:

\[
L = 128.1 + 37.6 \times \log_{10}(D) \text{ (dB)}
\]  

where \(L\) should under no circumstances be less than the Free Space Loss. This model is valid for Non-Line of Sight cases only and describes worst-case propagation.

#### 4.2.3.2 Shadowing model

The long-term (log-normal) fading is characterised by a Gaussian distribution with zero mean on the logarithmic scale. Due to the slow fading process as distance varies, adjacent values are correlated. The normalised autocorrelation function \(R(\Delta x)\), can be described with sufficient accuracy by the exponential function given below:

\[
R(\Delta x) = e^{-\frac{\Delta x}{d_{corr}}},
\]  

where \(d_{corr}\) is the decorrelation length.
Assume that the log-normal component of the path loss at position $P_j$ has been determined to be $L_j$ and we wish to compute the log-normal component $L_2$ at the next position $P_2$, where $P_2$ is $\Delta x$ metres away from $P_1$. Then $L_2$ is normally distributed and can be calculated as:

$$L_2 = R(\Delta x) \times L_1 + \sqrt{1 - R(\Delta x)^2} \times \xi$$

(4-6)

where $\xi$ is a sample of a white Gaussian variable with mean of zero and standard deviation of $\sigma$. This was chosen to be 7 dB for MS speed of 120 km/h and the decorrelation length is $d_{corr} = 20 m$ [ETSI98].

### 4.2.4 Simulation approach

#### 4.2.4.1 SIR calculation

In order to evaluate if a MS is in outage, the SIR of all the active users need to be calculated and compared to the SIR target. The SIR of all active MSs can be calculated at each step of simulation. If $G$ denotes the channel gain (path loss and shadowing), $P$ denotes the transmitter power and the uplink measured intracell and intercell interference at the $i$th BS are denoted by $I_{\text{intracell}}^i$ and $I_{\text{intercell}}^i$ respectively, the average received SIR of user $u$ can be expressed as:

$$SIR_{iu} = \frac{G_{iu} P_{iu}}{I_{\text{intracell}}^i + I_{\text{intercell}}^i + n_z}$$

(4.7)

Where $n_z$ represents the noise power, $G_{iu}$ represents the path loss between the user $u$ and BS $i$ and $P_{iu}$ represents the transmit power of user $u$ to the BS $i$.

If $N^i$ represents the number of users served by the $i$th BS, $I_{\text{intracell}}^i$ can be expressed as:

$$I_{\text{intracell}}^i = \sum_{j \neq u}^N G_{ij} P_{ij}$$

(4.8)

If $N^i$ is the number of users that are served by the BS $m$ and $M$ the number of cells in the system, the intercell interference of user $k$ can be expressed as:

$$I_{\text{intercell}}^i = \sum_{m=1}^M \sum_{k=1}^{N^m} G_{ik} P_{ik}$$

(4.9)

The SIR target is dependant on the Eb/No target. For a predefined Eb/No target, the SIR target of the MS-BS link ($SIR_{MS,\gamma}$) can be calculated such as:
where $W$ represents the chip rate (3.84 Mcps) and $R_{MS}$ is the MS bit rate.

### 4.2.4.2 Power Control

In UMTS, since all active users transmit in the same frequency band and at the same time they interfere with each other. In addition, UMTS have a reuse factor of one, which means that they reuse the frequency in every cell. This implies that UMTS must contend with not only multiple interferers from within the cell but also from users in neighbouring cells. Therefore the capacity of a CDMA-based cellular system is interference limited. One solution to reduce the interference in the system and increase the capacity of the cellular system is the use of power control. With (perfect) power control, transmit power of all users in a cell are controlled in such a way that their signals at the base station are received with the same power. Power control is also used to balance the received power against the near-far problem. The near-far problem stems from the fact that users experience different propagation losses depending on their distances from the base station. As a result, large signals received from users close to the base station may mask the small signals from distant users. Furthermore, power control enables the users to transmit the power necessary for proper communication, in return, saving precious power and hence prolonging the user battery-life. Therefore, Power Control is essential in any CDMA-based cellular communication in order to reduce the interference in the system, and increase the capacity of the cellular system.

Power control analysis in the cellular system is complex as it uses an open loop power control (OLPC) strategy at the system level and a closed loop power control (CLPC) strategy at physical layer. The first strategy consists of reducing the interference of the system composed of many users under mobility. Users will move around the cell and experience mainly shadowing and path loss degradation. The objective of the open loop power control is to balance the users transmit power around an acceptable value. This open loop is applied at the slot level. On the contrary, the closed loop power control is employed at link level (or at chip level), where the user will adapt its transmit power to overcome the fast fading variations and satisfy its $E_b/N_0$ requirements. Since we do not consider fast fading it is unnecessary to implement the closed loop power control, the open loop power control can combat the path loss and slow fading.

The power control schemes can be classified in two categories: centralized and distributed power control schemes. Under a centralized power control scheme, the power control problem is formulated as an optimization problem for resource allocation within specified constraints. High computational complexity precludes its practical implementation. Under distributed power control on the other hand, the power control problem is formulated as a regulation problem whose aim is
to satisfy various performance requirements such as target received power or SIR [Gom03]. Algorithms under distributed power control scheme are iterative.

Therefore in this thesis, we implement a perfect distributed power control.

The transmitter power of each user $i$ for the next iteration in the simulation $P_i^{(n+1)}$ or time instant, is adjusted in terms of its current power $P_i^{(n)}$, the SIR target and the current received SIR. This is combined using the following formula:

$$P_i^{(n+1)} = \frac{SIR_{\text{target}}}{SIR_{\text{received}}} \times P_i^{(n)} \quad (4-11)$$

The power control algorithm used in most of the system level simulators is based on the distributed power control algorithm (4-11). But in the latest CDMA technology such as IS-95 and UMTS, the open loop power control is used for the same purpose. Indeed open loop power control is a distributed algorithm and if we express equation (4-11) in dB as:

$$P_i^{(n+1)} = SIR_{\text{target}} - SIR_{\text{received}} + P_i^{(n)} \quad (4-12)$$

We also know that the received SIR expressed in dB is:

$$SIR_{\text{received}} = P_i^{(n)} - PL - I \quad (4-13)$$

where $PL$ and $I$ represent respectively the link loss and the interference perceived by the mobile at time $n$. Inserting (4-13) into (4-12), we can write the power update algorithm as:

$$P_i^{(n+1)} = SIR_{\text{target}} + PL + I \quad (4-14)$$

From (4-14), the open loop power control is clearly recognised, where $PL$ represents the measured link loss, $I$ is the measured interference level (in dBm) and finally the $SIR_{\text{target}}$ is a constant value.

4.2.4.3 Handover model

Handover refers to the procedure where an active user has to change its access point to the network from one radio channel to another, when it continues to move during the communications and reaches a point where the current serving channel cannot provide sufficient signal coverage and/or other cells can provide better signal coverage. There are two different ways of performing handovers in existing mobile systems, namely hard handover and soft handover. In hard handover, the MS keeps the connection to only one BS at a time and breaks the connection to the serving base station immediately before making the new connection to the target BS. It can be seen that a ‘hard’ decision of target base station has to be made before the handover procedure takes place. Whereas in soft handover, the mobile user can enter a ‘soft handover’ state where
together with its serving cell, one or more potential target cells are included into connections to
the user and the communication is kept to all these cells simultaneously for a period of time,
before giving up the worse links. Thereafter, a ‘soft’ decision is made before the network can
really decide which cell the user needs to handover to.

Generally in a system level simulator, in an uplink model, the MS is assumed to be assigned to
one BS. The soft handover is mainly simulated for downlink purposes. Furthermore, to make fair
comparison between the non-relaying and the relaying models (chapter 5 and 6), the soft handover
should be implemented in both models. However, more investigations need to be done before
including soft handover in cellular network with relaying. Therefore, we assume the same hard
handover mechanism for both models.

One of the disadvantages of hard handover is the “ping pong effect”. This phenomenon happens
when a call is repetitively switched back and forth between two cells when the mobile user is near
a cell border. This increases the chance of a call getting dropped and imposes a huge amount of
signalling load to the network. In order to alleviate the ping-pong effect and to reduce handover
attempts, normally in hard handover, a hysteresis value is used, which means that handover
happens only when the target cell is better than the serving cell by a hysteresis [Mur91]. This
hysteresis parameter considered in our simulator is the typical value of 4dB.
### 4.2.4.4 Main simulation parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>System scenario</td>
<td>UTRA FDD Uplink</td>
</tr>
<tr>
<td>Environment</td>
<td>Vehicular</td>
</tr>
<tr>
<td>MS speed</td>
<td>120 km/h</td>
</tr>
<tr>
<td>Simulation area</td>
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</tr>
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<td>Measure interval</td>
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<td>Bandwidth</td>
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<td>Handover Scheme</td>
<td>Hard Handover</td>
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<td>Handover hysterisis parameter</td>
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</tr>
<tr>
<td>Power control interval</td>
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</tr>
<tr>
<td>MS maximum transmit power</td>
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</tr>
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<td>UTRA model</td>
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</tr>
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<tr>
<td>Shadowing Decorrelation length</td>
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<td>Background noise</td>
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<td>BS antenna gain</td>
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</tr>
<tr>
<td>Number of simulation steps</td>
<td>1000</td>
</tr>
</tbody>
</table>

*Table 4-2: System Level Simulator Parameters*
4.2.5 Results

Different simulations have been executed with different numbers of active users (load) distributed in the system for the uplink scenario. For each number of active users, the average probability of non-satisfied users is calculated for 1000 measurements/step. If the received SIR of a user is below the SIR target for a certain number of steps, the user is assumed to be unsatisfied.

Figure 4.3 shows the probability of non-satisfied users calculated for the central cell for the number of active users varying from 30 to 65. We can see the probability of non-satisfied users increase as the number of voice users per cell increases. When the numbers of users increases, the level of interference in the system raises and hence more users have difficulties to reach their SIR target, leading to more unsatisfied users. For a probability of 2% of non-satisfied users, on average 46 voice users can be supported per cell.

![Graph showing the probability of non-satisfied users vs. voice users/cell](image)

Figure 4.3 Non-satisfied users vs. voice users/cell

In the relaying model (studied in the chapters 5-7), two carrier frequencies have been used for the different links. Therefore for fair comparison, two carriers frequencies are also simulated in the model without relaying. In the conventional cellular network with two carrier frequencies employed, some users transmit on one carrier frequency (F1) and others users transmit on the second carrier frequency (F2). It is assumed that the users transmitting in F1 do not interfere with
users transmitting in F2. Therefore a simulation has been run with the same number of users transmitting in F1 and F2. It is obvious that the capacity of the system with two carrier frequencies employed should be twice the capacity of the system with one carrier frequency.

Figure 4.4 shows the comparison of the probability of non-satisfied user for the two systems (with one carrier and two carriers frequencies). Since the number of carrier frequencies used are different, the results are shown for the number of voice users per hertz per cell. We can observe that the two systems obtain almost the same result: for a probability of non-satisfied user equal to 2% the number of voice users per hertz per cell for the system with one carrier frequency and two carriers frequencies used are $9.2 \times 10^{-6}$ and $9.6 \times 10^{-6}$ respectively.

Simulations have been run for 45 active users per cell (which correspond to 2% of non-satisfied users) and the distance, the path loss, the shadowing and the total path loss between MS and their serving BS for the central cell have been stored and shown in the following figures.

Figure 4.5 shows the Cumulative distribution function (CDF) of the distance between the mobiles in outage (MO) and the mobiles not in outage (Mobile Intermediate, MI) from the BS. The MOs represent the MS that cannot achieve the SIR target and therefore cannot reach the BS. It is observed that most of the MOs are located further away from the BS than the MI. 75% of the
MOs are 1500m further away from the BS while 75% of the MIIs are not further away than 1500m from the BS. This proves that most of the MS that cannot reach the BS are located at the edge of the cell.

Figures 4.6 (a) and (b) illustrate the path loss and the shadowing of the MO and the MI with the BS.

In Figure 4.6 (a), we observe that over 90% of the MOs have a path loss above 130 dB while only 50% of the MIIs have a path loss above 130 dB with the BS. The MS which are located at the cell’s edge experience a greater path loss and therefore they have more difficulties to reach the BS, resulting in an outage state. In Figure 4.6 (b), we can see that 90% of the MOs experience a shadowing above 0 dB with the BS whilst only 30% of the MIIs have a shadowing above 0 dB. We can observe on average 10 dB difference between the MO’s curve and the MI’s curve.

These plots show that most of the MOs experience a large path loss and a strong shadowing with the BS.

![Figure 4.5 CDF of distance MS-BS](image-url)
Figures 4.7 (a) and (b) demonstrate the Probability Density Function (PDF) and CDF of the total Path loss between the MO and the MIs with the BS. The total path loss considers the path loss and the shadowing. It is obvious from Figure 4.7 (a) that most of the MOs have a total path loss above 137 dB whilst most of the MIs experience a total path loss less than 137 dB.

In Figure 4.7 (b), the total path loss difference between the MOS and the MIs is even more obvious.

Although almost all the MI have a total path loss less than 137 dB only 10% of the MOs have a total path loss below 137 dB. A difference of 10 to 20 dB is noticed between the MO and the MIs.
These results demonstrate that most of the MSs experiencing outage are located at the edge of the cell. However, some of the MOs that are not at the cell’s border experience a strong shadowing effect.

### 4.3 Two Dimensional Autocorrelation Shadowing Model

Shadowing or slow fading is an important propagation element, when considering system-level simulations in a mobile communication system. It has been shown that the shadowing in dB follows Gaussian distribution with zero mean [Sau99]. Shadowing exhibits two correlation properties, namely the auto-correlation between components upon radio links connecting two mobile locations and one base station (BS), and the cross-correlation between components upon links involving two BS and one mobile location.

Currently, shadowing auto-correlation (SAC) is modelled in one-dimension i.e. for a specific mobile user, the \( k \) th shadowing component from BS \( i \), \( x_{i,k} \), is derived as:

\[
x_{i,k} = \gamma \cdot x_{i,k-1} + \sqrt{1 - \gamma^2} \cdot \xi_{i,k}
\]

(4.15)

where \( \gamma \) denotes the SAC between two shadowing components. \( \xi_{i,k} \) represents an independent and identical Gaussian variable against the shadowing. The SAC can be accurately modelled by a function \( \gamma = \exp(-d / X_c) \) [Gud91], where \( d \) and \( X_c \) represent the distance between two shadowing components and the de-correlation distance, respectively.
This traditional method, however, is not accurate enough for the simulations. If a user moves to the same location twice, it should experience the same shadowing component from a specific BS. However, this cannot be achieved using this method. Moreover, two users near to each other should have correlated shadowing components, which this method is unable to realise.

We propose a method of generating two-dimensional shadowing for dynamic system-level simulations. The generated shadowing satisfies the two-dimensional SAC. Furthermore, the shadowing cross-correlation (SCC) between components from different BS can be accurately modelled.

4.3.1 Proposed Method

In order to generate two-dimensional shadowing components, the simulation area has to be considered as a whole. Each location of the simulation area is assigned a shadowing component and the total components have to satisfy the two-dimensional SAC. The easiest way to achieve this is to divide the simulation area into parts (bins) of an elementary grid, which are small enough to achieve the assumption that the area of the bin shares a single shadowing component. As long as a user moves into a bin, a specific shadowing component is assigned to him. In Figure 4.8(a), the rectangular simulation area, which covers three BS is divided into $K = MN$ small square bins, where $M$ and $N$ represent the numbers of rows and columns, respectively. Each bin has a length of $D$, which is calculated so that the distance between extremities of the bin is less than the de-correlation distance, i.e. $\sqrt{2D} < X_c$. In such a grid, the bin located at the row and the column can be indicated as bin $(k)$, where $k = iN + j$. It is obvious that in a multiple BS simulation scenario, each BS will need one unique shadowing grid generated from the same divided area. The shadowing grid for BS $l$ can be referred to as $X_l = [X_l^{(1)} X_l^{(2)} ... X_l^{(K-1)} X_l^{(K)}]$, where $X_i^{(k)}$ indicates the shadowing component assigned to bin $(k)$. Note that the SAC between bin $(i)$ and $(j)$ within a shadowing grid is only determined by the distance between them and is indicated as $\gamma_{ij}$.

This method is able to generate the correlation between the shadowing components $X_1^{(k)}$ and $X_2^{(k)}$ of bin $(k)$ for BS 1 and 2, respectively, which represents the SCC (see Figure 4.8(a)). At the same time, the correlation between the shadowing components of two different bins from the same BS (e.g. $X_1^{(k)}$ and $X_1^{(h)}$ in Figure 4.8(a)) can be implemented, which is the SAC.
4.3.1.1 Generation of auto-correlation

The linear regressive method can be used to generate a new random variable given a limited number of known random variables and the correlation amongst them. Assume we have H Gaussian variables $S = [S_1, S_2, ..., S_{H-1}, S_H]$, defined as the deciding set and all having zero mean and variance $\sigma^2$. The normalised correlation coefficient of these H variables can be represented by a symmetric matrix $M = (r_{ij})_{i \leq H, i \leq H}$, where $r_{ij}$ denotes the correlation coefficient between $S_i$ and $S_j$.

A new Gaussian variable $x$ therefore can be generated by these H variables. The $x$ should have zero mean and variance $\sigma^2$ and satisfy the correlation vector $R$ with existing H variables. $R$ can be defined as,

$$R = \begin{bmatrix} r_{0,1} \\
r_{0,2} \\ 
\vdots \\
r_{0,H} \end{bmatrix}$$

where $r_{0,i}$ represents the correlation coefficient between $x$ and $S_i$ with $1 \leq i \leq H$.

The $x$ then can be generated by,

$$x = \sum_{i=1}^{H} a_i S_i + by = S A + by$$

where $A = [a_1, a_2, ..., a_H]^T$ denotes a coefficients vector, $b$ represents another coefficient and $y$ is a Gaussian variable independent and identical against $S$.

The following two conditions are used to solve $A$ and $b$,

$$R = \frac{E[S^T x]}{\sigma^2} = \frac{E[S^T (SA + by)]}{\sigma^2} = \frac{E[S^T S]}{\sigma^2} A = MA$$

$$1 = \frac{E[x^T x]}{\sigma^2} = \frac{E[(SA + by)^T (SA + by)]}{\sigma^2} = A^T MA + b^2 = A^T R + b^2$$

Therefore, we have $A = M^{-1} R$ and $b = \sqrt{1 - A^T R}$.

This proves that if the shadowing components of different bins surrounding a to-be-assigned bin and the distance ($d$) among them are known, a correlated shadowing component $x$ for that bin can be generated.

When this method is applied to generate a shadowing grid for a specific BS e.g. 1, to avoid time-consuming calculations, we assume that beyond a certain distance, which is chosen as two-times
the de-correlation distance \((2X_c)\), the shadowing components are uncorrelated. Therefore, as shown in Figure 4.8 (b), any unknown shadowing component can be decided by a maximum of 24 known components around it. The correlation coefficients between them have 5 possible values \(r_j\) to \(r_5\) as shown in the figure.

![Diagram](image)

**Figure 4.8 Explanation of the proposed method**

In the initial state, the first shadowing component can be assigned to any bin, e.g. \(X_1^{(1)}\) for bin (1), by a random Gaussian variable. Then the other components will be generated row by row, based on the already generated components. Each bin’s correlation coefficients are calculated with all the bins already generated and within the range \(2X_c\).

For instance, \(X_1^{(2)}\) is generated by \(X_1^{(1)}\) only. In this case, \(S = [X_1^{(1)}]\), \(M = [1]\), and \(R = [r_j]\). It gives \(A = [r_j]\) and \(b = \sqrt{1-r_j^2}\). The \(X_1^{(3)}\) will be generated by \(S = [X_1^{(1)} X_1^{(2)}]\). Now \(M = \begin{bmatrix} 1 & r_2 \\ r_1 & 1 \end{bmatrix}\) and \(R = \begin{bmatrix} r_2 \\ r_1 \end{bmatrix}\), which gives \(A = \begin{bmatrix} 0 \\ r \end{bmatrix}\) and \(b = \sqrt{1-r^2}\). The same process is repeated for all other bins until the whole shadowing grid for this BS is completed. Figure 4.9 depicts the two-dimensional SAC property of generated shadowing samples between the central bin and its surrounding bins in a grid of 25x25 bins, where \(X_c = 20\) m, \(D = 14\) m and \(\sigma = 8\) dB.

The same process has to be repeated for all BS in order to create different shadowing grids for
them in the simulation. Furthermore, these different shadowing grids need to be correlated and this is performed by the following cross-correlation process.

![Two-dimensional SAC property from the proposed method](image)

**Figure 4.9 Two-dimensional SAC property from the proposed method**

### 4.3.1.2 Generation of cross-correlation

1) Constant SCC generation

Assume there are \( L \) BS existing in the simulation area. Then, \( L+1 \) two-dimensional shadowing grids \( X_0 \) to \( X_L \) need to be generated. Among them, the first grid \( X_0 \) is a reference. The \( L \) cross-correlated shadowing grids \( Y_1 \) to \( Y_L \) therefore can be generated by,

\[
Y_i = a X_0 + \sqrt{1-a^2} X_i; \quad 1 \leq i \leq L, \text{ and } 0 \leq a \leq 1
\]  

(4.20)

Therefore, for bin \((k)\) of any pair of BS \(i\) and \(j\), we have,

\[
SCC = \frac{E[Y_i^{(k)}Y_j^{(k)}]}{\sigma^2} = a^2
\]

(4.21)

where \( a^2 \) indicates the SCC between any two BS. Furthermore, the SAC of the new shadowing grid \( Y_i \) is maintained:
Practical SCC can be generated by the method proposed in [Yan03]. This method, however, distorts the original SAC property. It has been verified in [Yan03] that the accuracy of SAC is higher than 95% against the original SAC in a 19 BS scenario.

4.3.2 Complexity Reduction

When the simulation area is large, the total number of bins can be very high, especially if the decorrelation length is chosen to be small. In these cases, it might take a long time to calculate the shadowing for K bins and require a huge storage space. To tackle this problem, it is possible to generate only one quarter of the whole grid and then use the symmetry (like a mirror) to assign the correlated shadowing to the three quarter remaining. As demonstrated in Figure 4.10, the shadowing components in shaded bins are derived by the proposed method whereas the components in other bins are simply copied, following the rule that the bins having the same row and column index will be allocated the same shadowing component.

\[
SAC = \frac{E[Y_i^{(h)}]}{\sigma^2} = a^2 \frac{E[X_0^{(h)}]}{\sigma^2} + (1-a^2) \frac{E[X_i^{(h)}]}{\sigma^2}
\]

\[= a^2 \gamma_{k,h} + (1-a^2) \gamma_{k,h} = \gamma_{k,h} \quad (4.22)\]
4.3.3 Summary

In this section, a method of generating two-dimensional shadowing is explained in this section. With this model, a more accurate correlated shadowing process can be modelled for dynamic system-level simulators. Furthermore, a method to reduce the computational complexity and storage requirement is proposed in order to be able to use this method in a large simulation area.

This two dimensional auto-correlation model has been used at the first stage for the non relaying model and the relaying model. Although, the simulation time of the simulator without relaying is slowed down because of the computation of the two dimensional auto-correlation model, it is still possible to get results. However, the proposed shadowing model could not be tested in the simulator with relaying due to its long simulation time. In the relaying model, the computation for the elements involved in the link MS-MS and the fact that two carrier frequencies are used, slow down considerably the simulation time. Therefore for fair comparison, the two dimensional shadowing model has not been simulated in both models.

4.4 Conclusion

This chapter includes two main sections. The first section describes in detail the dynamic system level simulator used to assess the capacity of the conventional UMTS cellular network. This model is used as a base and reference to model and test the capacity of the UMTS cellular network with relaying integrated (discussed in the next chapter). Each entity of the radio resource management such as power control, handover, interference management have been explained in detail. Furthermore, a link budget has been calculated in order to find the exact radius of the cells regarding the different parameters used in the simulator. The simulator has been run for different number of active users per cell in a system area of 19 cells with radius of 2000m. We have evaluated that 46 voice users can be supported in a cell for a probability of non-satisfied users of 2%. The results showed that most of the MS that cannot reach the BS experience a strong shadowing or/and a great path loss with the BS. These users are usually located at the cell’s edge.

In the second section of this chapter, a new method of generating a two-dimensional shadowing component to be used in dynamic system level simulator is proposed. With this two-dimensional model, the shadowing component of multiple user located next to each other are correlated.
Chapter 5

5 Capacity Optimisation of UMTS Cellular Network with Mobile Relay Station

5.1 Introduction

In this chapter, the UMTS cellular network with integrated relaying is described. In this new architecture, the users' mobile stations (MS) work cooperatively with each other in relaying traffic to a central point base station (BS). The main objective of this chapter is to demonstrate achievable capacity gains under various relaying criteria compared with no-hopping (conventional) cellular architecture.

In the last few years, the capacity gain that relaying might bring to the conventional cellular network has been studied. Most of the works have shown that the capacity of the cellular network could be improved with relaying, [Pab04]-[Vid02]-[Her03]-[Jin04]-[Zad01]-[Cho03]-[Daw03]-[Yam02a]. However, few papers have succeeded to properly quantify the capacity gain of cellular networks with relaying. [Men01],[Men03] have shown that the communication distance between mobile terminal and the BS is reduced by using other mobile terminals as intermediate relays and hence mobile terminals can send their traffic at a maximum data rate while maintaining a target packet error rate and transmission power limit. They have shown that the capacity of the TDMA cellular network is improved by 30-40% with relaying via mobile relay stations. [Muk03] studied the optimal time-allocation strategies for a UMTS TDD cellular architecture with relays that can store and forward information between mobile terminals and the BS. The results produced through analysis showed that between 30%-50% capacity gains were achievable with the use of relays in the conventional cellular network. [Wei04] proposed a novel integrated 3G/WLAN two-hop-relay architecture that enhances the capacity of the cellular network. A mobile terminal with a bad channel quality in the direct link is able to communicate with the BS through the relay nodes (via a two-hop communication). A relay node is a dual-mode terminal, using the WLAN radio interface for the link with the mobile terminal and communicating with 3G radio interface with the BS. The results showed that the capacity gain is dependent on the WLAN range of the relay node and the node density. Therefore the capacity of the cellular network is enhanced by 15%-45% with a two-hop relay communication in the uplink scenario. [Rou02], [Rou05] proposes
congestion based routing strategies in multihop TDD-CDMA networks in order to minimize the overall power of the system. When combined with the congestion-based routing, a capacity of up to 44% over a conventional star topology is shown when peer-to-peer communication is involved. However, most of the works have considered a time division channel for the two hop communication link. On the other hand, there are only few works reported on the capacity gain for a UMTS FDD-mode based cellular network with relaying. [Bron01] has shown how the capacity of a single hop relay network can be increased by reducing the interference in UMTS cellular network. They investigated the achievable average transmit power reduction and capacity gain that results from using mobiles as relay stations for other terminals. Their results show that the use of single hop relay in a mobile network provides an increase in achievable capacity gain of around 20% for uplink transmission in UMTS cellular network. However, the simulation model proposed for relaying is a simplified model in order to quantify approximately the capacity gain of a cellular network with relaying. [Fuj02], [Yam03], [Bad04] have also studied the performance of UMTS cellular networks with relaying through other mobile terminals. Their results indicate that the capacity per base station of UMTS cellular system with relaying can be increased by 10%. However, the algorithms, they propose for deciding when a MS should be relayed and which MS should be used as a relay station, are not optimal. Therefore the interference in the system is not significantly decreased due to the inter-hop interference and hence the maximum capacity gain is not achieved in their model.

It is clear from the above discussions that multihop architecture is a promising approach to the capacity and coverage improvement of a cellular network [Pab04]. However, there are many issues that still need to be investigated. The first challenge is to properly qualify and quantify such enhancements for both capacity and coverage, and if there is improvement, what is the expected capacity gain? [Yan02]. This chapter focuses only on the capacity gains and the criteria to achieve them.

However there are many important issues in a relaying system which have remained unanswered such as; when should a MS be relayed and what criteria should be used in selecting a relaying node. Do all MSs need to be relayed or only the ones that are far away from the BS? These are some of the questions, which this chapter aims to provide answers to. When a MS needs to be relayed, it must choose a suitable mobile relay station amongst many possible candidates. Not choosing the optimal relaying/relayed node can have great impact on the overall system capacity. Therefore different relaying MS selection schemes are proposed and evaluated in order to find the best performance.

The system proposed here is based on a two-hop relay cellular network. In this work, the relay
stations are the mobile stations, which are in idle state. The advantage of using MS as a relay is due to accessibility of a greater number available MSs in a system comparison with fixed relay stations, offering a MS more chance to choose an appropriate MS for relaying. With fixed relay stations, the users far away may have difficulties to reach the fixed relay station. However, some would argue that using MSs as relays would impede the battery life-time of the MS. This is an unqualified statement. We believe in such a cooperative scenario all the MSs would benefit from relaying due to savings made in the required transmission powers in reaching a BS compared with non-relaying cases. One could consider a scenario where only high power terminals such as car-mounted ones or even taxis could be used as relaying stations, particularly in capacity limited environments such as urban areas and city centers where these are characterized as environments with high user-densities and potentially with more taxis.

For evaluation of capacity gains the UMTS FDD/TDD modes were used for the two hops. With the current technology, wireless terminals cannot transmit and receive simultaneously at the same carrier frequency [Nou04]. Therefore two carrier frequencies are used for the uplink scenario. One carrier (F1) is used for the link between MS-BS and another carrier (F2) is used for the link between MS-MS in uplink. Since two carrier frequencies are used in the system model with relaying, in order to make a fair comparison of capacities, two carrier frequencies are also considered in the system model for the non-relay case.

The system model proposed is explained in more details in section 5.2. Section 5.3 describes and evaluates the different schemes proposed for when a MS should be relayed. Section 5.4 define and assess the different mobile relay station selection algorithms proposed. Section 5.5 presents the system model with different carrier frequency usages/patterns for the relaying channel and conclusions are drawn in sections 5.6.

5.2 Two-hop model based cellular network

5.2.1 System description

This section describes in detail the cellular network with relaying architecture proposed. We evaluate the performance of a two-hop based cellular network for UMTS as most of the work done in the literature review on relaying is of this type, it has also been adopted here in. Limiting the number of hops to two offers several benefits such as: reduces the system complexity, avoids inefficient mobile ad hoc routing, and reduces the impact of inefficient random access protocols compared with greater than two-hop architecture and limits the transmission delay [Wei04]. Furthermore the effect of multihop relaying on the throughput of the downstream channel using
Chapter 5 Capacity Optimisation of UMTS cellular network with Mobile Relay Station

TDD-mode was studied in [Cho03]. The results showed that the throughput gain with more than 3 hops is not significant. The best performance is obtained with 2 or 3 hops at most. Therefore for simplicity, we evaluate the capacity gain of a two-hop cellular network.

In order to assess the capacity gain that can be achieved with relaying, two cellular networks are modelled: one without relaying (conventional cellular system) and one with relaying for the uplink scenario. The non-relaying model is explained in detail in chapter 4. In this section, we give more attention to the description of the relaying model.

As in the non-relaying model, a fixed number of users are uniformly distributed over the whole system. Some users are considered active, which means they transmit information on the data channel whilst the rest are considered to be in an idle state (non-active users). At the beginning of the simulation, the same number of active and non-active users are distributed in each cell. All the users follow the same mobility model as the one used for the non-relaying case. At each location, the total path loss (including path loss and shadowing) between all the users and all the BSs are calculated. After the handover mechanism, the active users select the BS with the strongest pilot signal as the serving BS and the non-active users are assigned to the closest BS. For fair comparison, the same handover model is applied for the non-relay and relay case. Once all the users know in which cell they belong, some active users might require relaying assistance to communicate with their BS (explained in section 5.3). After calculating the total path loss between all the active users and non-active users in the same cell, the active users that need to relay select a user from a pool of users in idle state based on some specific criteria (as explained in section 5.4). Then the relayed users are able to transmit their data to the BS with a two-hop communication via another non-active user terminal. Figure 5.1 (a) and (b) depict the scenario of the simulation model. Figure 5.1 (a) shows the active and non-active MSs in a non-relaying model. In the system with relaying (Figure 5.1 (b)), different MS states can be defined [ETSI97] as:

- **MO** (Mobile Originator): MS relayed,
- **MI** (Mobile Intermediate): MS non-relayed,
- **MS non-active** (idle state): MS not sending data to the BS but they are potential Relay Station
- **MRS**: Mobile Relay Station
In this model, one MRS can relay only one MO at a time. Therefore, if two MOs need to be relayed via the same MS, the priority will be given to the one with the worst link quality with the BS. However, there are enough non-active MS in each cell that all the MO's can find a MRS. Also, the MOs relay their signal to the same BS they were connected to in the direct link and not to another cell (intracell relaying). Therefore, they have to select a non-active MS connected to the same BS. Once the MO has selected the MRS, they transmit their data to their MRS and these MRS forward the data to the respective BS. It is worth noting that when the non-active user becomes MRS, it will be considered as an active one and hence contributes towards the overall interference in the system. A perfect power control is implemented in the system in order to control the power of the MRS, the MIs and the MO to combat the near-far effect. The goal of the power control is to balance the SIR of the link MO-MRS, MRS-BS and MI-BS around the SIR target. After the power control algorithm the SIR of the three different links are calculated. The MIs are considered in outage if their SIR with the BS is below the SIR target whilst the MOs are considered in outage if at least one of the two hops experiences a SIR below the SIR target (either the SIR MO-MRS or the SIR MRS-BS). Therefore the number of MS in outage in the relaying system can be calculated for the particular MS's location. Then the MS moves to another location following the mobility model and the same process is repeated. One step represents one location for all users. The simulation is run for several steps and the number of users in outage found for all the steps can be calculated and averaged at the end of the simulation.
5.2.2 SIR calculation

In order to evaluate if a MS is in outage, the SIR of all the active users needs to be calculated. The formulae to estimate the SIR of the active users transmitting directly to the BS have been defined in chapter 4. In this section, we concentrate on the SIR calculation of the links MO-MRS and MRS-BS. The SIR calculation is dependent on the interference model and therefore on the carrier frequencies used in the system. In this relaying system, two different carrier frequencies (F1/F2) are used for the different hops. In the proposed model here in, the MS transmitting directly to the BS (i.e. MI and MRS) uses carrier frequency (F1). While the MOs use carrier frequency (F2) to transmit to the MRSs. The carriers' frequency assignment and interference model for this scenario is represented in Figure 5.2. Note that different carrier frequency assignment schemes have been proposed and evaluated in section 5.5 and therefore different interference models should be considered. Since the MI and the MRS in all cells interfere with each other (use the same carrier frequency F1), their SIR can be expressed via the same formulae. If \( G \) denotes the channel gain between the user \( u \) and the BS \( i \) and \( P \) denotes the user's transmit power the average received SIR of user \( u \) (either MI or MRS) can be expressed as:

\[
SIR_u^i = \frac{G_u^i P_u^i}{I_{MI}^i + I_{MRS}^i + I_{intercell}^i + n_s}
\]

where \( I_{MI}^i \) and \( I_{MRS}^i \) represent the intracell interference at BS \( i \) from the MIs and MRS in the same cell, respectively whilst \( I_{intercell}^i \) represents the intercell interference received at the BS \( i \) from MIs and MRS in other cells and \( n_s \) represents the noise power. The intercell interference can be expressed by \( I_{intercell}^i = \sum_{m=1}^{M} \sum_{k=1}^{N^m} G_{ik} P_k \), where \( N^m \) is the number of MI and MRS that are served by the BS \( m \), and \( M \) is the number of cells in the system. Since all the MOs transmit to their MRS with carrier frequency (F2), they interfere with each other. If the MO \( u \) sends its signal to its serving MRS \( r \) within the cell of the BS \( i \), its SIR can be expressed as:

\[
SIR_{r,u}^i = \frac{G_{ru}^i P_{ru}^i}{I_{r,MO}^i + I_{r,intercell}^i + n_s}
\]

where \( I_{r,MO}^i \) and \( I_{r,intercell}^i \) represent the interference received at the MRS \( r \) from the MOs in the same cell and in other cells, respectively.
5.2.3 Environment model

The different relaying models proposed are tested through the same simulation environment model. Cell planning is an important issue when relaying needs to be implemented in cellular networks. The overlap area between neighboring cells should be kept to a minimum so that the system experiences minimum interference. Therefore a link budget for the vehicular environment, as in [Lai02], is performed in order to find the most accurate value for the radius of the cell. The system modeled includes 19 hexagonal cells of radius 2000m, with a BS at the center of the cells employing an omni directional antenna. Since with relaying it is possible to decrease the intercell interference, it is necessary to model at least two tier cells (19 cells) and that relaying should be
performed in all the cells. At the beginning of the simulation, 300 users (including actives and non-active users) are uniformly distributed in each cell. The MSs follow the mobility and the propagation model as proposed in [ETSI98] for the vehicular environment. In the propagation model, the path loss and the shadowing are considered for the link MS-BS but also for the MS-MRS link. For the communication between the MS and the BS, the same path loss model as in the non-relaying system is used. There are no appropriate path loss models that describe the channel between MSs since a mobile terminal is usually positioned close to the head. Due to the lack of an appropriate path loss model for low height terminals, we use the same path loss model between MS-BS and MS-MRS. An auto-correlated shadowing model is considered between the MS and the BS [ETSI98]. But due to a large number of MS in the system, it is difficult to keep track of the correlation between them. Therefore, we use a statistical shadowing model between MSs without considering the correlation. The same standard deviation shadowing is used between MS-BS and MS-MRS. For simplicity reasons, the fast fading is not performed between MSs. The uplink scenario with the same fixed transmission rate and therefore the same Eb/No target is applied to all the active users (MO, MRS and MI). The MRSs are assumed to have the same maximum transmit power as the MO and the MI (i.e. 21dBm). The model is simulated at system level and the simulations are run for 1000 step. The simulation result is based on the percentage of non-satisfied users. A user is considered non-satisfied if its SIR is not above or equal to the SIR target - 0.5 dB for a certain period of time (the period chosen is 5 consecutive seconds [ETSI98]). At the end of the simulation, the numbers of non-satisfied users were calculated with and without relaying for the central cell and compared.

5.3 When should a MS be relayed?

In a system with relaying, the most important issue to be decided is when a MS needs to relay and when it needs to release the MRS, see Figure 5.3. Therefore, we proposed three different algorithms. Each algorithm is based on a different criterion: The first one is based on the position of the MS, a second one is based on the transmit power of the direct link (MS-BS) and the third one is based on the received SIR of the direct link.
5.3.1 MS-BS Distance criteria

Selection of MOs based on their distance to a BS is simple. The MS at the boundaries of a cell are at the furthest points from a BS, therefore they experience a large path loss with their BS. With relaying, the furthest MS needs less power to reach a closer MRS than the BS, therefore leading to a decreased interference. Therefore only the MS located in the overlap area between two adjacent cells are relayed:

\[
\text{if } \begin{cases} 
  d_{u, BS_j} > d_{\text{overlap}}, & \text{Relay} \\
  d_{u, BS_j} < d_{\text{overlap}}, & \text{Release}
\end{cases}
\]  

(5.3)

Here, \(d_{u, BS_j}\) is the distance between MS\(_u\) and the pertinent BS\(_j\). \(d_{\text{overlap}}\) is defined to decide which MS should be relayed or should stop relaying.

5.3.2 Transmit power criteria

In this scenario, we only allow those MSs to relay that transmit with a high power level in reaching a BS. With this process, the total average transmit power in the system should be decreased and therefore also the overall interference. The decision to establish or release the relaying links depends on the transmit power used in the direct link. In order to evaluate this transmit power, two scenarios were considered. If the MS uses direct transmission in the previous step, we can make use of the direct transmit power to make the decision to establish a relaying link or not. If it was relaying in the previous step, we can estimate the transmit power, as shown in
(5.4), needed to reach the BS in the direct link in order to make the decision to release the MRS or not.

\[ P_{\text{Estimate},\text{direct}} = \frac{SIR_{\text{target}} \cdot (n_s + I_{n,BS_i})}{G_{n,BS_i}} \]  

(5.4)

Where \( SIR_{\text{target}} \) is the SIR target for \( MS_u \); it is assumed that all the MSs have the same SIR target. \( n_s \) represents the noise power; \( I_{n,BS_i} \) is the total interference encountered at \( BS_i \); \( G_{n,BS_i} \) is the path-gain between \( MS_u \) and \( BS_i \). The decision to establish or release the relaying links depends on the transmit power of the direct link (measured or estimated).

\[
\begin{align*}
\text{if} & \quad P_{u,\text{direct}} > P_{th} \quad \Rightarrow \text{Relay} \\
& \quad P_{\text{Estimate},\text{direct}} < P_{th} - P_{\text{hysteresis}} \quad \Rightarrow \text{Release}
\end{align*}
\]

(5.5)

\( P_{th} \) is a power threshold defined to determine which users should be relayed; \( P_{\text{hysteresis}} \) is a hysteresis defined to avoid frequent establishments and releases of MRS. \( P_{th} \) is below or equal to the maximum transmit power of a MS.

### 5.3.3 SIR criteria

In this criteria, in order to save on MS’s being in outage (i.e. the MS with a SIR below the SIR target), the decision to establish or release the relaying links depends on the SIR used on the direct link. If the MS uses direct transmission in the previous step, we can make use of the SIR received at the BS to make the decision to relay or not. If it was relaying in the previous step, we can estimate the SIR based on the link information of the direct link, as shown in (5.6), to make the decision to release the MS or not.

\[ SIR_{\text{Estimate},\text{direct}} = \frac{P_{\text{max}} \cdot G_{n,BS_i}}{n_s + I_{n,BS_i}} \]  

(5.6)

Where \( P_{\text{max}} \) is the maximum transmitting power of each MS.

The decision to establish or release the relaying links is dependent on the SIR of the direct link (measured or estimated):

\[
\begin{align*}
\text{if} & \quad SIR_{u,\text{direct}} < SIR_{th} \Rightarrow \text{Relay} \\
& \quad SIR_{\text{Estimate},\text{direct}} > SIR_{th} \Rightarrow \text{Release}
\end{align*}
\]

(5.7)

\( SIR_{th} \) is a SIR threshold defined to make an appropriate decision, \( SIR_{th} \) is below or equal the \( SIR_{\text{target}} \).
5.3.4 Results

Different simulation runs have been carried out in order to ascertain the predefined distance ($d_{\text{overlap}}$), transmit power threshold ($P_{th}$) and SIR reference or threshold ($SIR_{th}$). The results are shown with the best-predefined value for each algorithm. Figure 5.4 shows that the best performance is obtained when relaying is carried out for all the MS with a SIR less than the SIR target. The distance is not an efficient parameter, since it might relay some users with a good link quality with the BS and not relay some closer users with a bad link quality, for example due to a strong shadow effect. Although the criteria distance considers the path loss between MO and BS, it does not take into account the shadowing and the interference in the system. Furthermore it is important to notice that some further MS are able to reach the BS in a direct communication but they might not be able to reach a MRS (due to a strong shadowing effect or due to a non-appropriate MRS selected). Therefore, they will use their maximum power and create a lot of intercell interference since they are located at the borders of the cells. The algorithm based on transmit power and SIR yield almost similar results, since the SIR and the transmit power of a user are related. If a MS has a SIR below the SIR target, it usually transmits with the maximum power. The results show that relaying only the MS that cannot reach the BS has the best performance. Therefore, whenever a MS experiences a SIR below the SIR target, it should use relaying to transmit its data to the BS. This will decrease its maximum transmit power and therefore reduce the intercell interference and increase the system capacity. Furthermore, the MS that cannot reach the BS because they are obstructed by buildings or trees or because they are far away from their BS can be served with relaying, which also increase the system capacity.
5.4 MRS selection schemes

When the decision is made to relay a MS, the MOs have to choose a MS from a pool of non-active MSs, see Figure 5.5. This is an important issue in a relaying system, since not choosing the most suitable relay node might have considerable impact on the system performance. Therefore, we propose and evaluate four algorithms to select the Mobile Relay Station. The first one is to select a MS that can provide the minimum path loss for the two hops ($\min\{PL_1 + PL_2\}$), the second one is to select the MS with the minimum total transmit power for the two hops ($\min\{P_1 + P_3\}$), the third one is based on the maximum-total SIR ($\max\{SIR_1 + SIR_2\}$), and the final one is to choose the MS that can give the maximum-minimum SIR ($\max\{\min\{SIR_1, SIR_2\}\}$).

![Figure 5.5 MRS selection](image)

5.4.1 Minimum total path loss criteria

For MRS selection based on minimum total path-loss, the total path-loss of the two hops is considered as the metric to make the decision. The total path-loss with a non-active MS $m$ represents the sum of the path loss in each hop and can be written as

$$PL_{\text{total}} = PL_1^m + PL_2^m$$

(5.8)

Where $PL_1^m, PL_2^m$ represent the path loss for the first hop (MO-MS$m$) and the second hop (MS$m$-BS) respectively. Then the non-active MS that can provide the minimum total path-loss is selected as the serving MRS, i.e.

$$MRS_{\text{serving}} = \arg \min\{PL_{1,\text{total}}, PL_{2,\text{total}}, \ldots, PL_{N_{\text{set}},\text{total}}\}$$

(5.9)

$N_{\text{set}}$ represents the number of non-active MS in each cell.
5.4.2 Minimum total Transmit Power Criteria

In order to use the minimum possible transmit power in the relaying link, the chosen metric is total transmit power. Based on the link information (path-loss and interference) and the assumption of ideal power control, the transmit power of each hop can be estimated as:

\[ P_{MS}^n = \frac{SIR_{target} \cdot (n_x + I_{RS_n})}{G_{n,RS_n}}, \]
\[ P_{RS_m} = \frac{SIR_{target} \cdot (n_x + I_{RS_m})}{G_{RS_m,BS_i}}, \]  
(5.10)

where \( P_{MS}^n \) is the transmit power of the MS to the non-active MS \( m \), \( P_{RS_m} \) is the transmit power of the RS \( m \) (potential Relay Station), \( I_{RS_m} \) and \( I_{BS_i} \) are the interference encountered by \( RS_m \) and \( BS_i \), respectively, \( G_{n,RS_m} \) and \( G_{RS_m,BS_i} \) are the channel gain between MS \( n \) - RS \( m \) and RS \( m \) - BS \( i \), respectively. A non-active MS chosen as a relay station is the one, which has the minimum total transmit power in the two hops.

5.4.3 Maximum total SIR Criteria

For MRS selection based on the maximum total SIR criteria, the SIR of the two hops needs to be calculated. The SIR of the two hops can be defined as:

\[ SIR_1^m = \frac{P_{max} \cdot G_{n,RS_m}}{n_x + I_{RS_m}}, \]
\[ SIR_2^m = \frac{P_{max} \cdot G_{RS_m,BS_i}}{n_x + I_{BS_i}}, \]  
(5.11)

where \( SIR_1^m \) is the SIR for the first hop, i.e. MO-RS \( m \), \( SIR_2^m \) is the SIR for the second hop, i.e. RS \( m \)-BS and \( P_{max} \) denotes the maximum transmit power of each MS. Based on the digital relaying assumption (decode and forward relay), the total SIR of the relaying link for \( RS_m \) can be written as:

\[ SIR_{total}^m = SIR_1^m + SIR_2^m \]  
(5.12)

The non-active MS that can provide the maximum total SIR is selected as the serving MRS, i.e.

\[ RS_{serving} = \arg \max \{ SIR_1^{total}, SIR_2^{total}, \ldots, SIR_{N_{srs}}^{total} \} \]  
(5.13)

5.4.4 Maximum minimum SIR Criteria

As in the previous algorithm, the SIR for each hop is calculated using (5.11). Then the minimum SIR of the two hop links for a particular MS \( m \) can be written as:
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\[
SIR_{n} = \min \{ SIR_{1}^{n}, SIR_{2}^{n} \} 
\]

(5.14)

Then a non-active MS that can provide the maximum SIR will be selected as the serving RS, i.e.

\[
RS_{serving} = \arg \max J_{s/R, n} \right] \tag{5.15}
\]

\(N_{set}\) represents the number of non-active MS in each cell.

5.4.5 Results

Figure 5.6 shows the probability of non-satisfied users for different number of active users with the different MRS selection schemes. The best performance is obtained when the MRS scheme is based on the maximum total SIR. Conversely to the scheme based on total path loss and transmit power, the scheme based on SIR considers the path loss, the transmit power used but also the interference for each hop. Therefore it is expected that the MRS selected with the maximum total SIR along the two hops gives the best performance. When the MS requiring relaying assistance selects the non-active MS with whom it experiences the maximum SIR along the two hops, the level of interference is kept to its minimum and the system performance is optimal. It is worth noting that a particular non active MS experiences a very good propagation channel with the BS. Therefore, several MS might want to relay with the same MS. In this case, the priority is given to the MO with the greatest path loss in the direct link with the BS.

![Figure 5.6 MRS selection schemes](image-url)
5.5 Two-hop relay model with two different carrier frequencies

In a cellular network with relaying, another channel is needed for the communication between the MSs (i.e. MO-MRS link). Many works have considered the use of the TDMA air interface [Hu03], [Men01]. In TDMA cellular networks, different frequencies are assigned in each cell. Therefore, they suggest the reuse of the frequency channel from a further adjacent cell between the MS and its relay station. In other words, the MO transmits its data to a relay station in one cell with the frequency channel used in an adjacent cell. This is an interesting scheme since it does not need to assign a new frequency to the relaying channel (MO-MRS). Furthermore, reusing the channel from a distant adjacent cell avoids high interference between the two hops in the system. However, this scheme requires proper planning from the service provider. In other works, they propose to use the unlicensed band (such as WLAN) for the link between terminals (first hop) [Wu01], [Wei04], [Wal04]. This arrangement not only guarantees that no additional expensive cellular spectrum will be used to facilitate a two-hop link, but it also guarantees that if anything goes wrong in the first hop, this will not affect the performance of the terminals which directly communicate with the BS in the cellular band. However, using the unlicensed band allows any terminal to transmit at this frequency which creates interference for the link MO-MRS. Therefore, it is difficult for a service provider to estimate and control the level of interference in the system using the unlicensed band.

In this work, we consider a different approach. We use the UMTS FDD mode for all the MSs transmitting directly to the BS (i.e. MI-BS and MRS-BS). The MO can send their data to the MRS either in the FDD mode (with another carrier frequency) or in the TDD mode. These two models are described in this section.

5.5.1 Relaying in the UMTS FDD mode

5.5.1.1 With two carrier frequencies (scheme 1)

Since a MRS cannot transmit and receive at the same carrier frequency, two different carriers are needed in the relaying system. All the MO transmit their data to the MRS with frequency F2 while the MI and the MRS transmit their data to the BS with frequency F1, see Figure 5.7 (b). Since two carrier frequencies are used, in order to make a fair comparison, the model is compared with the non-relaying system also using two carriers, see Figure 5.7 (a). However in the latter case, the same number of MS should transmit in the frequency F1 and F2 resulting in two fully loaded carrier frequencies. While in the relaying scenario, the carrier frequency F2 is used only by the MO to transmit to the MRS and the frequency F1 is used by the MI and the MRS to transmit to the BS. Since the number of MO are less than the number of MI and MRS, the carrier
frequency F2 might not be fully loaded compared to the carrier frequency F1. This would result in a waste of resource. To avoid this problem, we propose another frequency scheme assignment, see below.

5.5.1.2 With two carrier frequencies fully loaded (scheme 2)

A new model is proposed in order to make a better comparison between the relaying and non-relaying cases using two fully loaded carriers in both systems. In this model, some MIs transmit directly to the BS either with frequency F1 or with frequency F2. While the MRSs still transmit to the BS with the frequency F1 and the MO with frequency F2 to the MRS, see Figure 5.7 (c). In this scenario, on average the same number of MSs should transmit on both carrier frequencies, F1 and F2.

5.5.1.3 Optimised model with two carrier frequencies fully loaded (scheme 3)

Another model, called the optimised model, is also proposed and evaluated. In this model, the MIs transmit either on frequency F1 or F2 but the MOs and the MRSs transmit in a different frequency according to the cell they belong to. In one cell, the MO transmit in F2 and the MRSs in F1 and in the adjacent cell the MOs transmit in F1 and the MRS in F2, see Figure 5.7 (d). Since most of the MOs are located at the edge of the cell, they create less interference to each other if they transmit on different carrier frequencies and more MO's can reach their MRS. This scheme should lead to a better capacity improvement.

For each scheme, different carriers frequencies are assigned to each MS. Only the users transmitting on the same carriers interfere with each other. Therefore the interference models are different in each scheme. In the following Table 5.1, a summary of the users transmitting in each carrier frequency for the different schemes is shown:

<table>
<thead>
<tr>
<th>Scheme 1</th>
<th>Scheme 2</th>
<th>Scheme 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>F2</td>
<td>F1</td>
</tr>
<tr>
<td>MI + MRS</td>
<td>MO</td>
<td>MI+MRS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MI+MO</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MI+MRS+MO</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MI+MRS+MO</td>
</tr>
</tbody>
</table>

Table 5.1 Interference Model for the different carrier frequency scheme
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(a) Without relaying

(b) With relaying with two carrier frequencies

(c) With relaying with two carrier frequencies fully loaded
MS non-relayed: F1 or F2
1st Hop MS-MS: F2 or F1
2nd Hop MS-BS: F1 or F2

(d) With relaying, optimised model with two carrier frequencies fully loaded

MS non-relayed: F1 or F2
1st Hop MS-MS: TDD
2nd Hop MS-BS: F1

(e) With relaying in the mode FDD/TDD

Figure 5.7 Different frequency planning for the relaying system

5.5.2 Relaying in UMTS TDD mode

Instead of transmitting in the FDD mode, another approach would be for the MOs to send their information to the MRSs in the TDD mode; see Figure 5.7 (e). The TDD mode offers some interesting features [ETSI97]. The utilization of TDD carrier frequencies is not fixed between uplink and downlink, unlike the case in FDD, and this flexibility in resource allocation can be utilized. Relaying information requires the use of radio resources such as timeslots and codes. In a conventional structure, the resources are used once per cell however in a multihop cellular network the resources can be used many times within the basic cell area. This is because transmissions are at lower power and so interference only has a localized effect. Also TDD is simpler than FDD, only a limited amount of additional features have to be added to a terminal in order to support relaying. Furthermore, asymmetric access (different bit rates can be used between
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Uplink and downlink) has the advantage of simplicity for relaying. In a multihop cellular network the relay might be done between close-by mobiles. Due to the relative short range of transmit power, the inclusion of relaying does not impose any additional guard period or frame synchronization requirements to those for standard TDD. Furthermore, with the TDD mode several time slots can be assigned for relaying purpose and the rest of the resource can be used for direct transmission. These features make the TDD mode a good candidate for the transmission mode between the MS and the MRS. The frame length of the TDD mode is divided into 15 timeslots. Each of the 15 timeslots is either allocated to either uplink or downlink [Hol00]. We assume that 7 time slots are allocated to uplink and 8 timeslots are allocated to downlink. For each time slot, a maximum of 16 codes (for voice services) are assigned. Figure 5.8. In other words, up to 16 users can transmit in the same time slot. For simplicity, we assume that the time slots are synchronized and no delay is considered between the transmissions. When a MO wants to relay its data to a MRS, a code is assigned to it. First all the codes in one time slot are assigned and if there are more than 16 MO in one cell, the codes of the second time slot are assigned. It is worth emphasizing that in one cell a maximum of 112 codes (16 codes*7 time slots) can be assigned to the MO. Hence if there are more MOs than available codes per cell, some MOs will transmit directly to the BS. For the interference model, only the MOs transmitting in the same time slot in all cells will interfere with each other. And the MI and the MRS transmitting in the FDD mode interfere with each others. We assume that the TDD band used is not an adjacent carrier to the FDD band. Hence no interference is considered between the TDD and the FDD modes in the system.

Figure 5.8 TDD frame (15 Time slots)
5.5.3 Results

5.5.3.1 Best scenario

In this section, we compare the performance of the relaying system with the non-relaying for different numbers of active users. The results shown for the non-relaying system represent a cellular network with two carrier frequencies used in each cell. For the relaying system, we consider the case with the best performance from amongst those found in the sections 5.3 and 5.4, i.e in the case when the MS decides to relay if its SIR is below the SIR target and the MRS selection scheme is based on the maximum total SIR. In this section we evaluate the performance of scheme 1; i.e. the MOs transmit in F2 to the MRS and the MRSs and MIs transmit to the BS in F1 only (Figure 5.7 (b)). Figure 5.9 shows the non-satisfied user probability for the models with and without relaying.

As shown in the figure, relaying slightly improves the capacity of the system compared to the non-relaying case. However, the simulation results show that most of the chosen MRSs could not reach the BS. Figure 5.10 shows the CDF of the distance between the MRS and the BS. This plot illustrates that a significant of the MRSs, i.e. 40%, are at least 1600 meters from the BS. Since they are at such a great distance, they have difficulty in countering the total path loss even by transmitting with their maximum power. This results in a SIR below the SIR target and they create a lot of interference in the system. If the MRS chosen cannot reach the BS, the MO will
stay in outage; hence the performance is similar for that without relaying. In order to ensure that a MO does not select a nearby MRS, a constraint is added to the model. This constraint ensures that a MO could choose a MRS only if the distance between the MRS and the BS is not greater than a specified distance. After several simulation runs, the best performance was found using a maximum distance of approximately 1200m between a MRS and a BS. This represents almost half of the cell's radius. This constraint forces the MO to find a non-active MS not further than 1200m from the BS.

Figure 5.10 CDF of distance between MRS and BS

Figure 5.11 shows the non-satisfied user probability for the non-relaying system, with and without relaying but with the use of the aforementioned constraint distance.

The plot shows that when the selected MRSs are closer to the BS, the capacity is significantly improved. For an unsatisfied user probability of 2%, the number of accepted users is 92 without relaying, whilst with relaying, it is almost 130, which translates to an improvement of 40%. This is due to the fact that some users can now successfully transmit their data to the BS via other users and therefore increase the system capacity. Additionally in the non-relaying case, the users that cannot reach the BS transmit their signal with maximum power. However, in the relaying case, they transmit to the MRS with lower transmit power, resulting in lower interference. Since the level of interference is lower, more users can be accepted into the system and hence the system capacity improves.
5.5.3.2 Best scenario with two Carrier frequencies fully loaded

Figure 5.12 demonstrates the number of non-satisfied users for the cellular network without relaying, with relaying and with relaying with two carrier frequencies fully loaded. The results indicate that this latter model outperforms the other two. This is due to the fact that the traffic and the interference are more evenly distributed between the two carrier frequencies. In this latter model, the MOs and some of the MIs transmit on frequency F2 and the MRSs and other MIs transmit on frequency F1 to the BS (Figure. 5.7 (c)). For example, in the case of 100 active users per cell, the simulation results show that 74 MS (37 MRSs and 37 MIs) transmit on F1 and 72 MSs (37 MOs and 35 MIs) transmit on F2. While in the previous model Figure 5.7 (b), for the same number of active users, 100 MSs (50 MRSs and 50 MIs) transmit on F1 and 50 MOs transmit on F2. In this case, the level of interference created in F1 is high and the resources might be fully used. However, on frequency F2, since only the MOs interfere with each other, the carrier frequency might not be fully loaded. Therefore the model in which the two carrier frequencies are equally exploited, gives better performance. For a probability of non-satisfied users equal to 2%, the relaying system can support 136 voice users per cell, which leads to a capacity improvement of 48%. However it is worth emphasizing that in this scheme, some MIs also transmit on F2. Therefore they create interference at the MRS for the MO also transmitting on F2, whilst in the previous scheme, only the MOs interfere with each other. Because of this, the capacity
improvement between the two schemes is not significant.

Figure 5.12 Best scenario with two carriers frequencies fully loaded

5.5.3.3 Best scenario with the optimised model

Figure 5.13 shows the performance of the non-relaying system and the different relaying models proposed. The optimised model has slightly better performance than the previous one. In this optimised model, the two carrier frequencies are also fully exploited but depending on the cell they belong to, the MOs transmit on F1 or F2 and the MRSs transmit on F2 or F1 respectively (Figure 5.7 (d)). Since the MOs from two adjacent cells transmit at a different frequency in each cell, they create less interference for each other. This improves the link between the MOs and the MRSs which leads to a slight increase in the whole system capacity with relaying. For 2% probability of non-satisfied users, 140 users are supported with the optimised model. The capacity is improved by 52% compared to the non-relaying system.
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Figure 5.13 Best scenario with the optimized model

5.5.3.4 Mode FDD/TDD

Figure 5.14 shows the non-satisfied users probability for different numbers of users per hertz per cell in a non-relaying system, with relaying in the FDD mode (with two carrier frequencies) and with relaying in the FDD/TDD mode. In order to make a fair comparison, the bandwidth used for each model is taken into account. The non-relaying system and the relaying system in the FDD mode both use 10 MHz (5MHz for F1 and 5 MHz for F2 in uplink), whilst the relaying system in the FDD/TDD mode uses 7.5MHz (5MHz for FDD and 2.5 MHz for TDD for the uplink scenario only). However, the relaying system in the FDD/TDD mode outperforms the relaying system in the FDD mode when the total bandwidth is considered. In the FDD/TDD mode, the relaying system improves the capacity of the cellular network by 65% for a non-satisfied user probability equal to 2%.
5.6 Conclusions

In this chapter, we have proposed a new set of criteria for capacity improvements of a multihop cellular system. We have tried to use practical metrics for relay station selection and defined criteria under which a MS should be chosen to relay its transmission rather than a direct transmission to a BS. It was shown that a multihop cellular system can offer another degree of freedom in joint planning and optimisation of coverage and capacity. A new dynamic system level simulator for non-relaying and relaying system has been setup in order to evaluate the performance of the two architectures under various carrier frequency usages/patterns. Since in a relaying system, extra bandwidth is needed for the communications between MSs different models as to how these two carrier frequencies can coexist together in a relaying system were proposed and evaluated. The simulation results showed that when the relay decision is based on SIR and the choice of the MRS is based on the maximum total SIR, relaying with the use of two frequencies band (F1/F2) could improve the network capacity. In a cellular network with relaying, the capacity is improved by 48%-52% with the use of two frequencies carriers (F1/F2) and by 65% in the FDD/TDD mode. This performance can be even further improved if the users are able to cooperate together. In cooperative relaying the users transmit data directly to the BS but also relay their data through other relay nodes [Her04]. However in a relaying system, the mobility of the relayed mobile station can create frequent inter-hop handovers and could increase the signalling overhead in the system. These issues need more investigation.
Chapter 6

6 Capacity and Coverage Improvement of UMTS Cellular Network with Fixed Relay Station

6.1 Introduction

In the previous chapter, a new cellular network architecture with relaying integrated has been introduced and described in detail. In this new architecture, the users are able to either communicate directly to the base station (BS) or use other non-active user terminals (called mobile relay stations) to relay their data to the BS. Simulation results showed that not only the interference of the conventional cellular network could be decreased but the capacity is also improved. Nevertheless, relaying through other users' terminal is not an easy task. There are a number of concerns such as: the number of potential relay candidates available, the users' terminal battery consumption, the users terminal complexity in terms of hardware and software, the mobile relay selection, an increase in the signaling overhead, the frequent inter-relay handoffs and finally the security issue. Therefore, there are many points that need more investigation before the realization of such network architecture. In this chapter, another approach is considered. Instead of relaying through other user terminals, the users requiring relaying assistance can forward their data to some fixed relay station which will transfer the data to the BS as represented in Figure 6.1. The fixed relay stations are low-cost radio relay elements placed at specific location in order to relay the received signal to the users (in downlink) or BS (in uplink). Most of the problems while relaying with mobile relay stations (cited above) can be solved or simplified when fixed relay stations (FRS) are used. In the next chapter, a detailed comparison of the two different relay stations (Mobile or Fixed) is given; in this chapter we evaluate the system performance with FRS.

The main goal of the fixed relay station is to receive and re-transmit signals between the users and the BS. Thus they are simple equipment compared to the BS and little more complex than the mobile terminal. This makes them easier to build and requires shorter deployment time than installing new cell sites. Unlike the BS which is capable of emitting large amounts of power, the
transmit power of a fixed relay station is comparable to the power of a mobile terminals. Therefore due to its limited functionality and lower transmit power; a fixed relay station will be much less expensive than a BS. Furthermore the height of FRS can be lower than the BS, it can be placed on rooftops or lampposts, and hence there is no need to build a tower as for the BS. For these reasons, the use of fixed relay stations in cellular networks can be a promising solution to improve the capacity and/or the coverage of the system without increasing the number of sites.

[Hu03] proposed to use digital fixed relays to extend the high data rate coverage of cellular network. In particular, they consider the downlink of the TDMA cellular network where 6 fixed relays are placed around each BS. Since a new channel is needed between the users and the fixed relays, a reuse channel scheme from a further adjacent cell is instead proposed in order to avoid allocating a new frequency which costs extra bandwidth. The results showed the covered area by a single BS providing high data rate coverage can significantly be increased by the employment of digital fixed relays without any penalty in capacity. [Rah04] suggested the use of repeaters to increase the capacity of a hot spot in UMTS cellular network. A repeater is a device that is situated between a BS and a user. It has two antennas, a donor antenna directed to the BS and a coverage antenna directed toward a service area. The goal of the repeaters is to amplify and retransmit received signals in both uplink and downlink. However the application of a repeater is limited because a repeater amplifies not only the useful received signal but also the noise. The amplification can be tuneable and is quantified in terms of repeater gain. They showed that with correct tuning, the capacity of one hot spot located halfway between the BS and the cell border can be improved by 80% in the downlink scenario. [Tam03] examined the use of intelligent deployed fixed relays to improve the performance of a UTRA-TDD 3G system. The study was carried out in a microcellular environment using propagation data from a site-specific model (Bristol area environment) and an optimization algorithm to determine the locations of BS and fixed relay nodes in the system. The results showed that the capacity of the UTRA-TDD system in this site-specific area can be improved by 8 to 75% depending on the number of fixed relays used in the system area. [Wu01] introduced a new architecture called iCAR (intelligent Cellular and Ad hoc Relaying) to provide load balancing between different cells. Some fixed adhoc relay stations are deployed at the edge of cells with the aim of forwarding the traffic from a congested cell to a neighboring lightly loaded cell. Thus, a blocked user in a cell can divert its traffic through a fixed relay to a neighboring cell. The iCAR system can dynamically balance the traffic among cells and reduce the call blocking probability and thus increase the capacity.

In this chapter, we propose and evaluate the performance of UMTS FDD cellular network with the deployment of Fixed Relay Station (FRS) for the uplink scenario. In this model, the users with good channel quality can communicate directly with the BS while users with bad channel quality can use the FRS to relay their traffic to the BS. The relayed users would transmit with less power
than in a direct communication, which decreases the system interference. With less interference, more users can be accepted in the system and the capacity is increased.

As well as capacity improvement, another important benefit is the coverage enhancement. Due to the varying characteristics of a wireless environment, there are usually blind spots in the coverage. With the use of relaying the blind spots can be effectively eliminated and hence the coverage of the system can be enhanced. The users, which are not in the covered area of a BS in a direct communication link, can use the FRS to relay their traffic to the BS and hence extend the coverage area of a BS with the use of FRS. Certain rural areas may benefit from such architectures.

The aim of this chapter is first to properly qualify and quantify the capacity and coverage enhancement of the cellular network with FRS. Then different factors that could affect the system performance with FRS are defined. For this, the description of a cellular network with FRS deployment and the system level simulator used to evaluate the capacity gain are given in section 6.2. In section 6.3, the important characteristics of the FRS influencing the system performance are examined and evaluated. In section 6.4, the coverage of the cellular network without and with the use of FRS is studied. Finally the conclusion of the chapter is given in section 6.5

Figure 6.1 Cellular Network with FRS
6.2 System description of Cellular Network with FRS

6.2.1 Cellular network with FRS

In a conventional cellular network, a base station (BS) controls a number of mobile stations (MS) within its own coverage area and all the mobile stations (MS) communicate directly with the BS. When FRSs are used in the cellular network, the users are not only able to communicate directly with the BS but they can also use the FRS to relay their data to the BS. The advantage of relaying is that the link between MS and BS is broken down into shorter paths requiring less power and hence creates less interference to the neighboring cell, which leads to a capacity improvement. Moreover some users may have a poor channel quality with the BS due to strong shadowing or great path loss. These users, by relaying their signal through the FRS with a better channel quality, are able to transmit their data to the BS. In order to decide when a user should employ direct communication with the BS and when it should be relayed, various schemes were proposed and tested in chapter 5. The results showed that in order to achieve optimal performance, the MS should be relayed when its SIR received at the BS is below the SIR threshold. This scheme is also used for the relaying system with FRS. When a MS has a SIR below its SIR target, it will select a FRS to relay its traffic to the BS. In a cellular network with FRS, only a limited number of relay stations are placed at specific locations. Since there are only a small number of FRS in a cell, the relayed MS will have few choices to select a FRS. For this reason, the FRS selection is not as an important issue as with mobile relay stations (MRS), where the number of relay candidates depends on the density of the non-active users. Note that, in the relaying system with FRS, the non-active users are not potential candidates for relaying and their density does not affect the relaying system performance conversely to the relaying system with MRS. For the FRS selection, the SIR between the relayed MSs and its two closest FRS are computed and the FRS with the greatest SIR will be chosen as the relay station. Therefore in the relaying system, we will have some users communicating directly with the BS and others users communicating with the BS via a two-hop link (one hop for the MS-FRS and one hop for the FRS-BS communication). For simplicity reasons, a maximum of two hops is allowed in the relaying system.

Since there is only a limited number of FRS per cell, it may happen that there are more MSs requiring relaying than the number of FRS per cell. However, it is not unrealistic to assume that a FRS can have the appropriate hardware and software to relay the traffic of several MS at a time. In fact it will be more cost-efficient to deploy few FRS that can relay several MS than deploying as many FRS as the number of MS requiring relaying. In our relaying model, we assume the FRSs are able to relay several MS at a time. This means that a FRS will send as much data as the number of MS that it relays. This is taken into account in the model by increasing the data rate of
each FRS as a function of the number of relayed MS. We assume all the MS transmit with the same bit rate for the voice service (12.2 Kbps). The bit rate of a FRS $i$, $R_{frs}^i$, can be calculated such as,

$$R_{frs}^i = R_{ms} \times N^i$$  \hspace{1cm} (6.1)

where $R_{ms}$ represents the bit rate of a MS and $N^i$ represents the number of MS relayed by the FRS $i$.

Since the FRS transmit with a higher bit rate to the BS than the MS, the SIR target between the FRS and the BS should increase proportionally. For the same Eb/No target, the SIR target of the MS-BS link ($SIR_{ms, t}$) and the SIR target of the FRS-BS link ($SIR_{frs, t}$) will be calculated such as:

$$SIR_{ms, t} = \left( \frac{E_0 / N_0}{W / R_{ms}} \right), \quad SIR_{frs, t} = \left( \frac{E_0 / N_0}{W / R_{frs}} \right),$$  \hspace{1cm} (6.2)

where $W$ represents the chip rate (3.84Mcps).

Since a FRS transmits the data of several MS, it will need more power to achieve a greater SIR target. The larger the number of MS are relayed, the more power is required as well as more interference is created in the system. The interference calculation depends on the air interface used. In our model, the UMTS FDD mode is used for all the transmission. However, we propose the use of two carrier frequencies for the transmission of the two different hops in order to avoid excess levels of interference. The non-relayed MSs transmit directly to the BS with either the carrier frequency (F1) or a second carrier frequency (F2). The FRSs transmit to the BS with the frequency F1 and the relayed MS transmit with the frequency F2 to the FRS, see Figure 6.2 (a and b). In such a scenario, the same number of MSs should transmit in both carrier frequencies (F1 and F2) and thus the two carriers should be fully loaded [Nou05]. There is no interference between users transmitting in different carriers but only between the users transmitting in the same carrier frequency (F1 or F2). Figure 6.2 depicts the interference model for two adjacent cells with the use of FRS for the carrier frequency F1 (Figure 6.2 (b)) and the carrier frequency F2 (Figure 6.2 (a)).
Since a FRS relays the data of several MS, it is very important to have a good propagation channel between the FRS and the BS. If the channel quality between the FRS and the BS is not good, the traffic of a number of relayed MS cannot be transmitted to the BS. Therefore the location of the FRS is an important factor that should be taken into account in the realization of a relaying system with FRS. In our relaying model, we propose to place the FRS in two different locations. In one model, the FRSs use an omni directional antenna and are assumed to be placed at lampposts in the street (location 1). Their locations are chosen appropriately so as they can experience a line of sight (LOS) with the BS. In the other model, we assume the FRS are equipped with a directional antenna and are placed on the rooftops of the buildings where they also experience a LOS with the BS (location 2). Since the FRS's antenna is pointed at the BS, in this model they would create less interference to the neighboring cells. All FRS transmit with carrier frequency F1, therefore they create interference only to the FRS in the same cell and to the MS transmitting directly to the same serving BS with frequency F1. In Figure 6.3, the two
6.2.2 Fixed Relay Station Deployment

In this section, we evaluate the performance of the cellular network with FRS for the uplink scenario. In order to quantify the capacity gain that relaying brings to the cellular network, we compare the performance of the cellular network without and with FRS through a dynamic system level simulator. The same conventional cellular network model (i.e., without relaying) described in the previous chapters is also used in this section for comparison with FRS. In order to make a fair comparison, two carrier frequencies are also used in the system model without relaying. Apart from the interference model due to the deployment of the FRS in the cell, all other parameters and assumptions are the same for the relaying and non-relaying cases. The system modeled includes 19 hexagonal cells of radius 2000m, with BS at the center of the cells employing omni directional antenna. The MS follows the mobility and the propagation model as proposed in [ETSI97] for the
vehicular environment. All the MS transmit at the same fixed-rate voice services over the whole system.

In the cellular network with relaying, several FRS are placed at half of the cell’s radius from the BS. Relaying should be applied to the total cell in order to decrease the overall intercell interference. For this reason the FRS are deployed in all the 19 cells, see Figure 6.4. However, when a MS requires relaying assistance, it would select a FRS in the same cell to which it belongs. In our relaying model, the MSs are not able to relay their traffic to another cell. Thus the same load should be maintained in the different cells.

![Figure 6.4: FRS deployment](image)

(a) 4 FRS per cell  (b) 8 FRS per cell

The path loss and the shadowing effect are both considered in the radio propagation model. The path loss is a function of the distance as well as the height of the receiver. The path loss model between the MS and the BS is the same as in [ETSI98] for the vehicular environment. This model is applicable to the test scenarios in urban and suburban areas outside the high rise core where the buildings are of nearly uniform height.

\[
L = 40 \left[1 - 4 \times 10^3 \Delta h_b \right] \log_{10}(D) - 18 \log_{10}(\Delta h_b) + 21 \log_{10}(f) + 80
\]  

(6.3)

where \(D\) is the separation distance between the base station and the mobile station in kilometres, \(f\) is the carrier frequency of 2000 MHz and \(\Delta h_b\) is the base station antenna height in metres, measured from the average rooftop level. The base station antenna height is fixed at 15 m above
the average roof top level ($\Delta h_b = 15$ m). Considering the values given, the above equation becomes

$$L_1 = 128.1 + 37.6 \log_{10}(D) \quad (dB)$$  \hspace{1cm} (6.3)

This path loss model is used between the MS and the BS link in the relay and the non-relay case. In the relaying system, a different path loss model should be considered for the link MS-FRS and FRS-BS. In the state of the art, there are no appropriate path loss models proposed between a FRS and MS or BS. However, since a FRS can be represented by a BS with lower antenna height, we use the same path loss model for the link MS-BS but with different antenna heights for the FRS.

In the case where the FRS are placed on the rooftop of the buildings (location 2), we assume the FRS's antenna height to be fixed at 5 metres above the average rooftop in the equation (6.3). Therefore, the path loss model between the MS-FRS can be represented by:

$$L_2 = L_{MS-FRS} = 136.7 + 39.2 \log_{10}(D_2), \quad (dB)$$  \hspace{1cm} (6.4)

where $D_2$ represents the distance between the MS and the FRS in km.

It is obvious that for a given distance the path loss for the link MS-FRS is greater than the path loss between MS-BS since the BS is located at higher altitude than the FRS. Since the BS and the FRS are at high altitude and above the buildings, the channel condition between the BS and the FRS are in a very good state. Therefore the free space loss is used to calculate the path loss between the FRS and the BS:

$$L_3 = L_{FRS-BS} = 98.4 + 20 \log_{10}(D_3), \quad (dB)$$  \hspace{1cm} (6.5)

where $D_3$ represents the distance between the FRS and the BS in km.

For the location 1, the FRSs are located at the lampposts, and are almost at the same height as the MS. Therefore the same path loss model for the link MS-BS (equation 6.3) is assumed for the link FRS-BS.

There are no appropriate path loss models that describe the channel between MS and FRS at low antenna height. Therefore, we use the path loss model for the link MS-BS but with antenna height of 1 m to evaluate the path loss between MS and FRS for the location 1:
\[ L_4 = L_{MS-FRS} = 149.3 + 39.8 \log_{10}(D_4), \quad (dB), \] (6.6)

where \( D_4 \) represents the distance between FRS and the BS in km.

It is worth noting that the path loss models used for the link MS-FRS and FRS-BS are not the most appropriate; however we are considering the difference between the link MS-BS, MS-FRS and FRS-BS for each location. In order to show their difference, the path loss models are represented in the Figure 6.5 for the location 1 and 2.

In addition to the path loss, an auto-correlated shadowing model is also modelled between the MS and the BS. Since the FRS are assumed to have a LOS link with their serving BS, there is no shadowing between the FRS and their serving BS in both models (location 1 and 2). However the shadowing is considered between the FRS and the BS from others cells.

In the UMTS cellular network, all the users transmit at the same time and at the same frequency. Therefore it is essential that the level of interference should be kept to its minimum. For this reason, we implemented a perfect distributed power control for the different links to control the power of the non-relayed MS, the relayed MS and the FRS. The power control algorithm consists of balancing all the received SIR around the SIR target. Once the power of all the MS and the FRS are estimated and stabilised, the SIR of the different links (MS-BS, MS-FRS and FRS-BS) can be calculated and compared to the SIR target. The MS and the FRS that have a received SIR below the SIR target are considered in outage.
The MS transmitting directly to the BS are considered in outage if their SIR is below the SIR target. While the relayed MS are considered in outage if at least one of the two hops experiences a SIR below the SIR target \((\text{SIR}_{\text{FRS}} < \text{SIR}_{\text{FRS,T}} \text{ or SIR}_{\text{MS}} < \text{SIR}_{\text{MS,T}})\). This process is repeated for several steps. One step (or snapshot) represents one location for all users. If the user is in outage for a certain number of steps, the user is assumed to be unsatisfied. The simulation has been run for 1000 steps and at the end of the simulation; the numbers of non-satisfied users for the central cell with and without FRS were calculated and compared.

### 6.2.3 Results

A dynamic system level simulator has been running for the conventional cellular network, with FRS placed at the lampposts (location 1) and with FRS placed at the rooftops of the buildings (location 2). In the cellular network with relaying, 6 FRS are deployed in all 19 cells. The FRSs are placed at half cell’s radius away of the BS for the location 1. In the location 2, the FRS use directional antenna to communicate with the BS, therefore they can be positioned further away from the BS. First, we consider the FRS placed at 0.8 of the cell’s radius away from the BS. The maximum transmission power of the MS is 21dBm while the maximum transmission power of FRS is 24 dBm.

The probability of non-satisfied users for different number of active users per cell in each model are plotted in the Figure 6.6. It can be observed that the cellular network with FRS has a better performance than the conventional cellular network. And the MS, which are far away from the BS, use the FRS to relay their data to the BS. And the MS that are not necessarily far from the BS but they are obstructed by a strong shadowing effect, can use the FRS to go round the obstruction. With the help of the FRS, the MS experiencing strong shadowing or high path loss can now transmit their data to the BS and be accepted by the cell. Furthermore, the MS that were transmitting with the maximum power in the cellular network without relaying, use less power to reach the FRS and therefore they create less interference to the neighboring cell. Thus, more users can be accepted in the system and the capacity is increased. For a probability of non-satisfied user of 2%, the cellular network with FRS placed on the lampposts (location 1) can accept 118 voice users per cell, which leads to a capacity gain of 28%. When the FRSs are placed on the building rooftops (location 2), 140 voices users are supported in each cell and the capacity is improved by 52%. When FRSs are positioned at the location 2, the capacity gain is twice that in the case of location 1.

In the cellular network with FRS, the FRS experience a good channel condition with BS therefore the link that mainly limits the capacity is the link between MS and FRS. The relaying model with FRS placed at the buildings rooftop (location 2) achieves much better performance than in the
case where the FRS are placed on the lampposts (location 1). This is explainable since the FRSs are placed at higher altitude; it is easier for the MS to reach a FRS located at the rooftop of the buildings than a FRS located at the street level. Therefore, more users can transmit their data to the FRS and are relayed successfully when the FRSs are placed at higher altitude.

However, the results show that the probability of non-satisfied users increase rapidly for a great number of active users in the FRS scenario (location 1 and location 2). As the number of active users increase in the cells, the level of interference also increases in the system. Therefore the FRSs need to increase their power to reach the BS, which forces some MS transmitting directly to the BS to be unable to reach their BS and hence to communicate with the BS through the FRS. Since more MS require relaying assistance, more interference is created at the FRS and thus more MS fail to reach their FRS, which increases the number of non-satisfied users. Furthermore, since the FRS need to relay more MS, it may happen that some FRS are not able to reach their BS and consequently the data of its relayed MS. Therefore for a large number of active users (more than 120 for the location 1 and more than 140 for the location 2), the probability of non-satisfied users increases exponentially.

Figure 6.6: Cellular network capacity evaluation with FRS
6.3 Impact of the FRS related factors on the Cellular Network Capacity

In the previous section, the capacity gain obtained with FRS deployed in the conventional cellular network was studied. However, the enhancement is achieved with a specific FRS deployment where 6 FRS were placed at a certain distance away from the BS. Here, we look at the impact that different FRS deployment can have on the system performance.

6.3.1 Impact of the number of the FRS

First, the effect of the number of FRS deployed in one cell is studied through simulations. The same numbers of FRS have been deployed in all the cells; see Figure 6.4 (a) or (b). The probability of non-satisfied users for the central cell with different number of FRS is plotted in Figure 6.7. The simulations are run for the two different FRS's locations (location 1 and location 2) with an average of 120 actives users randomly and uniformly distributed in all the cells. The result shows that with greater number of FRS deployed in each cell, the probability of non-satisfied users decreases for both locations. For location 1, the probability of non-satisfied users is equal to 2.7 % with 4 FRS per cell while it is equal to 1.2% with the use of 12 FRS. By adding three times more FRS in the cell more than half of the non-satisfied users are accepted. As stated before, the link which limits the capacity of the cellular network with FRS is the communication link between the MS and the FRS. As the number of FRS increase, the relayed MS locates a closer FRS, thus they select a more appropriate FRS and achieve their traffic to the FRS. Furthermore, as the number of FRS increases, the number of relayed MS communicating with the same FRS decreases. Since there are less relayed MS relaying with the same FRS, they create less interference for each other at their serving FRS and more relayed MS can achieve their SIR target at the FRS. Thus more MS can successfully relay their data to the BS and as a consequence the number of non-satisfied decreases. For the same reason, the probability of non-satisfied users decreases as the number of FRS increases in the case where the latter are placed at the rooftop of the buildings (location 2). The probability of non-satisfied users decrease from 1.4% to 0.2% when the number of FRS increases from 4 FRS to 12 FRS.

However, it is also observed in the Figure 6.7 that the probability of non-satisfied users remains constant when more than 12 FRS are deployed in the cell. After a certain number of deployed FRS in the cells, the numbers of MSs are small enough to maintain a low level of interference at the FRS. Therefore adding more FRS in the cell will not change the performance of the relaying system. Only the relayed MS that are affected by a strong shadowing effect or experience a great path loss with their serving FRS are not able to achieve their SIR target. For more than 12 FRS per cell, the probability of non-satisfied users stagnates at 1.2 % and 0.2% for the location 1 and 2
This explanation is confirmed by the results shown in Figure 6.8. Figure 6.8 shows the average number of MS relayed per FRS in the central cell function of number of FRS per cell. As the number of FRS increase, the number of MS relayed per FRS decreases. It can be observed that the numbers of relayed MS per FRS decrease exponentially for a number up to 12 FRS and decrease linearly for more than 12 FRS deployment. When 4 FRS are employed in the cells, each FRS relay on average 12 MS while with 12 FRS, each FRS relay on average 4 MS. As the number of relayed MS decreases from 12 to 4, the interference created at the FRS is significantly decreased and more MS can be satisfied. However, when more than 12 FRS are used in the cell, each FRS relay the traffic of 2 or 4 MS. The level of interference received at the FRS does not vary greatly when the FRS relay less than 4 MS. Therefore almost all the relayed MS can reach their serving FRS when 12 or more FRSs are deployed in the cells and the probability of non-satisfied users remains constant in this case.

As a conclusion we can say that the relaying system performance is dependent of the number of FRS used. The result shows the capacity gain achieved with relaying increases as the number of FRS increases. However, it is also demonstrated that the capacity gain stagnates after a certain number of deployed FRS.
6.3.2 Impact of the FRS position

Another important factor that should be considered in the deployment of FRS in the cellular network is the FRS’s position. In other words, how far from the BS the FRSs should be placed in the cells in order to get the optimal system performance? For this, several simulation tests were run with the same numbers of FRS placed at different distance from the BS in the two tiers systems. The Figure 6.9 represents 4 FRS placed at 1/3 and 2/3 away from the BS.

The simulations were run with 6 FRS placed at different distances from the cell’s BS and again assume 120 active users are uniformly distributed in each cell. Here, the FRS’s positions are
indicated by a parameter \( f \) representing the FRS distance to the serving BS:

\[
f = \frac{r}{R}
\]

Where \( r \) represents the distance between the FRS and its serving BS and \( R \) is the radius of the cell. For each value of \( f \), the probabilities of non-satisfied users are calculated and shown in the Figure 6.10. The models with the two different locations of FRS (location 1 and location 2) are simulated. For location 1, the result show that the performance is optimal for \( f \) equal to 0.5, i.e. when the FRS are placed at half cell’s radius away from the BS. In chapter 4 and 5, it has been shown that most of the MS requiring relaying are located between 1200m and 2300m (Figure 4.5). These values correspond to a value of \( f \) between 0.6 and 1.15. Therefore, when the FRS are placed close to the BS (\( f < 0.5 \)), there are many MSs requiring relaying that cannot reach their FRS resulting to a greater number of non-satisfied users. When the FRSs are placed near the cell’s edge, most of the relayed MS are close to their FRS and have a higher chance to reach their serving FRS. However, the FRSs are far away from the BS and some of the FRS may have difficulty to reach their BS. Since the FRS relays the traffic of several MS, a FRS that cannot reach its serving BS would not be able to transmit the traffic of all the MS that it relays. Thus, the number of non-satisfied users increases rapidly for values of \( f \) above 0.5. Furthermore, a FRS that cannot achieve its SIR target transmits at a maximum power. This high power transmission causes interference for the neighbouring cells (for the location 1 only) which also increases the number of unsatisfied users. Therefore, this result shows how important is to appropriately position the FRS in order to have a good channel condition between the FRS and its serving BS.

For the location 2 scenario, the results are different than location 1. The optimal performance is obtained when the FRS are placed closer to the edge of the cells. In the location 2, the FRSs are located at the building rooftops and are equipped with directional antenna. Hence they experience a very good channel state with their serving BS and they do not create interference for the neighbouring cells. Therefore, by placing the FRS closer to the cell’s edge and hence closer to the MSs requiring relaying, more MS can reach their FRS. As a result the capacity of the relaying system is improved. The optimal performance is obtained for value of \( f \) equal to 0.8 where the probability of non-satisfied users is equal to 0.5%. For values of \( f \) above 0.8, the FRS is located in the neighbouring cell. The relayed MS from the neighbouring cell will create greater interference to the FRS located in their cell. As a result, larger numbers of relayed MS will not reach their serving FRS located in the other cells and hence increase the number of non-satisfied users (see Figure 6.10, for \( f > 0.8 \)).
6.4 Impact of the FRS deployment on the Cellular Network Coverage

In addition to capacity improvement and power saving, another important benefit is the coverage enhancement. In a cellular network the transmission powers of mobile terminals and BS are limited; therefore the coverage area of a cell is also limited. In a conventional cellular network the users communicate directly with the BS, therefore only the users in the cell’s coverage area successfully transmit their traffic to the BS. In a cellular network with relaying, the users that are not in the coverage area of the cell and hence cannot reach the BS with direct communication are able to send their traffic to a closer FRS, which will relay the data to the BS. In this process, the users without coverage can successfully transmit their data to the BS using a two-hop communication. Thus the coverage area of the conventional cellular network can be enhanced with relaying.
In this section, we study and quantify the coverage enhancement of the cellular network with FRS deployment. For this, we compare the coverage area of the cellular network without and with FRS via dynamic system level simulator. In both model, the same number of active users are randomly distributed in each cell over the whole system. We vary the radius of the cells in the non-relay and relay case and calculate their non-satisfied users probability. In the relaying model, the users are able to either communicate directly with the BS or use the FRS to relay their traffic to the BS. Six FRS are placed at 0.5 and 0.8 from the BS in all the cells for the location 1 and 2, respectively. Figure 6.12 shows the probabilities of non-satisfied users with different cell’s radius for the relay and non-relay cases with on average 90 active users distributed in each cell. It is observed from the graph that the probability of non-active users increases as the cell’s range increases. When the radius of the cell increases, the inter-site distance between the BS also increases. Therefore the further the users are from the BS and hence more users cannot transmit their traffic to the BS leads to a greater non-satisfied users probability. However the results show that the coverage of the cellular network with FRS can be extended with the FRS placed in any location (1 or 2). In the relaying model, the users that cannot reach the BS in a direct communication are able to relay their traffic through the FRS. Hence, users further distance from the BS can be satisfied with a two-hop communication and therefore the cell’s coverage can be extended. The result shows that for a probability of 2% non-satisfied users, the conventional cellular network can cover cells with radius equal to 2250m whilst with relaying capability, the cell’s range is equal to 3400m for the location 1. Therefore for the same load, the cell’s radius of the conventional cellular network can be increased by 50% when FRS are deployed in the cells. This results in a cell area increase by a factor of \((3400/2250)^2=2.3\). For example, a region which will necessitate 2 BSs can be covered with only 1 BS and 6 FRS deployed on the lampposts. Therefore by installing 6 FRS, the service provider can save 1 BSs.
For location 2, since the FRSs are located at the building rooftops, it is easier for the MS to reach their FRS. Therefore even when the cell's radius is large, the MS can still reach their FRS and communicate to the BS via their FRS. For a probability of non-satisfied users equal to 2%, the cell's radius of the cellular network can be extended to 6400m with FRS deployed at the building rooftops. This lead to a cell's range improvement of 185%.

![Figure 6.12 Coverage evaluation with FRS](image)

### 6.5 Conclusions

In this chapter, we have studied the performance of the cellular network with Fixed Relay Station integrated. The study has been done through dynamic system level simulator and the performance of the relaying system has been compared to the conventional cellular network. The results showed that the capacity of the cellular network can be improved with the use of FRS. In the case where six FRS are deployed in each cell at half cell's radius away from the BS, the capacity is improved by 28% to 51%. However, the capacity gain obtained with relaying is a function of several parameters related to the FRS. It is shown that the capacity gain varies with the number of FRS deployed in the cells. The results have demonstrated that the capacity gain increases as the number of FRS increases. However, this observation is valid until a maximum number of FRS deployed in the cells but the capacity remains constant for a greater value. Another parameter which affects the performance of the relaying system is the position of the FRS within the cells. The results show that the performance depends on the location of the FRS. Two models with two different locations were evaluated. In the first model, the FRS are located at the lampposts.
(location 1) and in the second model, the FRS are located at the building rooftops (location 2). For location 1, the optimal performance is obtained when the FRS are positioned at half cell's radius from the BS. For location 2, since the FRSs are located at higher altitude, they can have a good channel condition with the BS and therefore be positioned further away from the BS (or closer to the cell edge). However in both models, it is important to note that the link between the FRS and the BS should be properly assigned. If a FRS cannot reach its BS, it will consequently not be able to transmit the traffic of its relayed MS, therefore decreasing considerably the performance of the cellular network with FRS.

The coverage enhancement due to relaying with FRS has also been studied in this chapter. The results showed that with the same load, the cell's range of the conventional cellular network can be improved by 50% and 185% when 6 FRS are deployed in the location 1 and 2 respectively. Thus for the location 1, the same coverage area can be achieved with either 2 BS without relaying or with 1 BS and 6 FRS. Since the cost of the FRS is much less than the cost of the BS, it would be more cost-efficient for a service provider to install FRS in the existing cells than adding a new site.
Chapter 7 Comparison between Mobile and Fixed Relay Station and Impacts of Inter-Relay Handoffs

7.1 Introduction

In a multihop cellular network, the users are able to send their traffic to the BS through some Relay Station (RS). These relay stations can either be mobile (studied in chapter 5) or fixed (studied in chapter 6). First, [Dru88,Qui86,Lef88] proposed to relay the signal through Fixed Relay Station (FRS, also called repeaters) in order to improve the cell coverage. Then, [ETSI97] suggested to relay through others user’s terminal (Mobile Relay Station, MRS) in order to provide more flexibility to the cellular network. The two different concepts are illustrated in the figure 7.1.

![Diagram showing multihop cellular network with FRS and MRS](image)

(a) with FRS  
(b) with MRS

Figure 7.1 Multihop cellular network
Since then much work has been done on relaying systems with either FRS [Hu03, Pab04, Mol04] or MRS [Svr02, Vid02, Wei04, Her03]. On the other hand very few works have modeled and compared the two systems. Therefore it is still not clear which concept will be more advantageous in terms of performance but also practicality. [Bad04] simulated a relaying system with MRS and FRS for a UMTS cellular network. They have shown that the performance is not significantly improved with MRS but can be improved by 20% with FRS using Time Division Multiplexing and directional antennas. However in the model with MRS, the MS and Relay Station (RS) transmit at the same carrier frequency, which creates high interference at the RS and therefore degrades the performance of the relaying system. [Yam02b] has given the definitions of multihop cellular network architecture with MRS and with FRS. They showed that the transmission power, due to the path loss reduction with relaying, can be reduced in both cases, which can be turned into a capacity gain.

The goal of this chapter is to compare the performance of the relaying system with FRS and with MRS. In the first part, the different advantages and disadvantages of each type of relay station are defined and discussed.

Due to the MS’s mobility, the propagation channel condition between the relayed users and their RS change all the time. If the quality of the channel is deteriorated, the relayed users would probably need to handover from one RS to another RS with better channel quality. This process, particular to the relaying system, is called the inter-relay handoff (IRHO). Then the impact that the IRHO can have on the relaying system performance is here in evaluated by simulation.

### 7.2 Relaying through others Mobiles

In the multihop cellular network with MRS proposed in this work, the relay stations are the non-active users (or idle users). Due to their mobility and their density, several advantages and disadvantages should be considered in a realization of such a relaying network.

#### 7.2.1 Benefits

The different benefits of relaying with MRS are listed below:

- The main advantage of a relaying system using MRS would be the low deployment/maintenance cost. Since other user’s terminals can potentially act as relays for the MS that require relaying, a multihop network using MRS does not require any additional network infrastructure cost. The users are able to find their route, in an ad hoc manner, to relay their traffic to the BS. The only cost that should be considered is the hardware terminal to have
relaying capability [Vid02, Lak03].

- Relaying with MRS can facilitate the coverage planning for operators. Even the most sophisticated planning tools are unable to predict the dead spot especially in indoor and urban areas. In a multihop cellular network with MRS, the MS are able to organize themselves in order to cover these unknown dead spots [Vid02].

- If there are a large number of idle MS, the MS requiring relaying will have more choice to select an appropriate RS in order to minimize the total amount of interference and therefore optimize the system performance. Moreover, there is a greater possibility that the relayed user can find a MRS with whom it experiences a LOS link.

- MRS can help with unpredictable/unknown events like accidents or infrequently occurring events such as demonstrations, sport events or seminars. They can also be used where it is not cost effective to install FRS such as mountainous environments, on top of riverboat or subway train platform in order to improve the coverage.

- In a multihop cellular network with MRS, the users are able to communicate with each other. Therefore if the source terminal and the destination terminal are close to each others, they can communicate directly without sending their traffic via the BS as in conventional cellular networks.

7.2.2 Disadvantages

However, adding the communication capability between the users in cellular networks brings several disadvantages:

- It is obvious that the relaying opportunity depends strongly on the user's density. If there are not enough MS candidates to relay the traffic, the system performance would not be improved.

- Relaying through other users terminals can decrease the battery life of the relay station [Hu03].
• The selection of the RS among the non-active MS is an important issue. The relaying system performance is highly dependent of the RS selection scheme [Svr02, Rou02]. Without a good MRS selection scheme, the capacity of the cellular network cannot be improved with relaying [Bad04].

• In comparison to the conventional cellular network, the signaling for the relaying system will increase since new channels (e.g. traffic and control channel) are required between the MS and the RS. In a relaying system with MRS, if the number of non-active MS candidate is large, the signaling information will increase considerably in the network. [Svr02].

• In order to relay the traffic, the MS should be equipped with a more advanced hardware and software which will increase the cost of the terminal [Yan02]. In addition, the implementations at the hardware become even more difficult if a MRS needs to relay more than one MS’s traffic at the same time.

• In an interference limited system such as UMTS, the interference should be kept as low as possible. Therefore in order to reduce the interference in a relaying system using CDMA, power control might be implemented between the MSs. In a conventional cellular network, the powers of the users are controlled by the BS. But in a relaying system, it is not clear how the power can be controlled in a MS-MS communication link.

• During a relaying communication process, the MRS might move to an area where weaker propagation condition is experienced either to the BS or to the relayed MS and hence it might no longer be the ideal RS. As a result the relayed MS might handover to another MRS. Thus, frequent inter-relay handoffs might occur because of the mobility of the RS and the relayed MS. This might increase the signalling or/and affect the relaying system performance.

• The fast fading between two MS might be a major concern especially in the presence of high mobility.

• In a relaying system, the relayed MS communicate with the BS through another MRS. This can potentially be a security issue that needs further investigation.
7.3 Relaying through Fixed Station

In a multihop cellular network with Fixed Relay Stations, a limited number of relay stations are placed at specific locations in order to enhance the conventional cellular network’s performance. These fixed relay stations have some advantages and disadvantages, which are listed below.

7.3.1 Benefits

- In a multihop cellular network, the FRS are part of the network infrastructure, therefore their deployment will be an integral part of the network planning, design and deployment process. Hence, the operators will have a better control of the coverage and capacity expected in a specific area when FRS is employed.

- The FRS can be deployed at strategic locations in order to maintain a LOS with the BS and also make use of the directional antenna to improve the propagation link with the BS. Therefore the only restricted link for a two-hop communication will be the link between the FRS and the relayed MS.

- The FRS are more powerful in computation and are less constrained by energy consumption compared to MRS. They may potentially be equipped with more advanced hardware and signal processing techniques, which enable them to operate in any frequency band as well as allow them to relay more than one MS at a time.

- The use of FRS eases the problem of routing since the link FRS-BS is more stable. Furthermore the relayed MS will need to select a RS from among only a few number of FRS, conversely to the case with MRS selection. Therefore the signaling overhead required for the RS selection will not be a major issue when relaying is via the FRS.

- The inter-relay Handoffs will occur only when the relayed MS moves from one FRS to another. This will not strongly effect the performance of the system.

- Due to their sophisticated hardware, it is more secure to relay through a FRS than MRS. The data are always transferred through a known (fixed) RS.

- Since the FRSs are spread evenly in a cell, any MS can find a proper relay even if the cell
7.3.2 Disadvantages

- The main disadvantage of the FRS is the infrastructure’s cost. The dimensioning, planning, optimization and maintenance of the FRS can be expensive and cost inefficient. Furthermore it might be cost ineffective to install FRS if there are many sparse coverage holes, in which only a few mobile terminals are located. [Svr02]

- Since the number of FRS is limited and their locations are fixed, some MS might not be able to reach the FRS. Although this depends on the number of FRS deployed in the system. Here, there is a trade off between the number of FRS (which affect the coverage and capacity gain) vs. the infrastructure cost.

- It is difficult or cost ineffective to deploy FRS at unknown dead spot or at unpredictable events.

7.4 Discussions

From the MRS’s and FRS’s characteristics listed above, it can be noticed that relaying with MRS is more challenging as far as networking is concerned. Thus before a relaying system with MRS can be realized, many issues need to be investigated.

In this section, we try to give some ideas of the issues which can make relaying with MRS a possible solution to enhance the performance of the cellular network.

One of the main challenges of relaying through other user’s terminals is allowing the MRS’s battery to be used for someone else’s call. One potential scheme to convince the user’s terminals to be used as relay would be to provide them a share of the excess revenue. Since the performance of the network is enhanced with relaying, the operators can give some free minutes or reduce the bills of the users cooperating as relay stations when they are in idle mode. Another alternative solution to avoid the battery consumption of the RS would be to relay the signal through vehicles (such as cars or taxi). Since the latter do not have a problem to charge their battery, relaying through vehicles is a viable solution for relaying systems. However it is worth noticing that in a relaying system with MRS, the users should cooperate as a single team to improve the performance. Hence, the users that require relaying should also be potential relay station for the users that were relaying.

Another main issue of the MRS’s use is the increase of the signaling overhead compared to the conventional cellular network. [Hol02] showed that the capacity of the cellular network cannot be
increased with relaying due to greater overhead signaling. However in order to reduce the amount of overhead, another option is presented in [ETSI97]. A MS can exchange signaling with a BS for call set-up authentication/encryption/user profiles. Nevertheless the data content of the calls could be transmitted via MRS or direct MS-MS. The capacity of such a system may be greater and can be considered analogous to having a larger number of BS within a given area.

In the future, it should be possible to provide a variety of complex types of MS, cost and capabilities in order to satisfy the needs of different types of users. For a relay system to work well there must be as many relay nodes as possible. It is therefore a goal to support relaying in all MS. One may think that the additional hardware and software will increase the terminal’s cost but the investigations done in [ETSI97] suggest that the required functionality for the MS to support relaying has negligible impact on mobile terminal cost or complexity.

In chapter 5 and 6, power control has been implemented between MS and RS in order to minimize the interference in the network. More investigations are required as how to efficiently control the power of the MS and the RS during such communications. However instead of implementing power control for the relaying link (MS-RS), another alternative would be for the relayed MS to transmit at a fixed transmission power. Since the MS and RS are usually close to each other and sometimes experiences a good link (possibly LOS), they can transmit at a low fixed transmission power.

In comparison to the relaying system with FRS, one of the main challenges of relaying with MRS is the frequent inter-relay Handoffs. In a relaying system with MRS, not only the relayed MS but also the MRSs are constantly change. Therefore, the propagation link between the MS-MRS and the MRS-BS keep change. In the case where these channels conditions deteriorate, the relayed MS might need to handover to another MRS; this process is called inter-relay handoffs (IRHO) (see figure 7.2). If the IRHO happens frequently, the relaying system will not be realizable due to excess signaling. It is therefore essential to investigate the impact of the IRHO when relaying is done with MRS. In the literature review on relaying with MRS, there is no work that has treated this issue. In the next section, the impact of IRHO on the system performance of relaying with MRS but also with FRS is studied.
7.5 Effect of inter-relay Handover on the relaying system performance with MRS

7.5.1 Period of time that a user is relayed

In a multihop cellular network, some of the active MS might decide to relay their traffic through the RS (Fixed or Mobile relay station). Various schemes were proposed in chapter 5 to govern how a MS should decide whether or not to employ relaying. The results showed that in order to achieve optimal performance, the MS should be relayed when its SIR received at the BS is below the SIR threshold. The MS's SIR is dependent on the level of interference occurring in the system as well as the channel condition between the MS and its serving BS. Therefore, the MS would use relaying for different periods of time depending on its location. If a MS is in a non-shadowed area (for example at the edge of the cell) for a long period of time, it will also need to relay its signal for a long period. On the other hand, a MS might use relaying for a short time if it experiences a strong shadowing (such as building or tree or driving on a motorway, etc...). In order to identify the behavior of the relay period duration, a simulation for the system model with relaying is run. The periods of time that the MS employs relaying are logged and the CDF of the users relay duration is plotted in the Figure 7.3.
Chapter 7 Comparison between Mobile and Fixed RS and Impacts of Inter-Relay Handoffs

![Figure 7.3 CDF of Relay Period Duration](image)

The plot shows that most of the MS use relaying for a short period of time. Almost 90% of the MS require relaying for less than 4 seconds, whereas 50% of the users relay for less than 2 seconds (1 simulation step is equal to 0.5s).

In a multihop cellular network with MRS, all the MS (including the relayed MS as well as the MRS) are moving all the time. During the relaying communication, the link quality of the link MS-MRS or/and MRS-BS might drop below the given threshold. Consequently the relayed MS might need to change its MRS in order to achieve its traffic to the BS but also to minimize the overall interference in the system. Thus the question is: how much the inter-relay handover affects the system capacity when relaying with Mobile RS? Also under which conditions, a relayed MS should handover to another RS (see figure 7.4)?

To answer these questions, three algorithms were proposed and compared via the simulation results.
7.5.2 Inter-relay Handover Instantaneous (Inst-IRHO)

The first proposed algorithm is called “Instantaneous-IRHO”. As seen in chapter 5, whenever a MS requires relaying it will choose from amongst the non-active MS the one with the maximum total SIR. Total SIR means the sum of the SIR in the two hop links (MS-MRS and MRS-BS). Therefore at anytime, the relayed MS will perform inter-relay handoff if it finds another non-active MS with greater total SIR. For example in Figure 7.4:

If Total SIR2 > Total SIR1 → inter-relay Handover from MRS1 to MRS2

7.5.3 No Inter-relay Handover (No-IRHO)

The second proposed algorithm is called “No-IRHO”. In this scheme, when a MS selects a non active MS, it will keep the same MRS until it stops relaying. As a result IRHO will be avoided. However the relayed MS might handover to another non-active MS if its RS moves to another cell.

7.5.4 Inter-relay Handover based on requirement (SIR-IRHO)

The third proposed algorithm is called “IRHO based on requirement (SIR-IRHO)”. In this algorithm, IRHO is carried out only when the quality of the two-hop link drops below another link SIR with a certain margin. The relayed MS will do inter-relay handoff only if there is another non-active MS with better link quality. In order to avoid frequent handover, the serving MRS will be changed only if the total SIR of another non-active MS is greater than the total SIR of the current MRS plus a SIR margin for IRHO:

If Total SIR2 > Total SIR1 + SIRm_HO → inter-relay Handover from MRS1 to MRS2
SIRm\_HO is a margin value that decides on the inter-relay handover frequency.

### 7.5.5 Results

Each algorithm has been tested with the system level simulator. In order to make a fair comparison, the same relaying model is implemented for each algorithm. Several active and non-active MS are placed in the 19 cells system. The decision to relay is based on the received SIR at the BS for the different proposed algorithms. Whenever the MS's SIR drops below the SIR threshold, it will select a non-active MS to relay. The selection of the MRS is based on the maximum total SIR. The decision to IRHO are different for each algorithm, hence different interference levels will occur in each system, which will effect the system capacity. For each algorithm, the probabilities of non-satisfied users for different number of active users are plotted in the figure 7.5.

The three different algorithms are compared with the non-relaying system. First, it is important to note that the relaying system with any of the proposed scheme have a better performance than the non-relaying system. For a probability of 2% of non-satisfied users, the non-relaying system can support 92 users per cell.

Amongst the three different proposed schemes, the best performance is obtained with the Inst-IRHO. This is perhaps obvious since the relayed MS will choose the best MRS at any time.
selecting the non active MS which provides the strongest total SIR, the interference in the system is minimized and the system performance is optimal. For 2% of non-satisfied users, the number of users accepted in the cell in the relaying system with Inst-IRHO is 136, leading to 48% of capacity gain compared to the non-relaying system. However, this scheme does not consider the expenses due to frequent inter-relay handoffs.

It is seen that the second proposed scheme “No-IRHO” has the worst performance. When a relayed MS selects a MRS, it will keep the same MRS until it does not need to relay. This is an efficient scheme to avoid IRHO. However the relayed MS and its MRS are moving all the time, so their channel condition might not therefore always be the best. In a bad channel condition, the relayed MS will need more transmit power to reach its MRS and the MRS might also need to increase its transmit power to reach the BS, which will increase the interference for other users and hence increase the overall interference. Nevertheless, even with this scheme, the capacity is improved by 20% for 2% of non-satisfied users.

The third algorithm SIR-IRHO has better performance than the No-IRHO scheme but less than the Inst-IRHO scheme. Regarding the value of SIRm_HO, the capacity gain with this scheme is between 20% - 48% for 2% of non-satisfied users. In this scheme, the relayed MS will inter-relay handoff only if the link quality with another MRS is much greater. Therefore, this scheme avoids frequent handovers such as in the Inst-RHO scheme whilst providing a reasonable performance gain for the system.

The capacity gain of the relaying system with inter-relay handoff based on requirement depends on the SIRm_HO. Hence, different SIRm_HO were tested to decide what was adequate for IRHO. The greater the SIRm_HO, the less inter-relay handoff occurs. For a SIRm_HO equal to zero, the system performance will be the same as the case with Inst-IRHO. For 2% of non satisfied users, the capacity gain is equal to 36% for a SIRm_HO of 14dB.

For different algorithms of IRHO, the relayed MS will experience different average relay periods. Table 7.1 shows the average duration that the MSs in the center cell are relaying with the same MRS during the relaying process.

<table>
<thead>
<tr>
<th>Inter-relay Handoffs schemes</th>
<th>Relay period duration (s)</th>
<th>Relay period duration with the same MRS (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inst-IRHO</td>
<td>2.1</td>
<td>0.5</td>
</tr>
<tr>
<td>No-IRHO</td>
<td>2.8</td>
<td>2.6</td>
</tr>
<tr>
<td>SIR-IRHO</td>
<td>2.4</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 7.1 Relay period duration per cell for different inter-relay handoff schemes
The results show that the MRS is changed frequently with the Inst_IRHO scheme. This scheme provide the best performance but at the expense of frequent IRHO, which will increase the signaling overhead of the system. In the No-IRHO scheme, the same MRS is retained until the end of the relaying process. This scheme does not experience so great signaling overhead but the performance will not be optimal. A good trade-off between the signaling overhead and the number of inter-relay handoffs is the SIR-IRHO scheme (by adapting the SIRM_HO, the level of inter-relay handoff can be controlled).

### 7.6 Effect of inter-relay Handover on the relaying system performance with FRS

In a relaying system with FRS, the inter-relay handover is affected only by the mobility of the relayed MS since the RS have a fixed location. Therefore the inter-relay handover has less impact on the system performance of the relaying system with FRS than with MRS. Since the FRS are located in a specific place where they can experience a very good propagation channel with the BS (e.g. LOS), the inter-relay Handover will mainly depend on the link quality between the MS and FRS. For most of the time, the inter-relay handover occurs when the relayed MS moves closer to another FRS than its serving FRS. In the RS selection algorithm proposed in chapter 6, the MS that requires relaying, will choose from amongst the two closest FRS, the one that experiences the best SIR.

A simulation has been run in the relaying system with 6 FRS per cell where the relay periods of a MS with the same FRS were computed. The result is shown in the table 7.2.

<table>
<thead>
<tr>
<th>Relay period duration (s)</th>
<th>Relay period duration with the same MRS (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>1.3</td>
</tr>
</tbody>
</table>

*Table 7.2 Relay period duration per cell in the relaying system with FRS*

On average, the MS employ relaying for a period of 2.5s. During this period, the relayed MS relay with the same FRS for 1.3s on average. Hence during the two-hop communication, the relayed MS handoffs only once to another FRS. Since the number of IRHO is reasonable, there is no need to model different algorithms.
It can be noted that if the relayed MS moves at a higher speed it will handover between FRS more frequently. In the same way if there are many FRS, the relayed MS will often experience better channel quality with other FRS, leading to a greater number of IRHO. Thus, the inter-relay handover will depend mainly on the speed of the MS and the number of FRS in the system.

7.7 Probability of inter-relay Handover vs. speed

In section 7.4, the performance of relaying system with mobile relay station for different IRHO algorithms were tested through simulations. The results showed that the maximum capacity gain is obtained with the Inst-IRHO algorithm. In this scheme, the relayed MS chooses the best MRS at any time, which minimizes the system interference. However this scheme is due to the expense of frequent handovers.

In this section, we compare how frequent the inter-relay handover occurs for each algorithm. In order to compare them, the probability of IRHO for different MS speeds is calculated via simulation. The probability of IRHO means the probability that a relayed MS changes its RS during the relaying communication. It represents among the MS that were relaying, the number that handover to another RS. The probabilities of IRHO for different MS’s speed with MRS and FRS are plotted in the figure 7.6.

As expected, the Inst-IRHO is the scheme that causes the most inter-relay handovers. Although, it can provide the best performance, the frequent inter-relay handover will considerably increase the
signaling in the relaying system. In order to keep the signaling overhead in the inter-relay handover as low as possible, the No-IRHO scheme is considered the most suitable. It is apparent from the plot (Figure 7.6) that the probability of No-IRHO is almost negligible. This scheme will keep the signaling low at the expenses of a reduced gain in the system performance. A good compromise would be to employ the SIR-IRHO scheme. The scheme is simulated for SIRm_HO equal to 8dB and 14dB. The results show that the probability of IRHO based on requirement is quite low whilst retaining a good capacity improvement. At a speed of 120km/h, the probability for the SIRm_HO of 8dB and 14dB are equal to 38% and 24% respectively. This algorithm is a good trade-off between the extra signaling and gain in the system performance.

Predictably, the probability of IRHO in the relaying system with FRS is quite low. At a speed of 120km/h, the probability of IRHO with 10 FRS per cell is equal to 24%.

One can see that the probability of IRHO with MRS based on the requirement with a SIRm_HO of 14 dB is equal to the probability of IRHO with FRS. This shows that in this scheme, the relayed MS change MRS as often as in the relaying system with FRS.

### 7.8 Performances comparison between MRS and FRS

In a multihop cellular network, the MS can be relayed either via other Mobile stations (MRS) or by some fixed relay stations (FRS) placed at specific locations. Due to their different characteristics, it is still not clear which relaying system will be more advantageous. Moreover, it can be asked which relaying model has a better performance in terms of capacity gain compare to the conventional cellular network?

In a relaying system with MRS, the performance will mainly depend on:

- the density of non-active MS candidate,
- when relaying should be employed,
- the MRS selection scheme
- the inter-relay handover mechanism.

Whilst in a relaying system with FRS, the performance will essentially depend on the number and the location of the FRS.

For the performance comparison of the relaying system with both types of relay station, two system level simulators with relaying capability (one with MRS and one with FRS) were built. The RS's characteristics are different in each simulator mainly due to the mobility of the RS, but all others assumptions are the same (such as cell deployment, number of BS, multiple access scheme, BS handover, power control, mobility, channel model between MS and BS, etc...). In the simulator for relaying with MRS, there are enough available non-active MS to be used as RS. The
decision as to when a MS should be relayed and the selection of MRS are both based on the SIR link quality (as described in chapter 5). The decision to handover to another MRS is made on the IRHO based on the SIR_{m_HO} scheme. In the simulator for relaying with FRS, the FRSs are placed at half radius of the cell which is the optimal distance with the BS (see in chapter 6 for location 1).

Figure 7.7 shows the percentage of non-satisfied users for different numbers of user per cell for the conventional cellular network, the relaying system with MRS and the relaying system with different number of FRS.

![Figure 7.7 Performance comparison between MRS and FRS](image)

The results show that relaying with MRS can increase the capacity by 36% for a non satisfied users probability of 2%. The performance for relaying with FRS depends on the number of FRS. As the number of FRS increase, the performance is improved. The result shows that the performance of relaying with MRS is better than relaying with FRS with a number of FRS up to 10 FRS. With greater number of FRS, the relaying system with FRS outperform the one with MRS. As a conclusion, we can say the relaying system with MRS and 10 FRS have almost the same capacity and with the same number of IRHO.
7.9 Conclusions

In this chapter, the different characteristics between relaying with MRS and FRS were studied. First, the advantages and disadvantages of relaying system's type (MRS or FRS) were listed and summarized. The discussion assumed that the major disadvantages of relaying with MRS is the frequent number of inter-relay Handoff. Therefore, we proposed to study the effect of the inter-relay handover (IRHO) on the system performance gain.

For the relaying system with MRS, three different algorithms namely inter-relay Handover instantaneous (Inst-IRHO), no inter-relay Handover (No-IRHO) and inter-relay Handover based on requirement (SIR-IRHO) were proposed. Their performances were compared through simulation. The results showed that even with the No-IRHO scheme, where relayed user are not allowed to inter-relay handover, the capacity of the cellular network with MRS is still improved by 20%. Whilst providing the best performance with 50% capacity gain, the Inst-IRHO scheme showed a large number of handoffs which considerably increase the system signaling. On the other hand, the SIR-IRHO scheme is a good trade-off between the number of handoffs and the system performance gain. The results showed that with an appropriate SIR window in the IRHO scheme, the relaying system with MRS can improve the capacity of the conventional cellular network as well as limiting frequent handoffs to relay stations. The capacity of the cellular network with MRS is improved by 36% with the SIR-IRHO scheme. The simulation result with FRS showed that the same performance to relaying with MRS can be obtain with variable numbers of FRS per cell.

However several issues in both relaying system need more investigation. When relaying with MRS, the next main challenge is to study the signaling (e.g. extra channel) that a relaying system would require. More precisely, how the control signaling evolves in the MRS selection and link establishment affect the system performance? Furthermore, other issues such as power control implementation between two MS or security issues cannot be neglected and hence need further studies.

The characteristics of the relaying system with FRS showed that most of the issues existing with MRS could be solved or simplified without difficulty. Nevertheless, the deployment, planning and design of the FRS should also be cost efficient in order to use them as a cell performance enhancer. If these issues can be solved and show that relaying with FRS is profitable, it is reasonable to think that in an early phase, relaying will be performed through fixed relay stations.
Chapter 8

8 Conclusions and Future Work

8.1 Conclusions

The main goal of the thesis was to evaluate the performance of the cellular network with relaying. In order to define if integrating relaying in cellular network can improve their performance, two models were devised. One model represents the conventional cellular network (without relaying) and the other one is the cellular network with relaying capability.

Their performances in terms of capacity and coverage were evaluated and compared. The evaluation has been done through analysis and simulation methods. In both models, the users transmit using the CDMA air interface. However since another channel is required for the relaying channel, different division duplex schemes were used. We proposed and tested the relaying system performance when another carrier frequency is assigned to the relaying channel (FDD mode) but also when different time slots are assigned to the relaying channel (TDD mode). In the relaying system model, two different types of relay station were studied: mobile and fixed Relay Station. Their different characteristics were defined and their performances were compared through simulation. The inter-relay Handoff is also considered and analyzed in the relaying system model with mobile and fixed relay station.

At the end of each chapter, a corresponding summary is provided. It remains to draw a list of the new major achievements:

1. Relaying can improve the performance of the conventional cellular network in terms of capacity and coverage by decreasing the intercell interference. The performance is even greater when relaying is performed in an unstable radio environment. This improvement is achieved even though the implementation of a two hop relay concept has two major drawbacks: the requirement for additional resources and an increase in the number of transmitters/interferers.

2. The capacity gain that relaying with mobile relay station brings to the UMTS cellular network through the dynamic simulator is evaluated. The results showed that relaying with mobile relay stations can indeed improve the capacity of UMTS cellular network by 35% but only
under certain conditions.

3. The first condition is related to the decision of whether a MS should be relayed or not. The simulation results showed that the performance is optimal when the relaying decision is based on SIR. We observed that most of the MSs that cannot reach the BS experience a strong shadowing and/or a significant path loss with the BS. These users are usually located at the edge of the cell and are the ones most often require relaying assistance.

4. The second condition proper to the Mobile Relay Station characteristics is the relay station selection schemes. The best performances were obtained when the MRS chosen is based on the maximum total SIR.

5. Since an additional bandwidth is required for relaying purpose, the results showed the importance of having a good frequency pattern/usage in order to get sufficient capacity gain.

6. Another condition is to keep low the number of inter-relay handoffs. The results show that, although the inter-relay handoffs have great impact on the system performance, relaying with mobile relay stations can still improve the capacity of UMTS cellular network by 20% even when users are not allowed inter-relay handoffs. However with an appropriate inter-relay handoffs scheme, the relaying system with MRS can improve the capacity of the conventional cellular network as well as limiting frequent handoffs to relay station. The capacity of the cellular network with MRS is improved by 36% with an appropriate scheme.

7. The same capacity gain can be obtained with the use of Fixed Relay Station than Mobile Relay Station. However, the capacity gain obtained with FRS is a function of some parameters proper to the FRS's characteristics. The capacity gain varies with the number of FRS deployed in each cell but also with the location and position of the FRS.

8. The results demonstrated that the capacity gain increases as the number of FRS increases. However, this observation is valid until a maximum number of FRS deployed in the cells thereafter the capacity remains constant.

9. Another parameter which affects the performance of the relaying system is the position of the FRS in the cells. The results show that the performance depends on the location of the FRS. When the FRS are located at higher altitude (e.g. rooftops), the FRS experience a good link with the base station and therefore they could be placed further away from the BS. When the FRS are located at low altitude (e.g. lampposts), the FRS should be placed closer to the BS. In fact, the results showed that the best performance is obtained when the FRS are placed between 0.5 and 0.8 of the cell's radius from the BS.

10. However when relaying is done through Fixed relay stations, it is important to note that the link between the FRS and the BS should be properly assigned. If a FRS cannot reach its BS, it
will consequently not be able to transmit the traffic of its relayed MS, therefore decreasing considerably the performance of the cellular network with relaying.

11. The coverage enhancement due to relaying with FRS is also studied. The results showed that with the same load, the cell’s range of the conventional cellular network can be extended by 50% and 185% when 6 FRS are deployed for FRS located at different altitude. When the FRSs are located at low altitude, the same coverage area can be achieved with either 2 BS without relaying or with 1 BS and 6 FRS. Since the cost of the FRS is much less than the cost of the BS, it is more cost-efficient for a service provider to install FRS in the existing cells than adding new site.

12. The characteristics of the relaying system with FRS showed that most of the existing issues with MRS could be solved or simplified without difficulty. Nevertheless, the deployment, planning and design of the FRS should also be cost efficient in order to use them as a cell performance enhancer. If these issues can be solved and show that relaying with FRS is profitable, it is reasonable to think that in an early phase, relaying will be performed through fixed relay stations.

13. Finally, a new method of generating a two-dimensional shadowing component to be used in any dynamic system level simulator is proposed. This two-dimensional model enables the correlation of the shadowing components of multiple users with more than one base station, which was not possible with the conventional one-dimensional auto-correlation.
8.2 Future works

Since relaying is a new concept, several issues need more investigation. The following fields are suggested for further research:

Currently, there is no appropriate propagation model for the link between a transmitter and a receiver with low antenna heights. In a relaying system, a user might relay its signal through another user’s terminal or low height relay station. Therefore, a new path loss model should be devised in order to be used in any relaying system. Furthermore, an autocorrelation shadowing model between all the users should also be considered.

This work has been based mainly on the voice service in the vehicular environment for the uplink scenario. The work can be extended to mixed services in any environment for the uplink and downlink scenario. It would be interesting to look at the capacity gain with relaying especially in dense urban environments (like Manhattan grid) where the shadowing effects strongly the performance.

In UMTS, the users at the boundaries of the cells are able to communicate with several BS at the same time (i.e. Soft Handover), especially in the downlink. It has been shown that most users that require relaying are located at the cell edge. Therefore, it should be investigated how the soft handover and relaying mechanism can coexist.

In this work, we assumed a power control between users and fixed relay station where only the receiver suggests to the transmitter the required power. In the UMTS standard the decisions are made by the UTRAN, and naturally from a practical point of view as well as signalling, further investigations are required as to whether the UTRAN should still have an influence over the power transmitted between the MS and its RS.

In the relaying system a direct link (MS-BS) is substituted with a two hop communications (MS-RS and RS-BS), therefore some extra signaling will be added to the system for the control channel, link selection or re-selection. Nevertheless, “how the control signaling evolves in the relay station selection and link establishment will affect the system performance?”
The results in this work showed that a two hop communication can improve the system performance of the conventional UMTS cellular network. From an architecture point of view it would be interesting to see until how many hops the system could be improved. Nevertheless, a complexity will be added to the system. For number of hops greater than two, the routing, signaling as well as delay becomes crucial issues.

Another advantage of relaying is the load balancing it brings. When the traffic in a certain cell is overloaded, the relay may be able to divert an amount of traffic to the neighbouring cell, and thus the entire traffic load becomes more balanced. Future studies on this task are also recommended.
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List of Publications


Appendix A

9 Mathematical Background

The mathematical background for the calculations of the capacity of UMTS cellular network in chapter 3 is introduced in this appendix.

9.1 Probability Theory

If $X$ is a random variable with pdf $p_X(x)$ then the expected or mean value of $x$ is defined as:

$$E[X] = \bar{X} = \int_{-\infty}^{\infty} x p_X(x) \, dx$$  \hspace{1cm} (A.1)

The mean-square value or variance of a random variable $X$ is defined as:

$$\sigma^2 = E[(X - \bar{X})^2] = \int_{-\infty}^{\infty} (x - \bar{X})^2 p_X(x) \, dx = \text{var}[X]$$  \hspace{1cm} (A.2)

and $\sigma$ is called the standard deviation of $X$. The above two moments are related as follows:

$$\text{var}[X] = E[X^2] - E^2[X]$$  \hspace{1cm} (A.3)

If $c$ is a constant:

$$\text{var}[cX] = c^2 \cdot \text{var}[X]$$  \hspace{1cm} (A.4)

The fact that a random variable $X$ follows normal (or Gaussian) distribution with mean $m$ and variance $\sigma^2$ will be expressed as $X$ follows $\mathcal{N}(m, \sigma^2)$. The probability density function of such a variable is [Sza03]:

$$p_X(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(x-m)^2}{2\sigma^2}}, \quad -\infty < x < \infty$$  \hspace{1cm} (A.5)

A useful proposition is the following:

If the random variables $X, Y, Z, \ldots$ follow Gaussian distribution with mean and variance $(m_X, \sigma_X^2)$,
(m_Y, σ_Y²), (m_z, σ_z²), ... respectively then the random variable U = aX + bY + cZ + ..., (a, b, c, ... constants) also follows Gaussian distribution with mean and variance:

\[ m_u = a \cdot m_x + b \cdot m_y + c \cdot m_z + ... \]
\[ σ_u^2 = a^2 \cdot σ_x^2 + b^2 \cdot σ_y^2 + c^2 \cdot σ_z^2 + ... \] (A.6)

The mean value of a function Y = g(X) of a random variable X can be calculated from:

\[ E[Y] = E[g(X)] = \int_{-\infty}^{\infty} g(x) p_X(x) dx \] (A.7)

It is obvious that the pdf of a new random variable Y is not required to find the mean value of this variable (E[Y]) [Kok99].

### 9.2 Q-function

The Q-function is tail integral of a unit-Gaussian pdf and is defined as:

\[ Q(z) = \int_{z}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx \] (A.8)

The properties of the Q-function are:

\[ \lim_{z \to \infty} Q(z) = 0 \]
\[ \lim_{z \to -\infty} Q(z) = 1 \]
\[ Q(0) = 1/2 \]
\[ Q(-z) = 1 - Q(z) \] (A.9)

There are two other functions closely related to the Q-function: the erf(·) (error function) and erfc(·) (complementary error function) [Chu03]. These functions are defined as follows:

\[ \text{erf}(z) = \frac{2}{\sqrt{\pi}} \int_{0}^{z} e^{x^2} dx, \quad z \geq 0 \]
\[ \text{erfc}(z) = 1 - \text{erf}(z), \quad z \geq 0 \] (A.10)
The Q-function is related to erf(·) and erfc(·) by:

\[
Q(z) = \frac{1}{2} \left[ 1 - \text{erf} \left( \frac{z}{\sqrt{2}} \right) \right] = \frac{1}{2} \text{erfc} \left( \frac{z}{\sqrt{2}} \right), \quad z \geq 0
\]  

(A.11)

If \( Y(u) \) is Gaussian with mean \( m \) and variance \( \sigma^2 \) then:

\[
\Pr\{Y(u) > \alpha\} = Q \left( \frac{\alpha - m}{\sigma} \right)
\]

(A.12)

\[Q(z)\] vs \( z \) (with logarithmic scale)

**Figure A.1:** \( Q(z) \) vs \( z \) (with logarithmic scale)