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Cellular System with Co-existing and Spectrum Sharing in Single-hop and Multi-hop Cells

by

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Abstract

The limited capacity of the current wireless networks could potentially be expanded by reusing and managing the available radio resources for a given user population. To further increase the resource reuse ratio, the basic cellular architecture is implemented by subdividing each cell into smaller virtual cells that reuse the same resources. The data packets are transmitted from a virtual cell to another in a multihop fashion, through a relay node.

The trunking capacity increases while the resource reuse ratio is increased. However, the carrier-to-interference ratio (C/I) decreases, which is considered an important performance limiting factor. To overcome the C/I problem, the resource allocation has to be made such that interference is sufficiently low and the C/I is significantly high. The proposed system benefits from the resource allocation in the proposed scheme in that intracell interference is reduced and spectral efficiency is increased. The proposed method performs better than the pure TDMA cellular system, when the same load is applied in both systems.

Declaration of originality

I hereby declare that the research recorded in this thesis and the thesis itself was composed and originated entirely by myself in the School of Engineering and Science, International University bremen, Germany.

Khaled Shawky Hassan

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Acknowledgments

"All the praises and thanks are to Allah, the Lord of worlds;"

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Chapter 1

Introduction

The traditional spectrum sharing techniques are implemented using the frequency or time division multiplexing, where different users occupy different operating frequencies or time slots. The tractional frequency/time multiplexed signals are easily separated without introducing any intracell interference in the cellular architecture. However, the complete avoiding of the intracell interference will inefficiently handle the available limited resource. Therefore, the need for an efficient spectrum sharing is increasing to fulfil the future demands.

The basic step for an efficient spectrum sharing is done by selecting the appropriate frequency and time slot for a particular wireless transmission. Furthermore, extending the spectrum sharing utilization could be done by reconfiguring, reallocating and redesigning the available spectrum resources to decrease the chance of frequency/time resources overlapping of different users.

The recent research interests focus on utilizing the scarce resources more efficiently to cater for the increase in the wireless service demands. The resources utilization can be done by simultaneously sharing the available spectrum by different users, which are occupying different locations, by using non-overlapping time slots (TS). These spectrum sharing aspects open a new era in spectrum planing and managing. The new research aspects will consent to the future wireless networks demands, by increasing the spectral efficiency.

The most promising path towards an efficiently utilized spectrum could be achieved by dividing the conventional cellular system, that is mapped over the coverage area, into smaller virtual cells (VC) which is known as multihop cells. These multihop cells are allocated a portion of the resources for establishing internal communication. The external communication for these VC(s) is done through a gateway (GW) in a *multihop* fashion. The GW is responsible for monitoring, controlling and arranging the external transmission from/to another virtual or real cell.

Recently, the multihop extension of cellular networks (hybrid networks) is envisaged to be an integral element of 4^{th} generation wireless networks. These systems have to support variable service classes with different QoS requirements, variable reliability and secure level of emergency requests. A key challenge is to design a system which supports these different service classes and at the same time enables efficient utilization of the radio spectrum fulfilling the previous requirements and needs. Another challenge is to reduce the interference that arises implicitly from the admissible resource reuse. The undesired interference can be reduced by either carefully planning the allocated resources or controlling the transmitted power to realize an acceptable carrier to interference (C/I) level.

The different transmitted signal types confine their availability, reliability, coverage, transmission symmetry and bandwidth. For the typical user equipments, there are two most unlike classes of service types that require different properties, which can be identified as follows:

1- Voice: real time, symmetric, low data rate, high mobility, etc.

2- Data: non-real time, asymmetric, very high data rate, low mobility, etc.

A system is proposed that jointly supports these two *extreme* service classes. The concept is based on a basic cellular architecture with an integrated 2-hop multihop mode. VC(s) are formed which are linked to base stations via gateway stations (GWs). In these VC(s), the TDD (time division duplex) mode is employed which is operated within the paired frequency bands of the FDD (frequency division duplex) mode. The FDD mode supports the underlying cellular architecture which is to serve high mobility voice users.

A particular frame structure and resource reuse mechanism in the multihop cells is proposed to guarantee high spectral efficiency. However, the resource reuse introduces intracell interference. The interference is the most critical capacity-limiting factor in a cellular system as the throughput is proportional to the C/I, and C/I decreases as the resource reuse factor increases. The sources of interference in the proposed system are the intracell interference, which is introduced due to resource reusing in the VC(s), and the regular intercell interference, which arises from the full-reuse of the radio resources in the neighboring cells.

To maintain an acceptable C/I, with the co-existence of spectrum sharing and unprohibited interference, these proposed schemes are implemented as follows:

Resources planing: carefully plan the available resources to increase the separations between the overlapped resources.

Power Control: control the transmission power to maintain a certain C/I, this is called C/I power control.

Beamforming: directed antennas are used to increase the overlapped spectrum separation and to limit interference power from dissimilar neighboring antennas.

In this thesis, a study of the interference power, the received power, the transmitted power and the C/I ratio for the proposed system is carried out using the previous different schemes for limiting the interference. For comparison, the same analysis is conducted for a pure TDMA cellular network with a reuse factor of *one*. The focus of this investigation is placed on the second service class (data) which is supported by short range multihop cells and the TDD mode operation within the paired FDD bands. The system performance for the standard cellular TDMA-FDD based voice service is well known from literature. The frame timing calculations are done using the UMTS standards [1].

This thesis is organized as follows, Chapter 2 gives a brief background about the current and the proposed spectrum sharing techniques. Chapter 3 discusses the proposed system model, cellular structure and multihop with the underlay concept, the interference scenarios, resource planing, power control and antenna beamforming. Chapter 4 draws the outline of the simulated cellular parameter and the simulation results. Chapter 5 concludes this thesis. Finally, Chapter 6 proposes some possible future working directions.

Chapter 2

Background and Problem Identification

It is envisaged that the future of the wireless communication will experience an enormous increase in the data rate and the number of users, so that the demand for the radio resources will significantly increase. The traditional radio planning for voice and data services is consuming a huge amount of the limited radio resources. With growing demands for the radio resources, efficient spectrum management techniques have been developed to reuse the available limited resources. The following sections discuss the conducted spectrum management efforts that have been carried out to utilize the wireless spectrum.

The current spectrum management efforts are concerning the entire radio access among the users in the system, manage the transmission in both communication bands (uplink and downlink), and reuse the available frequencies such that the spectral efficiency increases. Moreover, the multihop networks introduces more flexibility and efficient reuse of the available limited resources. Furthermore, the interference level could be reduced using highly directed smart-antenna system [3].

The previously mentioned schemes show the inability of withstanding the full frequency reuse interference problem, which is seen as a critical obstacle for the single frequency network deployment. The proposed system in this work introduces a new methodology for handling the interference problem, and increases the spectral efficiency for the single frequency cellular system.

2.1 Multiuser Access and Duplexing Techniques

2.1.1 Access Techniques

In the multiuser wireless systems, users share the radio resources (frequency or time). The users are multiplexed over the available time and/or frequency resources such that users acquires the appropriate resources without conflicts. The frequency or time resources are multiplexed across the users using the frequency division multiple access (FDMA) and the time division multiple access (TDMA) techniques respectively.

The FDMA technique divides the available spectrum into separated frequencies bands. The users are assigned to appropriate frequencies such that each user reserves a single frequency through the entire transmission time. The FDMA technique was suitable for analog communications, where the analog filters can easily separate the required bands.

The TDMA technique divides the channel time into time-slots (TS), where the users access the total channel for a certain TS in a periodic manner. The BS switches transmission among users, while the used frequency band is not changing during the transmission time. This technique became more applicable because of the fast digital signal processors.

In order to increase the spectral efficiency, all the users should be permitted to occupy the total channel frequency and time resources. This can be achieved if the users transmit using different orthogonal codes, such that users transmission can be resolved by decoding with the same orthogonal code at the receiver. This technique is called "code division multiple access" (CDMA). Figure 2.1, illustrates FDMA, TDMA, and CDMA access schemes.

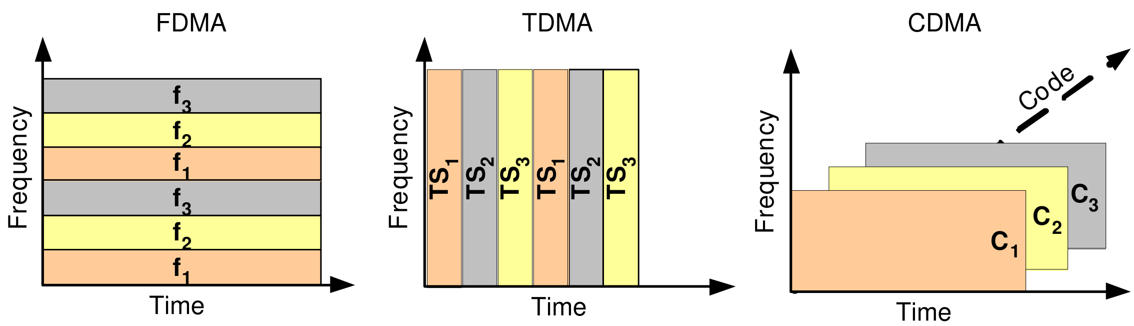

Figure 2.1: Comparison between FDMA, TDMA and CDMA

2.1.2 Duplexing Techniques

Either time-division duplexing (TDD) or frequency-division duplexing (FDD) techniques have been traditionally considered as the convenient scheme for dividing the radio resources for the downlink (DL) and uplink (UL) radio links. There are challenges with each of these two approaches, related to implementation feasibility, flexibility, sensitivity, network synchronization, latency, asymmetrical traffic, automatic gain control, and the number of filters [5]. Figure 2.2 illustrate the FDD and TDD implementation.

FDD is the duplexing technique that divides the total radio spectrum into two different/orthogonal frequency bands. Each of these two bands can be accommodated to dual radio links simultaneously. FDD is the traditional solution for voice networks, due to the channel symmetry. However, channel asymmetry in FDD can be implemented by allocating different bandwidths for the DL and UL [5], which requires variable duplexing distances that is difficult to achieve. The traditional FDD is designed to support full duplex

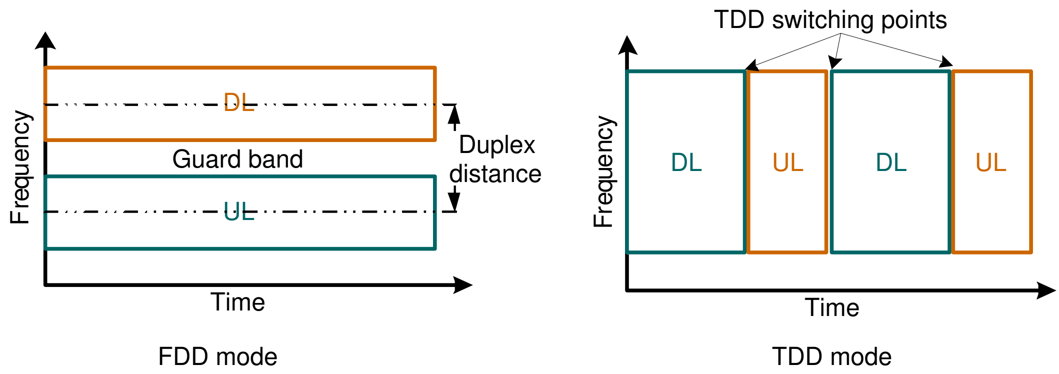

Figure 2.2: Comparison between the FDD and the TDD

transmission and reception, although the impact of the transmitted signal on the received signal must be reduced. The impact of the transmitted signal is accomplished by the duplex filter [13] which increases the cost and complexity of the MS and BS.

In TDD networks, the frequency is used for the DL and UL data. The radio frequency (RF) components of the transmitter and receiver is just the same, while the system switches from DL to UL at certain switching points. The switching point position enables the asymmetric UL/DL allocation to ensure high flexibility. The symmetric case is considered for speech communication, where the time for the DL is exactly equivalent to the time of the UL. The asymmetric case can be utilized for packet data switching communication, where the time requirements for the DL and UL may vary. The channel asymmetry allocation, as yet, is not dynamic, but it can be an important cellular design parameter [13].

Strictly speaking TDD is a half duplex transmission mode and therefore enjoys channel reciprocity. The systems that exploit channel reciprocity need simpler hardware, for example the TDD system can be implemented by using a single RF front end. Therefore, the advantages of TDD clearly outweight the advantages of FDD, especially when packet data service networks are selected.

A combination between the FDD and TDD is developed to exploit the advantages of each. This new technique is referred to as *hybrid division duplexing* (HDD). FDD is configured whenever there is requirement for high mobility wide area deployment and link continuity [4].

The HDD interference can be reduced by using the following techniques:

- The implemented equipment should be synchronized by selecting synchronized switching points in the TDD deployment.
- The FDD duplexing distance should be kept maximum.
- Efficient radio resource allocation is required aiming at increasing the separation between any interfering sources.

2.2 Cellular Model and Reuse Factor

Traditionally, the wireless communication system is between a user and base station (BS) that covers a certain footprint, which is known as a cell. The spectral efficiency of this cell is measured by bits/sec/Hz/m^2, which determines the system capacity per time, frequency and square meter. The available resources (frequency and time) are reused within the coverage area with a certain reuse factor. In order to achieve the maximum capacity, it is required to fully reuse the available resources in the smallest possible cell size.

Practically, this small reuse distance (for the full frequency deployment) is very difficult to achieve because of interference, which is the main capacity limiting factor. The full frequency reuse can be achieved only by developing new spectrum management techniques to increase the separation between each probable interference node. Figure 2.3 illustrates the cellular system with 100% frequency reuse. The scenario, in Figure 2.3 presumes three cells where the frequency f_1 is reused in each cell. The interference occurs when the undesired MS or the undesired BS of the neighboring cells transmit over the transmission range of the cell of interest.

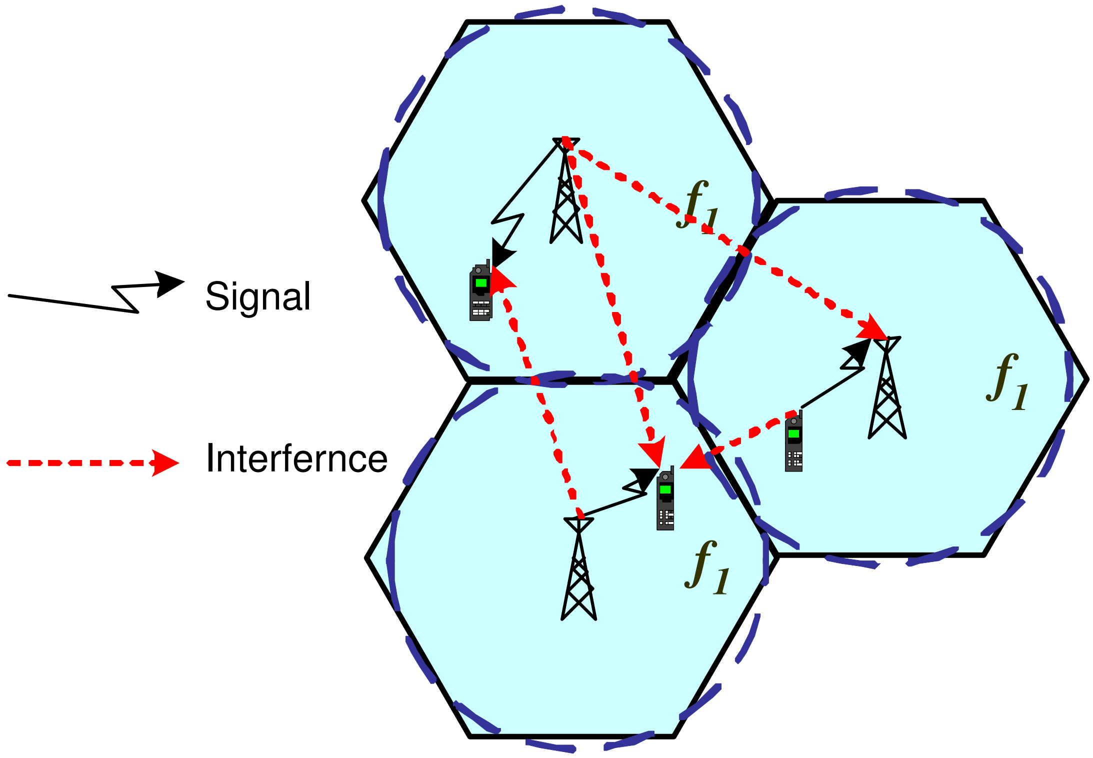

Figure 2.3: Cellular system reusing the same frequency f_1

To further reduce the co-channel interference, applying the the full frequency reuse, the multihop networks can be deployed as shown in the next section.

2.3 The Multi-hop System

The single hop cellular system, which was the main building block of the conventional cellular architecture, suffers from the capacity limitations as discussed before. Another kind of network is the ad-hoc network. The ad-hoc network principle is based on the packets store and forward from one MS to another in a multihop fashion. The ad-hoc is seen as a solution for the current cellular architecture capacity limitation. This could be done by allowing simultaneous transmission form other MS(s) in the system that operate on the same reserved resources but in other ad-hoc cells. The restriction that must be satisfied here is reducing the transmission range of the MS such that the ad-hoc cell size is much smaller than the conventional cell, and co-existing ad-hoc cells are separated by high distance [10].

The infrastructure and the wireline backbone of the ad-hoc system is almost negligible, where the other scientific term given for these networks is (*infrastructureless networks*). The absence of any centralized coordination increases the routing effort in the ad-hoc networks, while a simple solution is proposed in [9] suggesting a hybrid-wireless network. The hybrid wireless networks assumes a BS at the cell center where the MS can communicate to the BS through a single-hop, 2-hops, or multihop transmission.

The paths are selected depending on the signal power strength and the interference pattern, where the highest signal strength path is chosen for routing. This means that the interference is minimized for the selected transmission path, and the multihop network can benefit form the multihop reuse gain [11].

Finally, the hybrid, multihop and single-hop networks are considered as a solution to overcome the physical limitations of long range versus high data rate communication, on the one hand, and short range versus high connectivity, on the other hand.

Figure 2.4, illustrates the reuse strategy for the multihop cellular system with a fixed BS. A portion of the single frequency network resources is reused simultaneously in different ad-hoc cells, such that their transmission range do not coincide.

2.4 The Spatial Multiplexing Using Directed Antennas

The interference's influence increases by using a single omni-directed antenna at the cell center in the conventional cellular system model. The omni-direction antenna propagates its signal over the entire cell coverage. The problem is severe at the cell boundaries, where the coverage beams of the neighboring BS(s) interfere with the beam of the cell of interest at the desired MS.

To solve the above dilemma, a highly directed *smart-antennas* system is discussed in [1] and is shown in Figure 2.5. This system aims to allocate the available resources over highly directed antennas, where the resources can be reused by different users located at different spatial positions in the same cell.

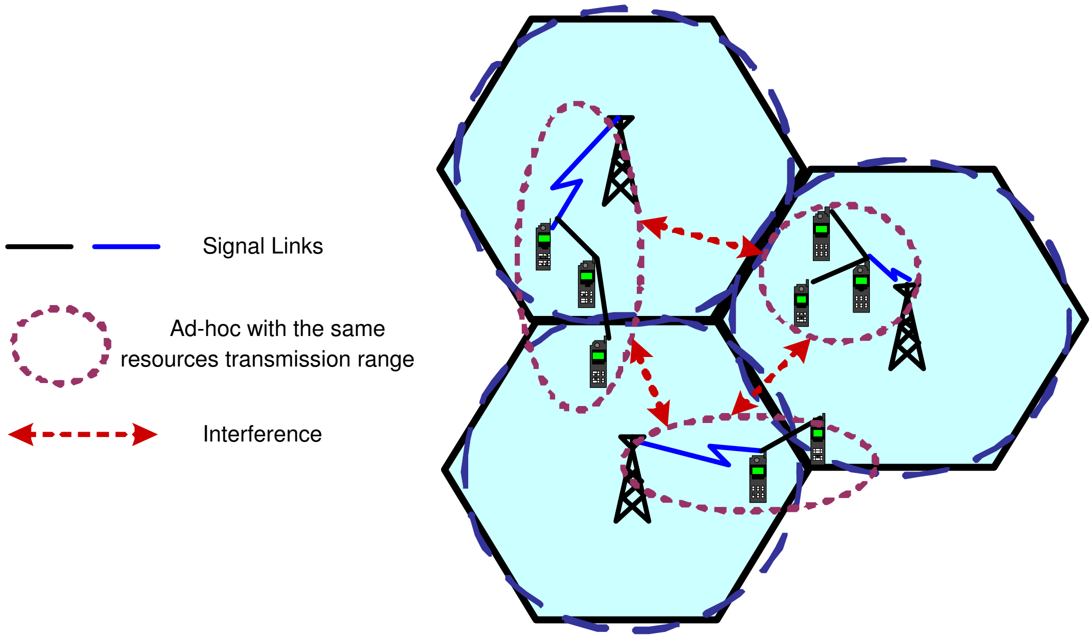

Figure 2.4: Cellular system reusing the same frequency f_1

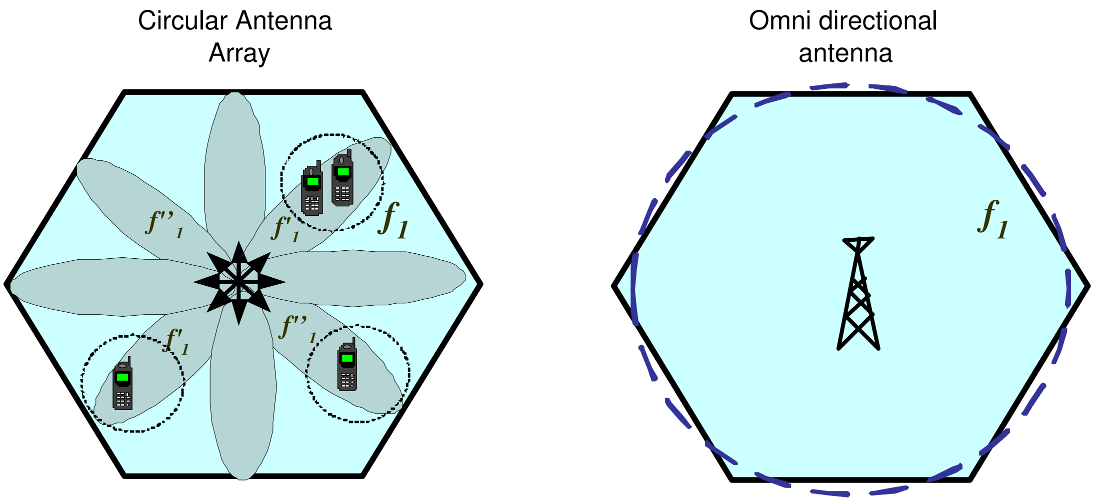

Figure 2.5: The omnidirectional antenna vs. the directed antenna

In a different fashion than the fixed clustering techniques, the directed antennas aim to allocate the resources depending on the current resource pattern intelligently. The intelligency resides in the digital signal processing (DSP) part rather than the radio-frequency (RF) antenna port [3].

The smart-antenna arrays is a collection of highly directed antennas where these antennas do exactly as the human-brain does in interpreting the sound signal. Humans can directly change their position towards the sound source in a dark room, the smart-antenna systems follow exactly the same tactic.

The leakage of the directed antenna is that the beam depth increases by increasing the antenna directivity. These penetrating beams may result in a severe interference in the neighboring cells, presuming a probability of interference between the neighboring directed antenna patterns. The only solution for this crucial problem, is to control the transmission power dynamically such that the beam power is not penetrating much more than their cell boundaries.

2.5 Transmission Power Control

The transmission power control (TPC) solution is a generic methodology to minimize the transmission power keeping a reliable link performance. The TPC algorithms are designed to achieve a certain signal strength to decrease the possible interference and increase the C/I [14]. The MS(s) re-tune its transmission power depending on either the feedback information or the previous received signal strengthes.

The advantage of the TPC is to reduce the interference at the cell boundaries. The MS located at the cell boundaries adjust its power depending on the interference level. This solution is considered for the single frequency networks to reduce the intracell interference, especially when directed antennas are used to limit the antenna beam penetration into the neighboring cells

2.6 The Proposed Solution

The current spectrum management approaches, stated above, are targeting the interference suppression and spectral efficiency increase. However, these approaches are still beyond the accepted performance for the single frequency network.

To further enhance the performance, a system concept of a hybrid multihop network is proposed which aims at avoiding interference at the first place. In addition, where interference cannot be avoided, the design goal is to reduce interference to the largest possible extent using either TPC or directed antennas. The previous traditional spectrum management techniques are intelligently enrolled in this proposed system to assess the performance. The overheads and the controlling efforts of the proposed system are minimized to be comparable to the conventional cellular system, while the performance is better than the conventional cellular system as in the results chapter.

Chapter 3

System Model

This research proposes a network that combines the single-hop conventional cellular system and the multihop schemes to compose a new hybrid cellular system. The proposed hybrid cellular system assumes a two-hops hierarchy, inside the cell of interest (COI), for communication between the MS and the BS[1]. The hybrid cellular hierarchy could benefit from the multihop resource reuse gain, on the one hand, and from the BS synchronization and centralized coordination on the other hand. The presence of BS also enriches the system by carrying out the excess controlling and synchronization effort that may be required for the pure multihop ad-hoc networks.

Inside the COI, the MS(s) are uniformly distributed within the cell, where the adjacent MS(s) can be assumed as cluster coverage that can form a multihop cell. The available MS communicate to the BS through a relay node denoted as GW. By using this hierarchy, the transmission packets are forwarded, by the 'source', to the GW, then these packets are hopped once again to the 'destination'. The two transmission hops could be performed with a short transmission range, such that the cumulative transmission ranges should not exceed the COI coverage.

The proposed system introduces a resource (time and frequency) reuse scheme in the multihop cells, which causes intracell interference between these multihop cells inside the COI. Beside this, a hexagonal cellular coverage is assumed, with a full resource reuse scheme, which causes an extra intercell interference among MS(s), GW(s) and BS(s). The proposed system considers the interference of the first tier only. Each cell, of the first tier cells, is loaded with the same number of MS(s), and resemble the COI architectural deployment.

3.1 System Topology

The problem of the full frequency reuse system arises at the regions near to the cell boundaries, where the MS(s) are considered very close to the neighboring sources of interference. The next sections models the proposed solution steps

[1] This means that every MS needs to go through a neighboring node for communicating to its BS.

for resolving interference problem at the cell boundaries.

3.1.1 Proposed Cell Layering

The proposed solution starts by splitting the cell, of radius R, into two circular layers,

inner layer this is the circular area contiguous to the BS with a cell radius R_i, where the MS in this zone are directly communicating to the BS using a single hop scheme with high data rates.

outer layer the circular cluster around the inner zone, where the MS(s) could indirectly communicate to the BS through the GW(s).

The inner layer in each cell reuses the same resources, while the beam coverage is implemented using short range antennas[2]. The outer layer is considered as the cell boundaries. The proposed system assumes that every outer layer reuse portion of the resources that differs from the inner layer resources.

To further reduce the interference level at the cell boundaries, the outer layers are clustered into number of smaller multihop cells that reuse the same resources. The multihop cells serve a number of MS(s) that indirectly communicate to the BS through a dedicated GW(s). These GW(s) are selected to satisfy the minimum pathloss (PL) condition from the multihop cell and the BS. The GW could be either a pre-installed fixed terminal that could be attached to a public services, like the traffic/street lights, or could be chosen from the MS(s) in the multihop cell satisfying the same PL condition.

3.1.2 The Transmission Classes

The two service classes of communication, data and voice, are considered in this model. The data and the voice traffics are routed using the different routing paths in the proposed system topology, depending on the priority, availability and the link symmetry as in the following sections.

The Data-Traffic

Data-traffic is originated from the BS and routed via the respective GW to the 'destination'. In turn, the 'destination' transmits data traffic via the same GW to the BS using the same TDD route. Therefore, the number of hops is exactly two. The channel reciprocity, for the BS to 'destination', could be exploited using TDD. The TDD mode could be also used for data traffic to account for traffic asymmetries and to enable multihop operation.

For the existing FDD networks, the TDD scheme could be implemented on the top of this network without considering any extra radio frequency band. The proposed system is designed such that the FDD frequency bands of the cellular system are dynamically segmented into a standard FDD segment and

[2]The coverage does not exceed a circle of radius R_i.

two TDD segments (see Figure 3.1). The access technology used is TDMA, where users are assigned to certain TS(s) for transmission or reception.

The Voice-Traffic

The FDD segment of the air interface is used to carry voice traffic in the conventional cellular due to its symmetric properties. The transmission is carried out using a single hop fashion. This scheme gives higher availability and higher priority to the voice recourses, to support sudden data traffic failure. The access technology used is TDMA, where the system performance for the standard cellular TDMA-FDD based voice service is well known from the literature and is not considered in this research.

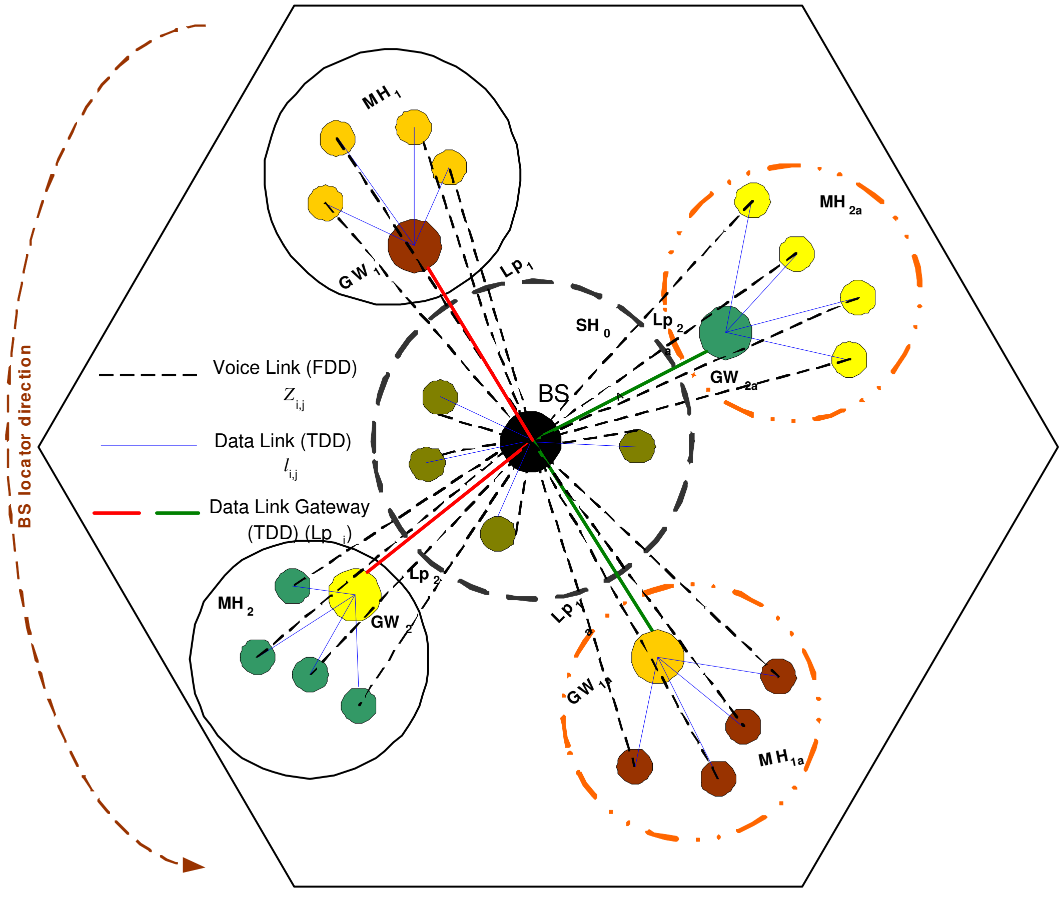

Figure 3.1: One cell design of a hybrid network

3.1.3 The System Structure

In this thesis, the performance of the multihop cells, which are clustered and located in the outer layer, is studied. The system set-up is depicted in Figure 3.1, where:

- SH_0 is the inner layer single-hop cell, and MH_1, MH_2 nd MH_3 are the multihop cells in the outer layer.

- $Lp_{1/a}$, $Lp_{2/a}$ and $Lp_{3/a}$, are the path-losses between the gateways and the BS for data transmission.

- $GW_{1/a}$, $GW_{2/a}$ and $GW_{3/a}$ are respectively the gateway for $MH_{1/a}$, $MH_{2/a}$ and $MH_{3/a}$, while the mobiles in SH_0 communicate directly to the base-station.

- l_{ij} is the pathloss between MS_j and GW_i for the data transmission, while Z_{ij} is the pathloss between any MS and the BS for the voice transmission.

The BS is responsible for locating the adjacent MS(s) to a certain multihop cell and assigning the appropriate resource to it. The BS continue locating separate multihop cells in anti clock wise direction (so that the synchronization between the cells are maintained). By applying this technique, the available resources can be reused to increase the spectral efficiency. The distances between the multihop cells, with overlapped resources, are kept as far as possible. The same radio resources are used in multihop cells that satisfies the maximum separation distance criteria, like MH_1 and MH_{1a}, etc..

The total traffic load is calculated depending on the number of the multihop cells, H_n, and the number of MS(s) in each of these multihop cells,M. The total number of MS(s), N_T, using data and voice services in the COI is $M \times H_n$.

3.2 Proposed Frequency Allocation

The proposed network uses two frequency bands (F_1 and F_2), which have been previously dedicated for an FDD transmission. These two bands are divided into two time segments (an FDD and a TDD segment) of lengths t_1 and t_2 time units respectively. Each segment is divided into a number of TS(s). The resultant duplexing technique is HDD, as discussed before. The FDD time segment is dedicated for single-hop, voice packets, transmission, while the two TDD time segments are divided into smaller TS(s) that carry the multihop data packets for the downlink and uplink traffic. Figure 3.2 illustrates the proposed frequency and time framing.

3.2.1 Framing Structure

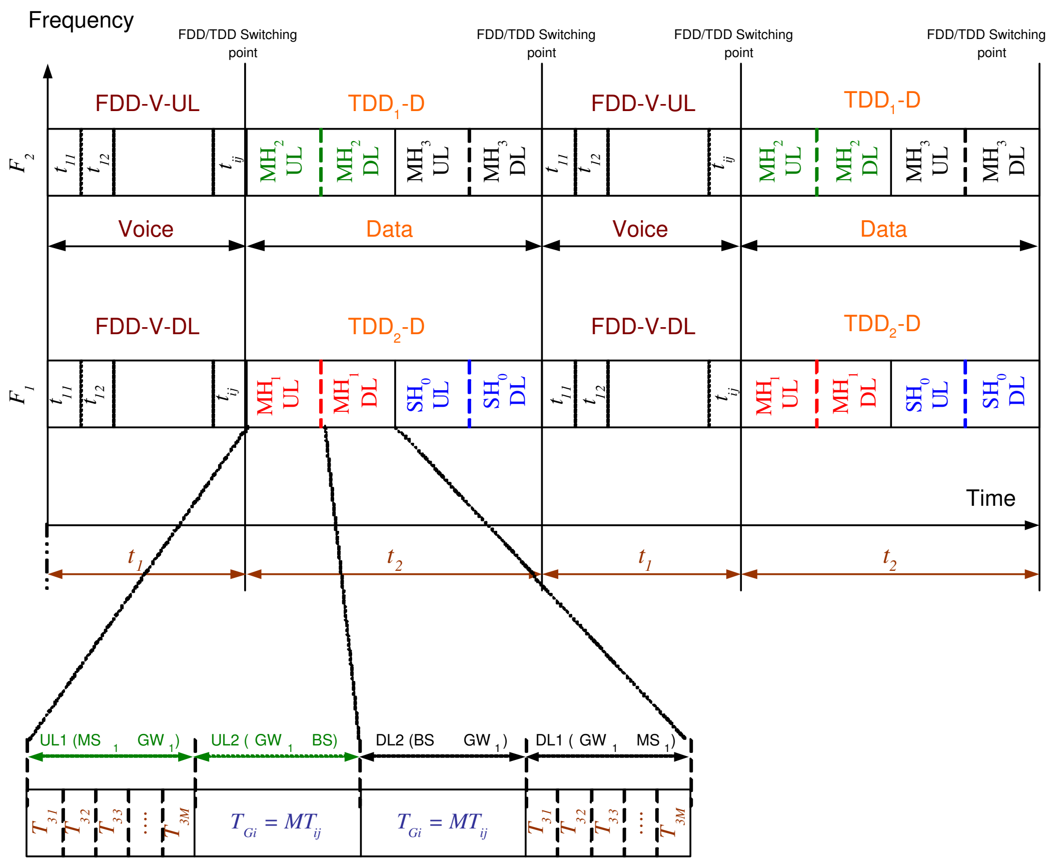

Figure 3.2: Frequency and time domain allocation in the hybrid network

In the single-hop FDD segment, the time t_1 is shared by all the users such that each user reserves two simultaneous TS(s) in each frequency band (downlink and uplink). The FDD TS(s) are dedicated to transmit a compressed voice samples in a full-duplex manner.

The TDD TS(s) are shared by the users in the multihop hierarchy such that each TS resource used in a certain multihop cell could be reused by another farther multihop cell. These TS(s) are smaller TS(s) that carry the downlink and uplink information. Moreover, a single TS is reserved for the single hop communication of the inner layer. For example, each sub frame, MH_1 and MH_2, can be shared among a number of multihop cells except SH_0, which is reserved for the single-hop inner layer.

In order to maintain flexibility, synchronization and optimal resource management, the TDD-FDD, TDD and FDD switching points are considered as variables that could be adjusted depending on the traffic load.

3.2.2 Voice and Data Transmission

The FDD segment for voice transmission is divided into a number of TS(s) equal to the number of MS(s) in the network. Voice is transmitted as compressed voice samples, where these compressed samples are transmitted using the real data rate on each of the FDD-TS. The transmission time of the voice block (t_{ij}) is calculated using the real data rate, while the actual voice packet delay ($T_{voice-min}$) is calculated using the voice sampling rate. The voice samples from all MS will be transmitted in t_1, where t_1 is less than $T_{voice-min}$.

Due to the voice compression, there could be a time difference (t_2) between the actual voice packet delay $T_{voice-min}$ and the aggregate voice transmission time t_1. This time difference can be utilized for data packet transmission by the multihop cells which are assigned to each band of the TDD bands. This time difference is calculated in Appendix A.

The data packets are transmitted using a two-hops scheme, where the data packets are transmitted from the MS(s) to the gateway assigned to this multihop cell (internal uplink), and from the GW to the BS of the cellular system (external uplink). The internal and the external downlink are just in the opposite direction, from the BS to the GW and from the GW to the MS(s). The aggregate time of the internal/external downlink/uplink should not exceed a single multihop segment (MH_i).

An example for the UMTS model (see Appendix A) is illustrated to get realistic values for data and voice transmission time, so that a practical traffic load could be computed. This example shows a maximum traffic for a low rate sampling voice quality (8 kbps) of 36 MS(s), each of which acquire 1.831 msec for data packet and 0.3052 msec for voice packet transmission at a bit rate of 2 Mbps. The aggregate data, t_2, and voice, t_1, transmission time respectively are 69.013 msec and 10.987 msec, with a total packet delay, $T_{voice-min}$, of 80 msec, which is assumed to be suitable for a poor voice quality transmission that accepts a large delay. The 80 msec can be also utilized for emergency notes and/or BS control signals to MS(s). The current UMTS specification [1] accept regular voice communication at delay less than or equal 30 msec.

3.3 Resource Reuse in Multihop Cellular System

In order to increase the capacity of the previous system, the only feasible option is to introduce a new frequency and time reuse mechanism inside the multihop cell. The resource reusing can be done by allowing more than one multihop network to occupy the same TS at the same frequency. The BS should reallocate the resources, of a certain multihop cell, to the other multihop cells that satisfies the criteria of maximum separation distance[3]. The scope of this research is focused on the dual-reuse-mode, where only two multihop cells could reuse the same resources.

Beside the spectral efficiency enhancement, for the above multihop resource reusing scheme, intracell interference is introduced along with the conventional cellular intercell interference. The intentions of this research can be stated as follows,

- reusing the available resource efficiently
- reducing the effect of both intercell and intracell interferences.

The interference could be suppressed by performing an algorithm to schedule the transmission slots between these overlapped resources multihop cells.

3.3.1 Implementation of the Dual-Reuse-Mode

The following section describes the frequency and time reuse scenario. The intracell interference, due to the resource reuse in the COI, is limited to a minimum value assuming a careful isolation in the transmission bands using a smart time scheduling. The gain of this system is accomplished by allowing two multihop cells to use the same resources with different time scheduling. This scenario is mapped using an omni-directional antenna at the BS which is located at the center of the cell. The algorithm is developed using the optimum power control, while the result of no-power control is conducted as well. For further enhancement, a highly directed antenna at the BS is assumed to solve the BS interference problems.

Some assumptions, which are enumerated below, describes the design aspects for this scenario,

1. The GW is either a MS or a fixed wireless terminal in the multihop cell, which has the least pathloss connecting the BS.
2. Each multihop cell contains a number of MS(s) that are capable of transmitting voice, data or voice and data at the same time.
3. A lookup table, in the BS, contains the polar location (radius, in meter, and phase, in radian) of each MS inside the COI, and this table is updated frequently.

[3]Keeping the resource overlapping nodes as far as possible to reduce interference.

4. Up to two multihop cells are allowed to use the same resources (using the dual mode), frequency and TS(s) (TS-MH_1, TS-MH_2,etc.), at the same time. This may generate interference which, however, is minimized by the proposed frame structure and resource allocation.

5. As the number of data users in proposed system increases, the time available for all MS(s) to use voice on FDD decreases, i.e., voice sampling rate of the existing users is allowed to be reduced to accommodate more data traffic.

6. The simulation is performed by considering that the COI has a total traffic of 32 MS(s), which are equally divided across the multihop cells. Each cell consists of 3 pairs of multihop cells; each pair shares the same resources, and each multihop cell consists of 4 MS(s) and a GW, where the GW is responsible for transmitting data between MS and BS (total number of data users 3 x 2 x 4 = 24).

7. The co-located single-hop (SH_0) gets a separate slot in one or two TDD domains which is not shared by any other multihop network. Due to the single-hop nature of this cell twice as many users can be accommodated (8 MS(s)).

8. This proposal also assumes an asymmetric uplink and downlink case where the uplink to the downlink ratio is less than one.

9. The MS(s) and the BS(s) are transmitting initially with a transmit power of 30 dBm.

10. The added complexity in the proposed system is set to the BS, where the main complexities are the MS location update and GW assigning.

11. The GW is as simple as a relay node, where its main function is to store and forward data periodically.

3.3.2 Dual-Reuse-Mode Time Scheduling

The proposed scheduling procedure allocates for the same TS, two different transmission ranges. Figure 3.3 shows an example for the multihop cell, MH_1, that operates on the first TS and uses the frequency band F_1. The available resources of the multihop MH_1 are reused by a farther multihop cell, MH_{1a}, with different transmission scheduling.

In order to organize transmission and reduce interference, the same TS is scheduled for different transmission ranges [4]. For example, for each TS,

The downlink: The GW of one of the multihop cells could be downloading to its MS, while the BS is downloading to the GW of the other multihop cell (TS_1 and TS_3).

[4] It is assumed here that the transmission ranges of the concurrent connections are not overlapping

The uplink: The MS of one of the multihop cells could be uploading to its GW, while the other GW is uploading to the BS (TS_2 and TS_4).

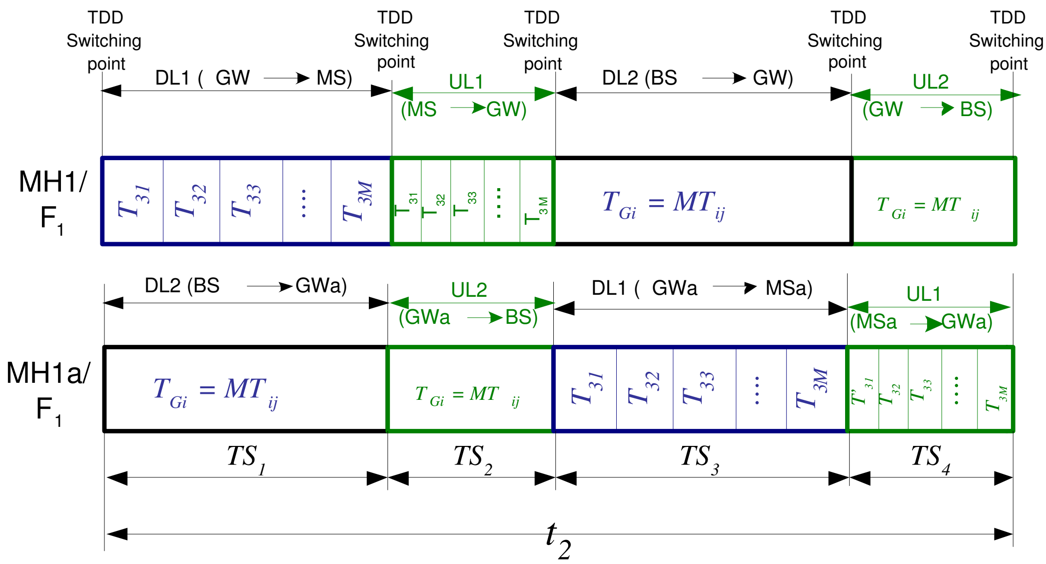

Figure 3.3: Transmission time scheduling for the dual mode

3.4 Transmission and Interference Scenarios

3.4.1 Pure TDMA Interference Scenarios

For performance comparison, a pure TDMA cellular system is implemented using 32 MS(s) per each hexagon cell where the MS(s) are distributed uniformly within the cells. A full resource reuse cellular system is considered, where the interference is assumed to be from the first tier only.

In the pure TDMA, due to the overlapped resources of the neighboring cell and the COI, interference is considered to be dominant in this system deployment. Two different interference scenarios, studied in two different TS(s), are considered due to the use of a TDD air interface for the pure TDMA technique. These two scenarios are:

1st Scenario (S1): Opposed TS deployment

First TS: The COI carries out the transmission from the BS to the MS(s), while the interfering cells carry out the transmission from the MS to the BS, i.e.: the MS(s) of the first tier cells interfere with the MS(s) of the COI (see Figure 3.4, where the curved arrows represent the interference, while the short arrows represent the transmission direction)

Second TS (not shown in Figure 3.4): The COI carries out the transmission from the MS(s) to the BS, while the interfering cells carry out the transmission from the BS to the MS(s), i.e.: the BS(s) of the first tier cells interfere with the BS of the COI.

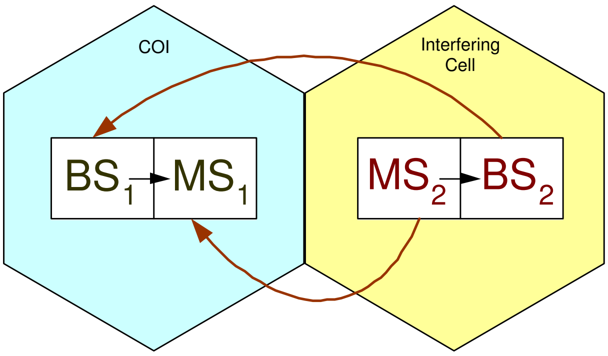

Figure 3.4: Opposed TS deployment and resulting interference at the first TS

2nd System (S2): Same TS deployment

First TS: The COI and the first tier cells carry out the transmission from the BS to the MS(s), i.e.: the BS(s) of the first tier cells interfere with the MS(s) in the COI (see Figure 3.5).

Second TS (not shown in Figure 3.5): The COI and the first tier cells carry out the transmission from the MS(s) to the BS, i.e.: the MS(s) of the first tier interfere with the BS in the COI.

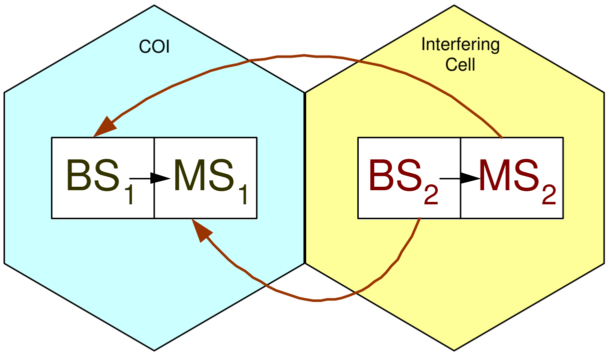

Figure 3.5: Same TS deployment and resulting interference at the first TS

3.4.2 Proposed Scheme Interference Scenarios

Two types of interferences are considered in this design, the intracell interference, due to multihop reuse scheme, and intercell interference. Both interferences are efficiently suppressed using the synchronization scheduling in Figure 3.3. Therefore, the previous scheduling scheme is assumed to be deployed in each of the neighboring cells, and synchronized with the COI. The multihop locations, in the 7-cells, is also assumed to be perfectly coordinated with the COI. The cellular coordination could be satisfied by allowing the BS(s) to start the multihop positioning from the same angle in every cell.

The scheduling, in Figure 3.3, is used to determine the transmission and interference scenarios. By studying the intracell interference, it is found that GW_a and GW will experience two different interference levels, at TS_1 (when the GW on the opposite site transmits to the MSs) and TS_4 (when the GW on the opposite site transmits to the BS), and similarly for TS_2 and TS_3. Using the previous criteria, the intercell interference can be found similarly.

In the following, the interference from MH_1 to MH_{1a} is assumed. Furthermore, it is assumed that GW_a and GW are at the same distance from the base station which makes the interference scenarios symmetrical. Therefore, it suffices to study interference from MH_1 to MH_{1a} using the cellular model as follows,

TS_1: Interference at GW_a, GW respectively

1. GW interferes with GW_a, during transmission to MS(s) (in TS1).
2. The first tier GW(s), during transmission to BS, interfere with the GW_a in the COI.
3. The first tier BS(s), during transmission to GW_a(s), interfere with GW_a in the COI.

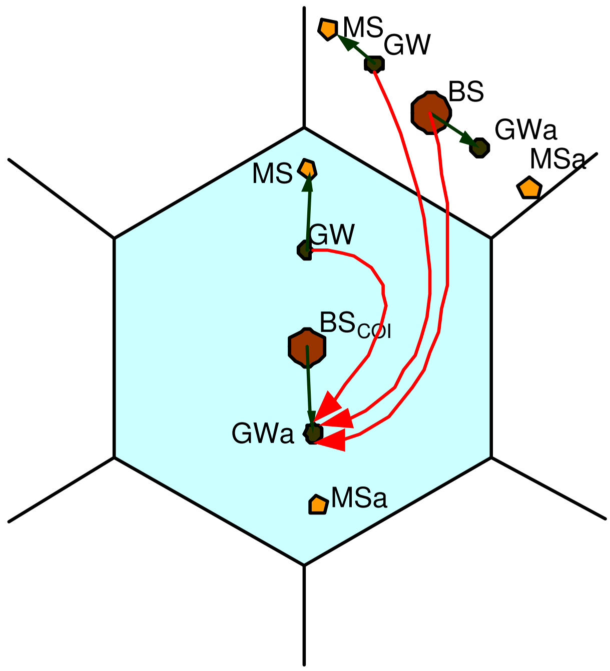

Figure 3.6: GW_a interference at TS_1

TS_2: Interference at BS

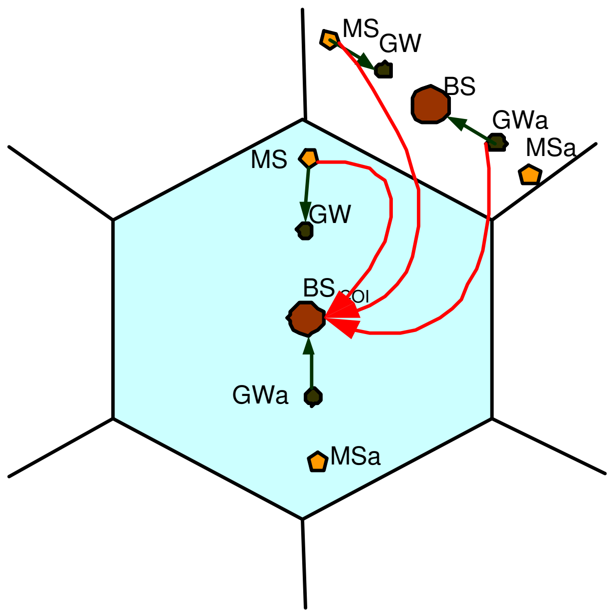

Figure 3.7: BS interference at TS_2

1. MS(s) interfere with BS, during transmission to GW (in TS2).
2. The first tier MS(s), during transmission to GW(s), interfere with the BS in the COI.

3. The first tier GW_a(s), during transmission to BS(s), interfere with the BS in the COI.

TS_3**: Interference at MSa, and MS respectively**

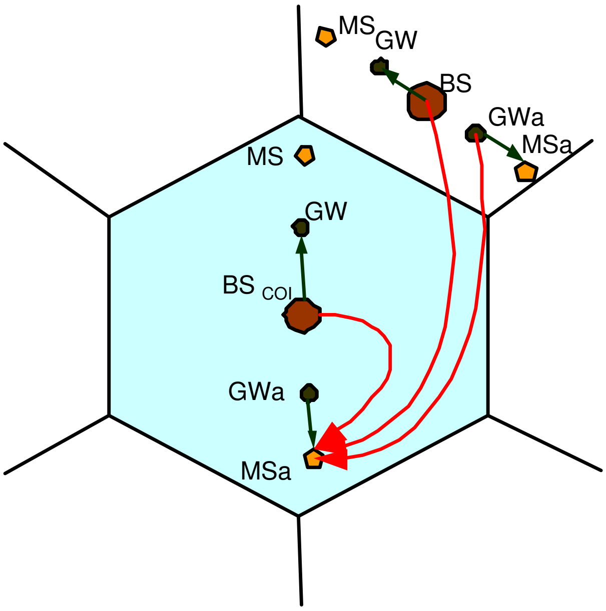

Figure 3.8: MSa interference at TS_3

1. BS interferes with MSa(s), during transmission to GW (at TS3).
2. The first tier BS(s), during transmission to GW(s), interfere with the MSa(s) in the COI.
3. The first tier GW_a(s), during transmission to MSa(s), interfere with the MSa(s) in the COI.

TS_4**: Interference at GW_a, GW respectively**

1. GW interferes with GW_a during transmission to BS (in TS4).
2. The first tier GW(s), during transmission to BS(s), interfere with GW_a(s) in the COI.
3. The first tier MSa(s), during transmission to GW_a(s), interfere with GW_a(s) in the COI.

3.4.3 Pathloss Calculations

The interference is calculated using the UMTS (universal mobile telecommunications system) outdoor pathloss model in [12]. The implemented cells are of

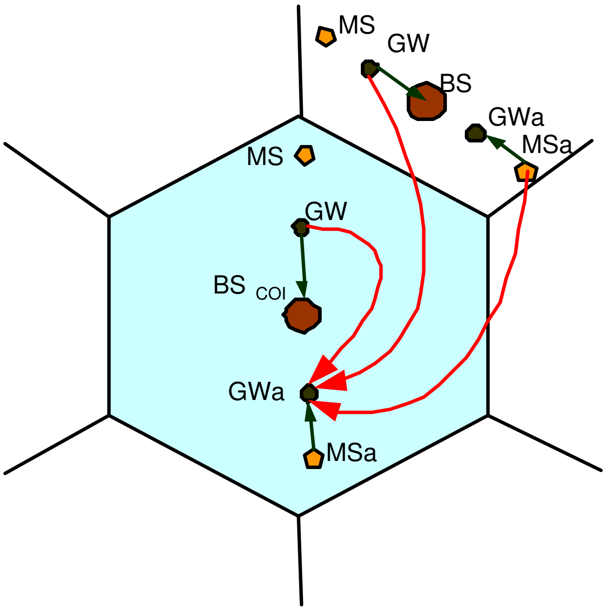

Figure 3.9: GW_a interference at TS_4

radius, R, equal to 5 kilometer (km), and the GW(s) are located at a minimum distance from the BS equals to $0.4 \times R$.

The following equation represents the implemented path-loss model.

$$\mathrm{PL}(d)|_{dB} = K + 10n\log(d) + X_\sigma \tag{3.1}$$

where n is the pathloss exponent of the cellular model, and equals to 4, d is the distance between the interfering source and the destination antenna in km, K is pathloss value at reference distance, equal 49 dB, and X_σ is the lognormal shadowing effect for the outdoor model with a variance, σ_X, of 10 dB. For more details see [12] section B.1.4.1.2.

With the generic representation of this pathloss model, the received and interference powers are calculated as follows.

1. The desired power, $P_{r-desired} = P_{t-desired} - (K + 10n\log\frac{d_{desired}}{d_0} + X_{\sigma-desired})$ in dB
2. The interference power, $P_{r-interference} = P_{t-interference} - (K + 10n\log\frac{d_{interference}}{d_0} + X_{\sigma-interference})$ in dB.
3. Carrier-to-interference ratio, $C/I = P_{r-desired} - P_{r-interference}$ in dB.

3.5 Power Control

In both systems, the pure TDMA and the proposed system, a C/I based closed loop power control algorithm is used. A C/I threshold (C/I_{target}) is defined which is mapped to a particular expected bit-error-ratio at the physical layer.

The serving node estimates the C/I ratio at the intended receiver and saves it as C/I_{est}, if $C/I_{est} > C/I_{target}$ then the power control sends a command to reduce the transmit power, while if $C/I_{est} < C/I_{target}$ then the power control sends a command to increase the transmit power to maintain the desired C/I_{target}.

In the proposed system, the simulation is implemented with a maximum allowed transmit power of 43 dBm and the minimum allowed transmit power of -40 dBm.

3.6 Directed Antenna Pattern

Sectorization at the BS(s) is considered recently as a solution for interference suppression in the system. Sectorization can be achieved using a directed antenna, at the BS, with arbitrary N sector antennas, $180^o/N$ for each sector. The number of sectors, N, can be a design parameter. The antenna pattern and the proposed transmission pattern for the multihop scenario are shown in Figure 3.10 and Figure 3.11.

Directional antennas, at the BS, are implemented such that only the GW, of a certain multihop cell, is covered by a directed beam from the directed antenna. The smart antenna direction is controlled by an intelligent DSP algorithm. This technique generates high beamformed pattern at the desired location (GW) and almost null antenna gain elsewhere. The coverage technique is switched antenna beam [3].

The GW may lie within the angle (Angle off-boresight) [7], $-\alpha$, 0, and α, from the beam direction, where α equals 1/2 the 3 dB beam-width. The relative antenna gains at the transmitter and receiver (G_T and G_R) at the previous angles off-boresight is assumed to be constant and equal to 0 dB, assuming 0 dB is the maximum relative antenna gain at the main antenna pattern lobe [3], and -22 to -35 dB at off-boresight greater than 90^o (see 4.1 for more details).

With the previous pathloss model, the receiver antenna gain G_R and transmitter antenna gain G_T, the new receive and interference powers are calculated as follows.

1. The desired power, $P_{r-desired} = P_{t-desired} - (K + 10n\log\frac{d_{desired}}{d_0} + X_{\sigma-desired} + G_{T-desired} + G_{R-desired})$ in dB, where X_σ models the log-normal shadowing

2. The interference power, $P_{r-interference} = P_{t-interference} - (K + 10n\log\frac{d_{interference}}{d_0} + X_{\sigma-interference} + G_{T-interference} + G_{R-interference})$ in dB.

Table 3.1: Used values for the relative antenna gains G_R and G_T

angles off-boresight	Relative Gain Value in dB
0^o to 20^o	0
20^o to 30^o	-5
30^o to 50^o	-10
50^o to 90^o	-17
90^o to 135^o	-22
135^o to 180^o	-35

3. Assuming $P_{t-desired} = P_{r-interference}$, then the carrier-to-interference ratio is, $C/I = 10n \log \frac{d_{interference}}{d_{desired}} + G_{T-desired} + G_{R-desired} + X_{\sigma-desired} - (G_{T-interference} + G_{R-interference} + X_{\sigma-interference})$ in dB.

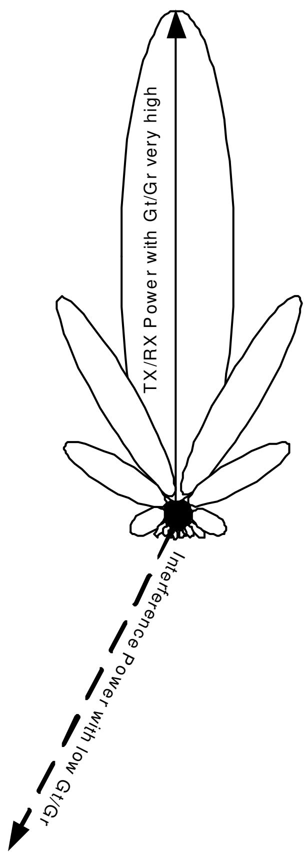

Figure 3.10: Antenna Pattern

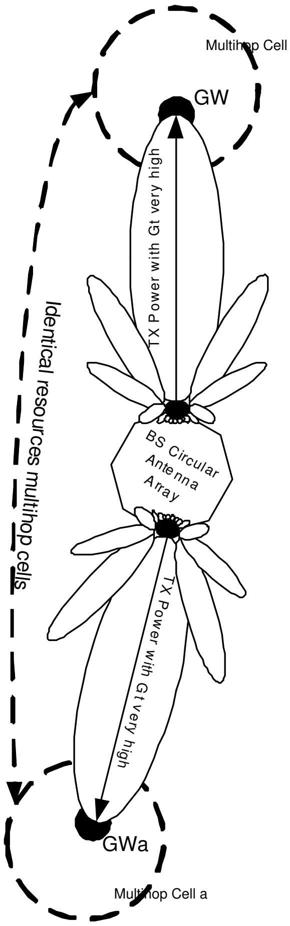

Figure 3.11: Proposed transmission pattern

Chapter 4

Simulation Results and Discussion

The following figures show the cdfs of interference, received power, transmitted power and the achieved C/I levels of the proposed system using a BS with omni-directional or directed antenna at the COI. The system is evaluated with and without power control. In the case of power control, a C/I based power control is applied with a target, C/I_{target}, of 5 dB. The interference results for the pure TDMA cellular system, with frequency reuse of 1, are implemented without power control and with power control for the same C/I_{target}. The performance of this system is compared against the proposed multihop system. The following table lists the scenarios of investigation and the corresponding results. Each plot of scenario No. 1 - 4 shows four graphs which correspond to the interference scenarios described in the previous section. The results for scenarios No. 5 - 6 include graphs for both TDD specific interference scenarios depicted in Figure 3.4 and Figure 3.5.

Table 4.1: Scenarios under investigation

No.	**Description**	**Figures**
1	Omni-directed-antenna without power control	Figure 4.1 - Figure 4.3
2	Omni-directed-antenna with power control	Figure 4.4 - Figure 4.7
3	Directed antenna without power control	Figure 4.8 - Figure 4.10
4	Directed antenna with power control	Figure 4.11 - Figure 4.14
5	Pure cellular TDMA without power control	Figure 4.15 - Figure 4.17
6	Pure cellular TDMA with power control	Figure 4.18 - Figure 4.21

4.1 The Proposed System Simulation Results

4.1.1 Omni-directional Antenna at the BS without Power Control (Scenario No. 1)

The Interference Power cdf Curves

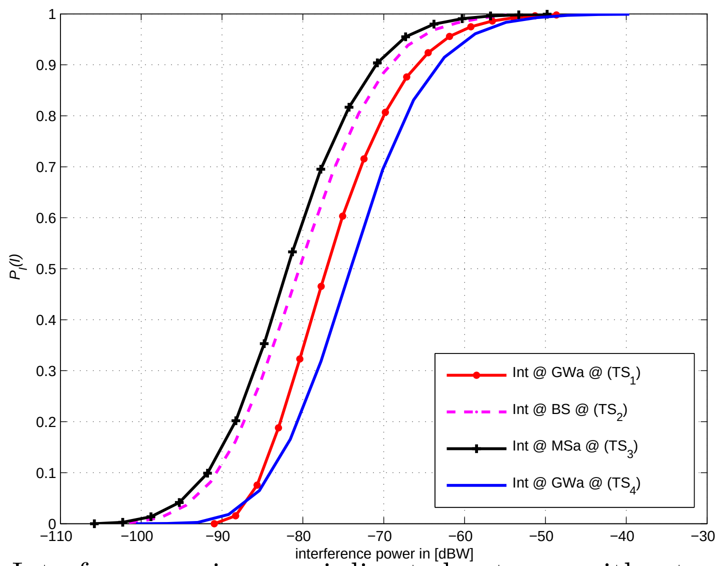

Figure 4.1: Interference using omni-directed antenna without power control

The Received Power cdf Curves

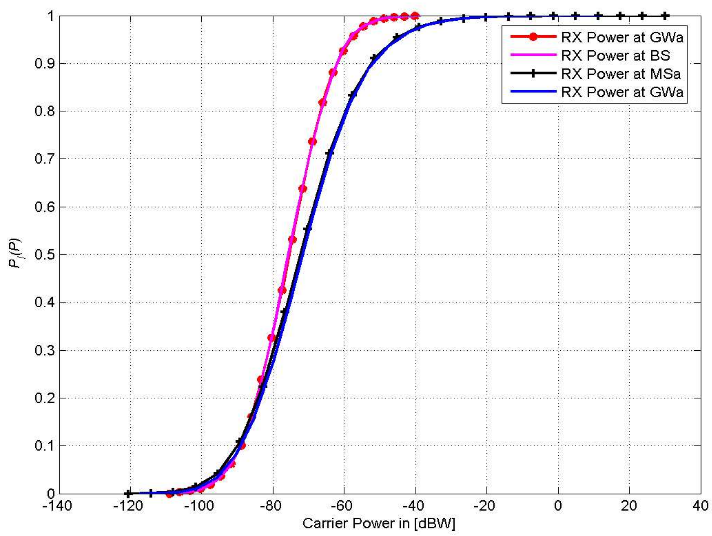

Figure 4.2: Received using omni-directed antenna without power control

The cdf curves of C/I ratio

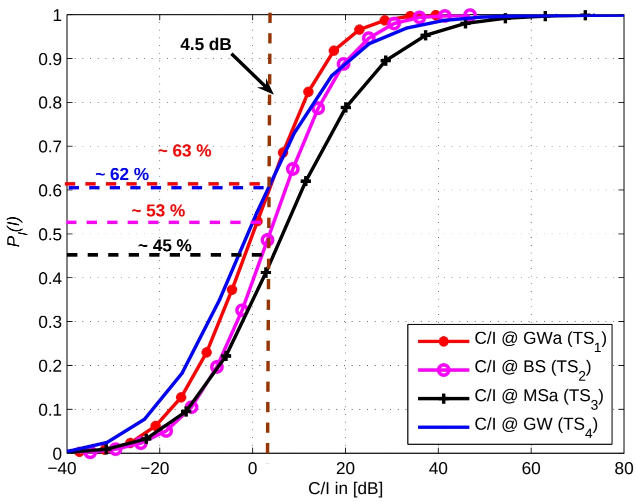

Figure 4.3: C/I ratio omni-directed antenna without power control

Summary

The outage probability is the probability that the C/I ratio falls below a certain C/I$_{min}$ [8]. The C/I$_{min}$ is selected to be slightly less than the C/I$_{target}$, which is equal to 4.5 dB. The following table indicates the outage probability for the results in Figure 4.3.

Table 4.2: Outage probability using omnidirectional antennas and no power control

Time Slot (TS)	**C/I calculated @**	**P(C/I < 4.5 dB)**
TS_1	GW_a	$\sim$ 63 %
TS_2	BS	$\sim$ 53 %
TS_3	MS_a	$\sim$ 47 %
TS_4	GW	$\sim$ 62 %

4.1.2 Omni-directional Antenna at the BS with Power Control(Scenario No. 2)

The Interference Power cdf Curves

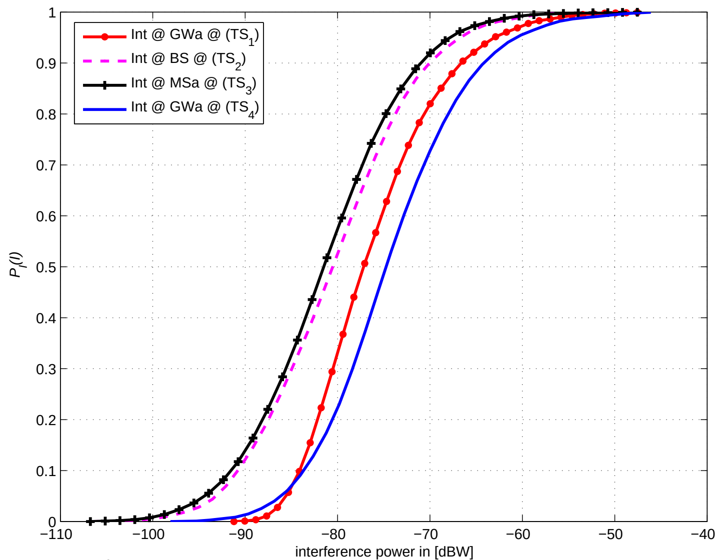

Figure 4.4: Interference using omni-directed antenna with power control

The Received Power cdf Curves

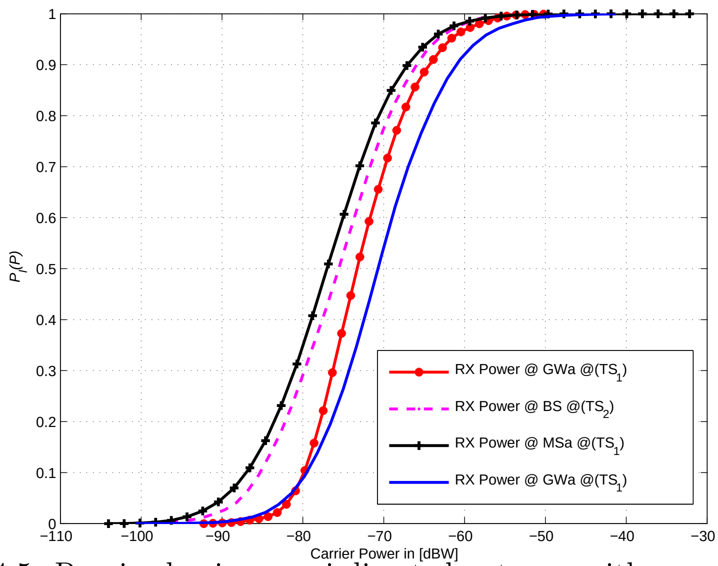

Figure 4.5: Received using omni-directed antenna with power control

It is obvious that the received power curves are proportional to the interference due to the C/I based power control, i.e. when interference increases, the power increases up to the maximum transmit power of 43 dBm.

The Transmitted Power cdf Curves

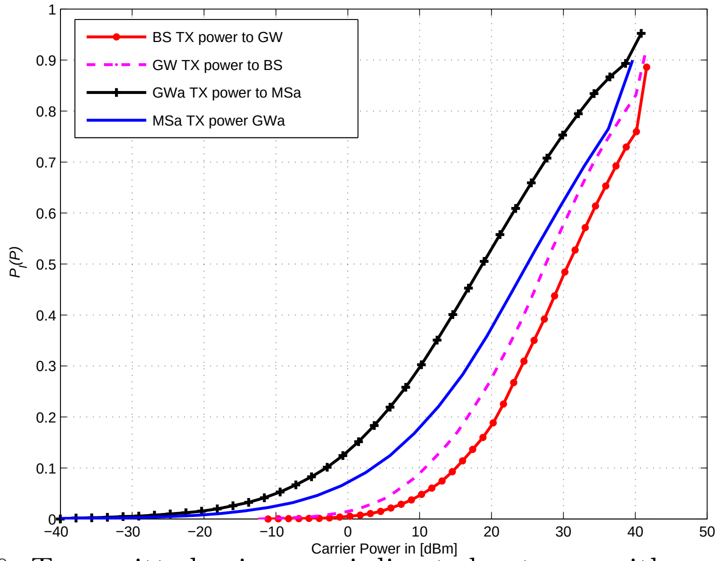

Figure 4.6: Transmitted using omni-directed antenna with power control

The cdf curves of C/I ratio

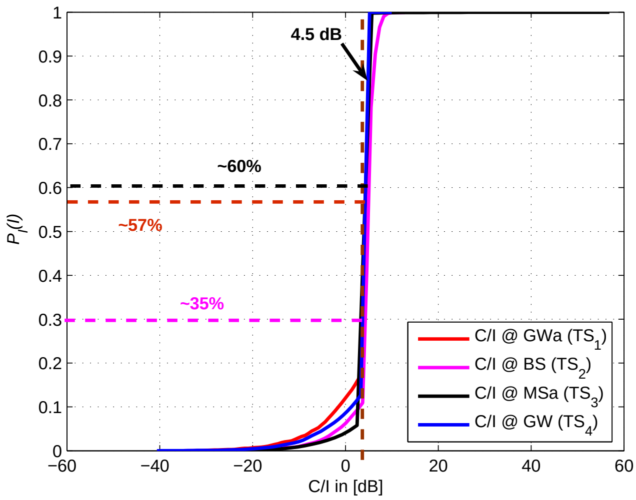

Figure 4.7: C/I ratio using omni-directed antenna with power control

It can be seen that with the given transmit power range, the target C/I is very well maintained.

Summary

The most critical entities in the systems are the gateway stations which can be deduced from the outage curves with fixed power assignments (Figure 4.3). The C/I power control algorithm is able to reduce outage to negligible levels (Figure 4.7). Again, from the cdf of the transmit powers in the case of power control (Figure 4.6), it can be seen that the BS has to use highest powers in order to achieve the target C/I at the GW indicating high interference at the GWs. For example, the probability of the transmit power of the BS being less than 20 dBm is only 20%, compared to 40% in the case of MSs, and between 29% - 40% in the case of the GWs.

The following Table, Table 4.3, summarizes the outage ratio for the previous technique. The outage could be reduced using the directed beamforming as in the coming sections.

Table 4.3: Outage probabilities using omni-directed antennas with power control

Time Slot (TS)	**C/I calculated @**	**P(C/I $<$ 4.5 dB)**
TS_1	GW_a	$\sim$ 57 %
TS_2	BS	$\sim$ 35 %
TS_3	MS_a	$\sim$ 60 %
TS_4	GW	$\sim$ 57 %

4.1.3 Directed Antenna at the BS without Power Control (Scenario No. 3)

The Interference Power cdf Curves

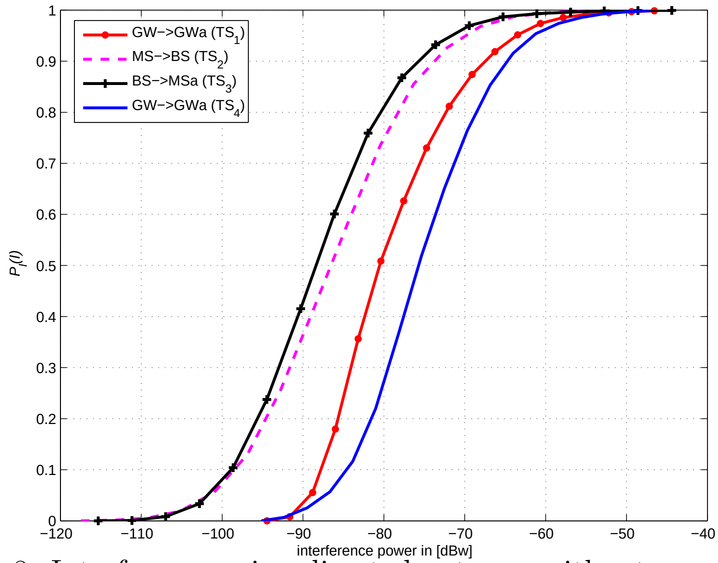

Figure 4.8: Interference using directed antenna without power control

The Received Power cdf Curves

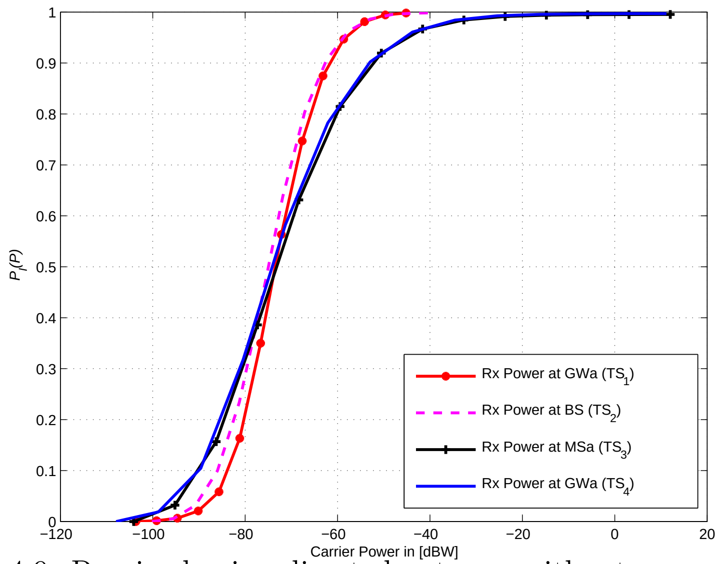

Figure 4.9: Received using directed antenna without power control

Figure 4.9 depicts the cdf of the useful received powers. It is expected that the received powers at TS_1 (BS) and TS_2 (GWa) are identical due to the point-to-point link (1st hop). The same applies to TS_3 (MS) and TS_4 (GWa) (2nd hop).

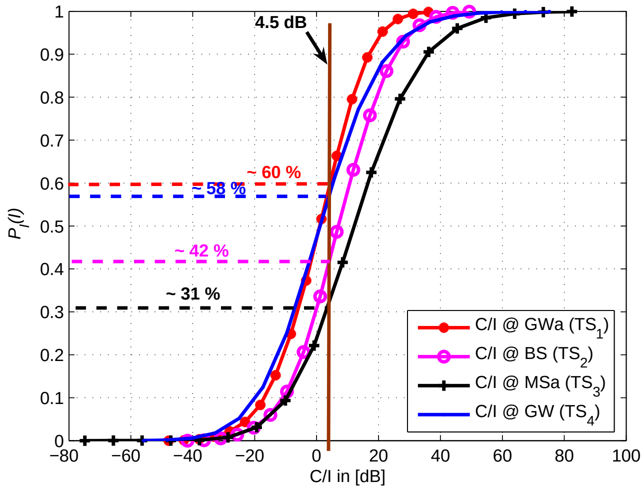

Figure 4.10: C/I ratio using directed antenna without power control

The cdf curves of C/I ratio

Summary

The following Table, Table 4.4, summarizes the outage results. The results shows that the directed antenna without power control scenario performs better than the omni-directed antenna with power control scenario. This means that the interference levels in the directed antenna without power control is lower than the case of omni-directed antenna with power control scenario without the complexity of the power control algorithm.

Table 4.4: Outage probabilities using directional antennas and no power control

Time Slot (TS)	**C/I calculated @**	**P(C/I < 4.5 dB)**
TS_1	GW_a	~ 60 %
TS_2	BS	~ 42 %
TS_3	MS_a	~ 31 %
TS_4	GW	~ 58 %

4.1.4 Directed Antenna at the BS with Power Control (Scenario No. 4)

The Interference Power cdf Curves

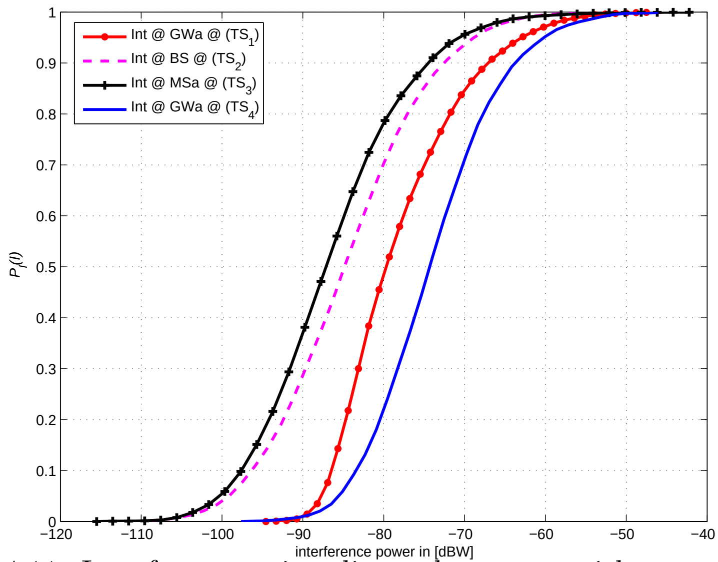

Figure 4.11: Interference using directed antenna with power control

The Received Power cdf Curves

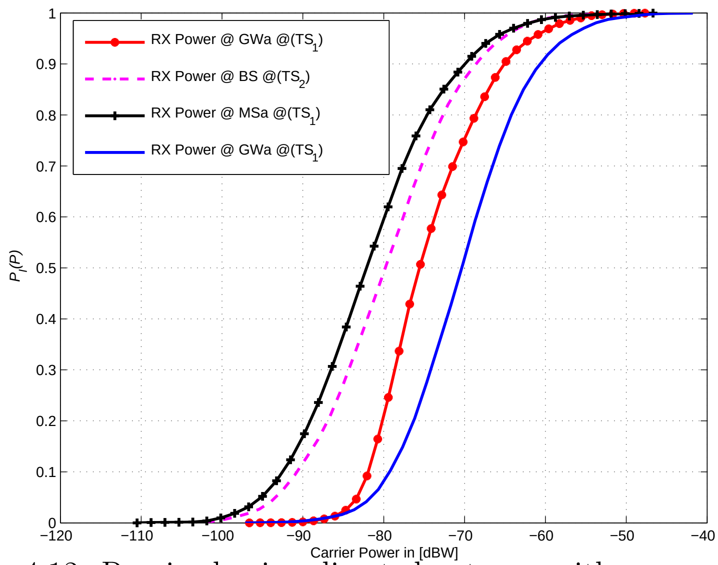

Figure 4.12: Received using directed antenna with power control

The Transmitted Power cdf Curves

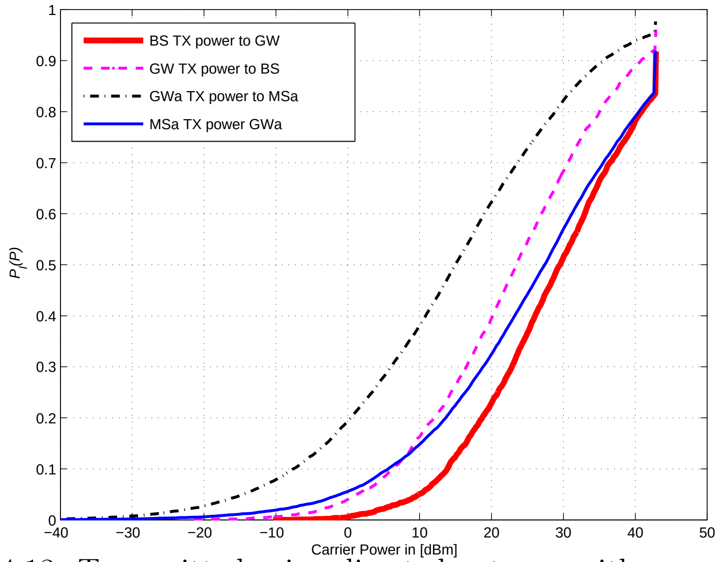

Figure 4.13: Transmitted using directed antenna with power control

The cdf curves of C/I ratio

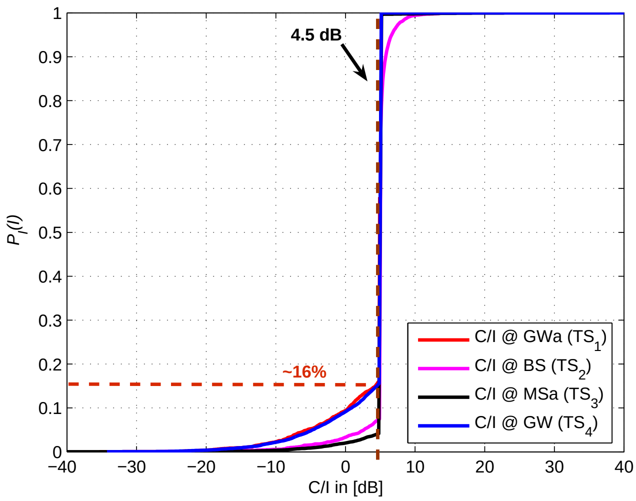

Figure 4.14: C/I ratio using directed antenna with power control

Summary

Beamforming primarily helps to reduce interference at the BS and the MS(s) (compare Figure 4.3 with Figure 4.10). In particular for fixed power assignments, outage of the MS(s) is reduced from 47% to 31% and outage of the BS is reduced from 53% to 42%. In contrast, outage of the GW(s) is only reduced from 63% to 60%, 62% to 58% respectively. Again, power control is able to almost entirely avoid outage such that 32 data users are fully served at a C/I of 4.5 dB. However, from the cdfs of the required transmit powers when using the C/I-based power control it can be found that beamforming causes higher transmit power levels at the MS(s) - due to higher interference at the GW(s). For example, the probability that the transmit power is less than 20 dBm in the case of the BS is 20% which is unchanged from the case without beamforming. With regard to MS(s) beamforming reduces this probability form 40% to 30% which means that now 70% of all MS require a transmit power greater than 20 dBm as opposed to only 60% in the case of no beamforming. With regard to the GW(s) in the case of beamforming the probability that less than 20 dBm are required is increased from 53% to 60%, and 29% to 40% respectively. This is due to the fact that the MS(s) and BS(s) experience less interference in the case of beamforming.

Finally, It is seen from the previous C/I ratio curves that the outage is reduced from 60%∼31% to only 16%.

4.2 Pure TDMA Cellular System Simulation Results

In the state-of-the-art solution of a pure TDMA network is considered. The same number of data users (32) per cell are uniformly distributed. As TDD is used, two different interference scenarios are analysed:

S1 opposed TX assignment. This means that, for example, all six neighbouring BSs transmit while the BS in the COI receives (causing BS-BS interference). Similarly, MS-MS interference occurs in S1.

S2 same TX assignment. This means that all BSs and all MSs in the network transmit and receive at the same time. In this case only BS-MS and MS-BS interference occurs.

4.2.1 Pure TDMA system without power control (Scenario No. 5)

The Interference Power cdf Curves

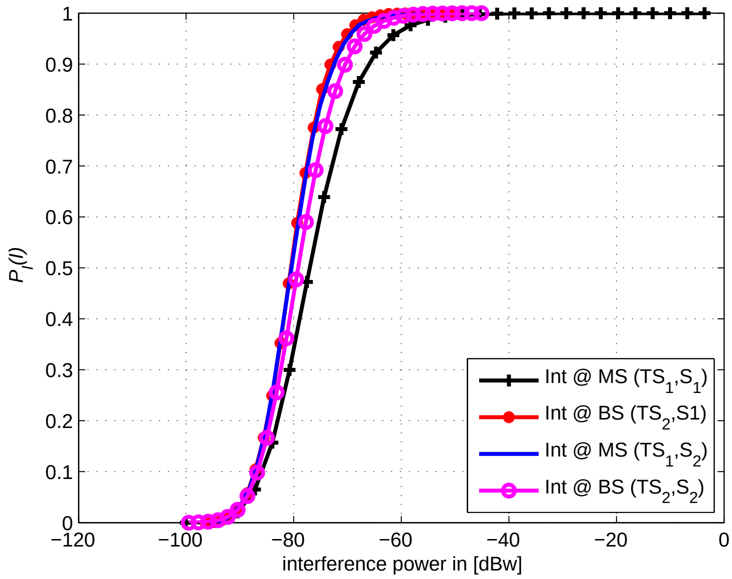

Figure 4.15: Interference using pure TDMA without power control

The Received Power cdf Curves

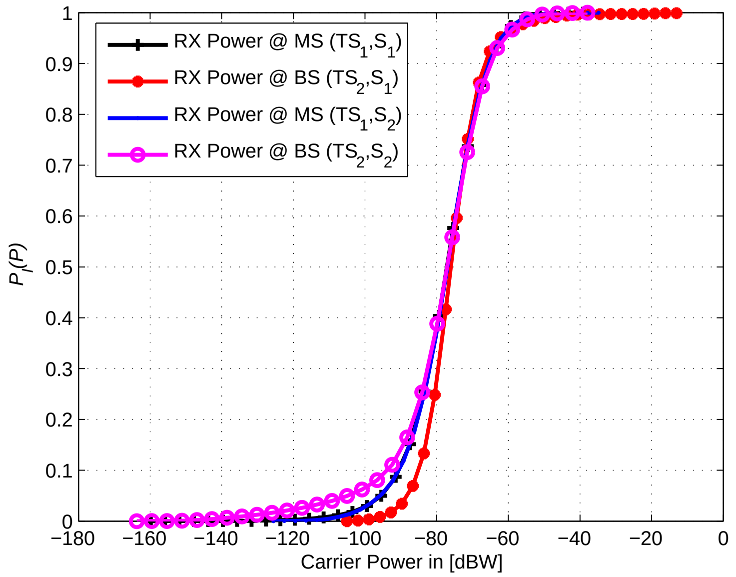

Figure 4.16: Received using pure TDMA without power control

The cdf curves of C/I ratio

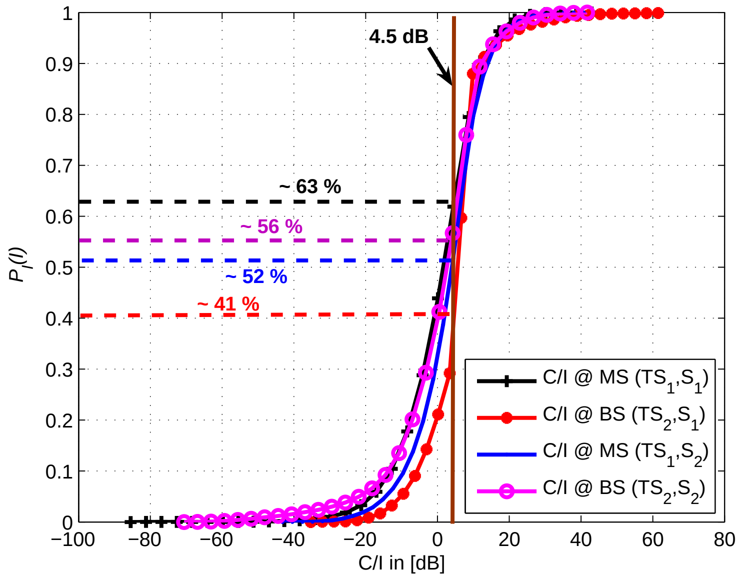

Figure 4.17: C/I ratio using pure TDMA without power control

Summary

The outage probabilities (below 4.5 dB) for a C/I_{target} threshold power control of 5 dB are depicted in Table 5.

Table 4.5: Outage probability for the C/I using pure TDMA without power control

Time Slot (TS)	**C/I calculated @**	**P(C/I < 4.5 dB)**
(TS_1,S1)	MS	∼ 63 %
(TS_2,S1)	BS	∼ 41 %
(TS_1,S2)	BS	∼ 52 %
(TS_2,S2)	MS	∼ 56 %

4.2.2 Pure TDMA with power control (Scenario No. 6)

The Interference Power cdf Curves

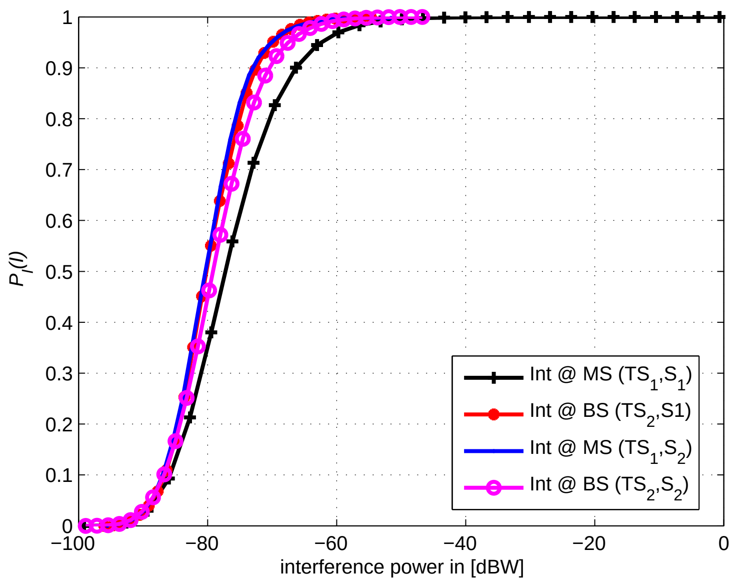

Figure 4.18: Interference using pure TDMA with power control

The Received Power cdf Curves

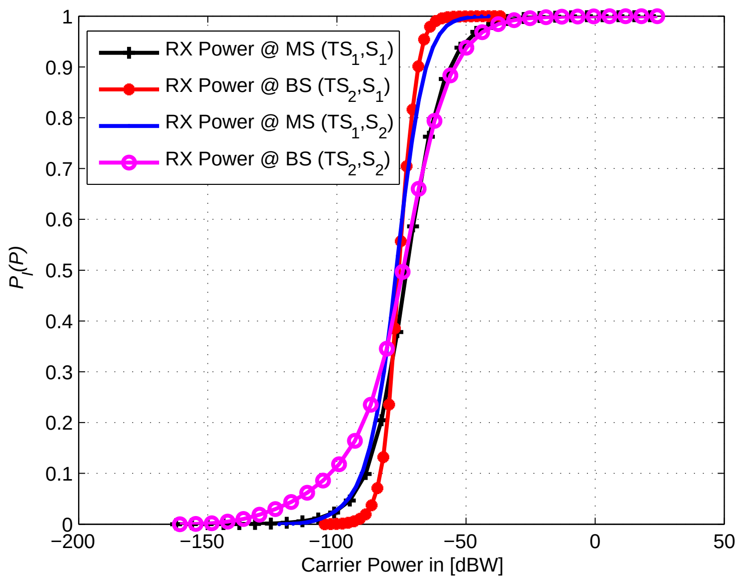

Figure 4.19: Received using pure TDMA with power control

The Transmitted Power cdf Curves

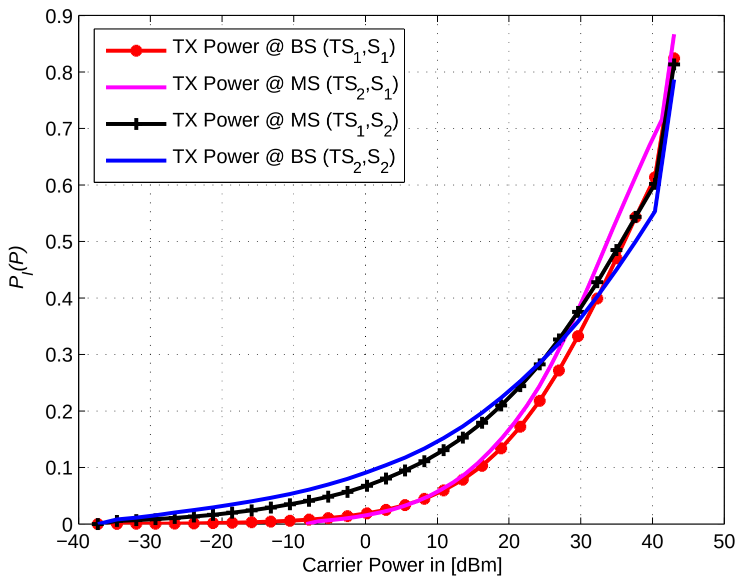

Figure 4.20: Transmitted using pure TDMA with power control

The cdf curves of C/I ratio

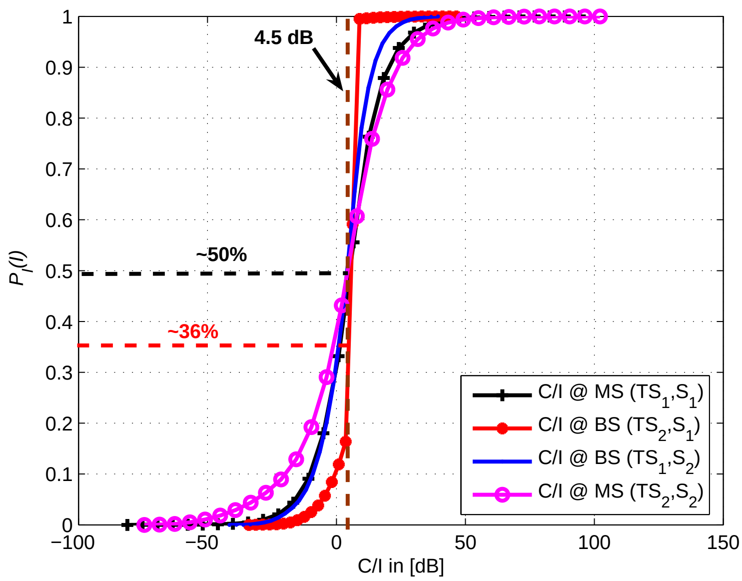

Figure 4.21: C/I ratio using pure TDMA with power control

Summary

With the assumed link budget, the C/I-based power control is not able to avoid outage in the case of a pure TDMA network. Note that when applying the 2-hop mode with the proposed novel frame structure, the outage is at negligible levels. In Table 4.6 the outage results are summarised when using the C/I based power control.

Table 4.6: Outage probability for the C/I using pure TDMA with power control

Time Slot (TS)	C/I calculated @	P(C/I < 4.5 dB)
(TS_1,S1)	MS	$\sim$ 50 %
(TS_2,S1)	BS	$\sim$ 36 %
(TS_1,S2)	BS	$\sim$ 50 %
(TS_2,S2)	MS	$\sim$ 50 %

Despite power control outage is still about 50%. This means that the pure TDMA system can only serve half as many users as the proposed 2-hop system. In addition, the transmit powers are much higher. For example, the probability that the transmit power is less than 20 dBm is only 15% in the case of opposed TS assignments and 23% in the case of same TS assignments. Similarly, the same probability for the MSs is 17%, and 22% respectively.

4.2.3 Final Summary

Table 4.7, summarizes the proposed scenarios outage results for a C/I of 4.5 dB and compare them to the pure TDMA scenarios with and without transmit power control (TPC). The scenarios description, scenario numbers and the corresponding figures are all linked in Table 4.8.

Table 4.7: Final outage ratios for the proposed scenario vs. pure TDMA scenario

Scenario No.	C/I**@**	C/I**@**	C/I**@**	C/I**@**
(Proposed)	**GWa(TS$_1$)**	**BS(TS$_2$)**	**MSa(TS$_3$)**	**GW(TS$_4$)**
1	∼ 63 %	∼ 53 %	∼ 47 %	∼ 62 %
2	∼ 57 %	∼ 35 %	∼ 60 %	∼ 57 %
3	∼ 60 %	∼ 42 %	∼ 31 %	∼ 58 %
4	∼ 16 %	∼ 16 %	∼ 16 %	∼ 16 %
(Pure TDMA)	**MS(TS$_1$,S$_1$)**	**BS(TS$_2$,S$_1$)**	**MS(TS$_1$,S$_2$)**	**BS(TS$_2$,S$_2$)**
5	∼ 63 %	∼ 41 %	∼ 52 %	∼ 56 %
6	∼ 50 %	∼ 36 %	∼ 50 %	∼ 50 %

Table 4.8: Scenarios under investigation

Scenarios No	**Description**	**Figures**
1	Omni-directed-antenna without power control	Figure 4.3
2	Omni-directed-antenna with power control	Figure 4.7
3	Directed antenna without power control	Figure 4.10
4	Directed antenna with power control	Figure 4.14
5	Pure cellular TDMA without power control	Figure 4.17
6	Pure cellular TDMA with power control	Figure 4.21

From the Table 4.7, the directed antenna with the power control scenario (scenario no. 4) shows the lowest outage ratio values among the other simulated scenarios. This mean that this proposed scenario is capable of reducing the intracell interference and the intercell interference of the cellular system with full frequency reuse.

Chapter 5

Conclusion

A new air-interface concept has been proposed which is tailored to the different needs of voice and data services. It is robust albeit flexible in that it allows the scaling of the air-interface with respect to the different services. As a result of the proposed concept, the trunking efficiencies increased because of reusing the same resources by means of hybrid duplexing. The work in this thesis focused on building a mechanism to support variable channel asymmetry. Using the channel asymmetry information and switching points, an algorithm for time scheduling is executed to reduce the interference.

The new systems aims at reducing the coverage size and reduce the transmission range, thereby the resource reuse gain could be exploited. Hence, the proposed system constructs a resizable system that accommodates users flexibly in a smaller coverage area. The suggested system coordinates the transmission between the BS and MS through the relay, GW, to reduce interference as much as possible. Also interference is reduced by considering the highly directed smart antennas. The applied smart antenna benefits from the space division multiple access (SDMA) technique, in the cell of interest, to reduce the interference at the BS antenna. The interference level at the MS(s) or the GW(s) can be significantly reduced using the power control scheme.

This research finding is summarized as follows:

- The multihop mode enables a highly efficient spectrum reuse within the same cell of a cellular underlay structure. The capacity is about doubled as compared to a pure cellular approach.

- The most critical entities in the system are the GWs which experience highest interference and are, therefore, most susceptible to outage. This might create a bottleneck situation. Therefore, future work will concentrate on identifying the key criteria for properly selecting the GWs. GW selection and signaling algorithms based on these criteria will be developed.

- Beamforming at the BS reduces interference at the MSs and BSs. However, the interference at the GW(s) is still realized by the means of power control.

Finally, it is concluded that the lowest achievable outage ratio for the current users in the system could be found as a result of combining: The cell splitting into smaller multihop cells, the new smart scheduling scheme and resizable HDD technique, the directed smart antenna at the BS, and the optimum power control that aims to achieve a target C/I ratio.

Chapter 6

Proposed Future Work

Intelligent resource reuse algorithms are contributing so deep in building up the future spectrum management field. The resource reuse algorithms aim at allocating the resources dynamically to achieve the highest possible spectral efficiency. The spectral efficiency of a system could be increased by applying an algorithm that aims at achieving the following requirements:

- The current available resources should be supplied dynamically to the areas or the users that currently require services.
- The interference is suppressed by selecting the resource which causes the least interference elsewhere.

Consequently, the system will dynamically adapt the transmission links, depending on some information that can be gathered instantaneously from the network. The current available traffic, the interference pattern, channel conditions and the required quality of services (QoS) are the sufficient information for performing dynamic link adaptation, adaptive coding, adaptive modulation and adaptive resource allocation.

6.1 Resource Reuse Methodology

Current spectrum utilization aims to reuse all the available limited resources. The limited spectrum could be efficiently utilized by using a well organized resource reuse scheme. The following are the possible reuse schemes:

1. Reuse resources assigned to the same system when the interferences between these overlapped resources is minimum.
2. Reuse resources assigned to a different system when some of its resources are unused.

The first scheme is proposed in this research. Therefore, the results of this research were developed by allowing the reuse mechanism among the same system resources. The implemented mechanism was restricted to a dual transmission mode scenario, where the resources are only reused twice in the COI.

Further development can be proposed to increase the number of times the resources are reused. This could be achieved by implementing an intelligent smart antenna system that directs the antenna beam towards the required users.

The other future direction that could be explored is the resource reuse of different systems. It has been observed that the spectrum utilization pattern in the bands above 3 GHz is actually quite limited. This limitation results in unutilized spectrum gabs, which could be considered for another possible transmission. This mechanism benefits form the unused resources of the licensed bands, where the resources can be shared instantaneously by the the unlicensed wireless networks. The two constraints for this sharing technique are, to be capable of operating at frequencies greater than 3 GHz and performing the resource reuse on a non-interfering basis. This sharing mechanism is called "cognitive radio" (CR) [15]. In order to achieve this fragment sharing between the licensed and the unlicensed network, a dynamic spectrum management algorithm should be designed to fulfil the previous constraints.

Eventually The CR systems are based on the orthogonal frequency division multiplexing (OFDM), where certain subchannels (subcarriers) could be selected for sharing when they are inactive. In order to discover suitable inactive subcarriers in the licensed system, a periodic interference sensing should be developed. The sensing scheme could relay on measuring the interference from one instant to another. The interference measurements could be handled in the OFDM system using the procedure proposed in [16]. Furthermore, an intelligent prediction of the upcoming interference can be considered also as a scheduling decision criterion. The prediction of the future interference pattern could be built on accurate behavioral models for the system. The optimum scheduling decision criteria is still an open research topic that can be considered for future work.

Finally, it is required to exploit the capability of CR(s) in sensing the spectral environment and locating free spectrum resources in a way that increases the spectral efficiency. In a similar fashion of this research, the CR(s) capability need to be performed for the centralized, multihop and ad-hoc network. Furthermore, some parameters for both the licensed and unlicensed network, like control channel and unified synchronization, need to be quantified in our research.

Khaled Shawky Hassan

Chapter 7

Appendix A

An Example Using UMTS

Assumptions:

- The voice block size is L_V [in bits]
- The data block size is L_D [in bits]
- Data rate of the DCH voice channel is L_V [kbps]
- The maximum data rate is R_D [Mpbs]
- Voice is sent from the MS(s) continuously to the BS

Therefore,

$$T_{\text{voice-min}} = (t_1 + t_2) = L_V/R_V \tag{A.1}$$

Where t_1 is the FDD segment time and t_2 is the TDD segment time. Assuming that the transmission is done at a rate of R_D, then we can calculate the actual voice block transmission time to be,

$$t_{\text{voice-block}} = L_V/R_D \tag{A.2}$$

And the total time of the cascaded mobiles voice block (t_1) can be found from

$$t_1 = N_T \times t_{\text{voice-block}} \tag{A.3}$$

Where N_T is the total number of the mobile stations. Hence, the remaining time for data transmission can be found from the following relation

$$t_2 = T_{\text{voice-min}} - t_1 \tag{A.4}$$

the number of available data time slots, $\# \, TS_{\text{data}}$, is

$$\# \, TS_{\text{data}} = t_2 / T_{\text{data-block}} \tag{A.6}$$

where the transmission time of one data block is

$$T_{\text{data-block}} = L_D / R_D \tag{A.5}$$

And the number of time slots equals to

Following the UMTS model and assuming a maximum transmission rate, R_D, of 2 Mbps for voice and data. It is also considered that the sampling rate, R_V, of the voice is 16 kbps in both directions in the FDD uplink and downlink channel. By substituting these values in (A.1) we find the $T_{voice-min}$ to be

$$T_{\text{voice-min}} = 40 \text{ msec} \tag{A.7}$$

which is the maximum allowed packet delay for voice at this rate. Assuming a voice packet of 640 bit and 2.09715×10^6 bits transmitted at a rate of 2 Mbps, it can be found that the minimum voice frame at this rate equals

$$t_{\text{voice-min}} = 640/(2 \text{ Mbps}) = 0.3052 \text{ msec} \tag{A.8}$$

Assuming that the total number of MS(s) inside the main cell, N_T, is 32 stations then the total voice transmission frame for all users, in either uplink or downlink, is given by

$$t_1 = 32 \times 0.3052 \text{ msec} = 9.7664 \text{ msec} \tag{A.9}$$

and the total time available for data transmission is given by

$$t_2 = 40 - 9.7664 \text{ msec} = 30.2336 \text{ msec} \tag{A.9}$$

where the ratio between $t_2 : t_1$ is approximately 2.9:1

The time required for the transmission of one data block for single MS, assuming that there is 3840 bits in the data block, is given by

$$T_{\text{data-block}} = L_D / R_D = 1.831 \text{ msec} \tag{A.10}$$

The total number of data timeslots available in each TDD band equals to, 30.2336/1.831 = 16.512 or 16 time slots by taking the next feasible integer as an approximation. The 16 timeslots can be divided over 2 multihop cells, where each multihop cell can use 8 timeslots. The multihop cell can use 4 timeslots for the internal uplink and external uplink, and 4 timeslots for the internal downlink and external downlink. In other words, this multihop cell can occupy 2 MS(s), out of 8 MS(s), sending and receiving data at the same time, while the rest can send only voice calls using the FDD band.

The system capacity can be doubled by reducing the sampling quality of the voice from full rate sampling quality (16 kbps) to half rate sampling quality (8 kbps). The system capacity is calculated using the previous example with a voice sample rate of 8 kbps. Also the total number of MS(s) inside the main cell, N_T, is assumed to be 36 stations this time. Therefore the new number of timeslots is

$$T_{\text{voice-min}} = 80 \text{ msec} \tag{A.11}$$

$$t_1 = 36 * 0.3052 \text{ msec} = 10.987 \text{ msec} \tag{A.12}$$

$$t_2 = 80 - 10.987 \text{ msec} = 69.013 \text{ msec} \tag{A.13}$$

This will lead to having a total number of data slots of $69.013/1.831 = 37.691$ or choosing only 36 data timeslots to be divisible by 4. These 36 timeslots can be divided into 2 multihop cells with 18 time slots each. Each multihop cell will support 4 active MS(s), this mean a total capacity of 36 MS(s) are using voice communication and 16 MS(s) can simultaneously send data packets beside their voice communication.

Chapter 8

Appendix B: Publications and Patents

8.1 Patent Application

Khaled Hassan and Harald Haas, "Cellular System with Co-existing and Spectrum Sharing in Single-hop and Multi-hop Cells", Proposed Patent to Samsung, May 2005.

8.2 Published Paper

Khaled Hassan and Harald Haas, "User Scheduling for Cellular Multi User Access OFDM System Using Opportunistic Beamforming", OFDM Workshop 05, Hamburg 2005.

User Scheduling for Cellular Multi User Access OFDM System Using Opportunistic Beamforming

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***Abstract*— Orthogonal frequency division multiplexing (OFDM) based wireless systems could potentially gain high performance from multi-user diversity due to time varying channels across different users. To further enhance the frequency selectivity at the receiver, transmit antenna diversity can be used at the base station (BS) in combination with opportunistic beamforming (OBF). Resources are assigned to users with the highest instantaneous signal-interference-plus-noise ratio (SINR) at the downlink (DL). The same scheduling is used in uplink (UL). In this paper, time division duplexing (TDD) and full frequency reuse is considered. Simulation results show that the proposed OBF in a cellular system using TDD greatly benefits from channel reciprocity. In addition, the proposed system benefits from scheduling and multi-user diversity in reducing the intercell interference – in particular a the cell boundary.**

***Index Terms*— OFDM, TDD, FDD, Opportunistic beamforming and Multiuser diversity**

I. Introduction

DUE to increase of the demand for high data rates in wireless systems, the spatial reuse of radio resources in the network is subject to intensive research. In a cellular system with frequency reuse of one, it is vitally important to consider the effect of intercell interference on the performance of the system. Intercell interference potentially prevents the system to reuse the same radio resources in all cells of the network. As a consequence, the spectral efficiency suffers.

In this paper, the multi-user access is arranged using OFDMA in combination with frequency division multiple access (FDMA). To effectively support high data rates, the increase of spectral efficiency is of main concern. On possibility of achieving high spectral efficiencies is to exploit multi-user diversity and to optimize user scheduling. The multi-user diversity refers to a type of diversity that utilizes the fading channel environment for different users by considering transmission only over the strongest channels. In the multi-user, multi-carrier system, as in OFDMA, scheduling is implemented by picking those sub-carriers with the highest channel gains. Thereby, the fact is exploited that this set of sub-channels varies for different users because of different user locations. Therefore, the normalized throughput increases by increasing the number of users.

Fading, traditionally, has been viewed as a form of unreliability that must be avoided. In the contrary, to keep proportional fairness, [1], [3], among users and to increase the system throughput by exploiting multi-user diversity, the channel dynamics should be increased. This can be accomplished by using the following techniques reported in literature [1], [2]:

a- Transmit diversity with multiple antennas at the BS, where the same symbol is transmitted on all antennas to enhance multipath transmission. It is assumed that the antennas are spaced such that uncorrelatedness is achieved.

b- OBF proposed in [1], in which the transmitted symbol is multiplied with a random complex weighting factor, referred to as opportunistic weighting factor (OWF).

The total number of sub-carriers is divided into sub-sets which are referred to as clusters in this paper. Scheduling is perform at the BS on the DL. The scheduling metric is the average cluster SINR. A cluster with the highest average SINR, measured at the mobile station (MS), is used for transmission. As a consequence, the metric for the cluster selection includes the level of intercell interference, i.e. despite a favourable channel transfer factor on the desired link, a cluster of sub-carriers might not be used if interference outweighs the good channel gains on the desired link. The mechanism of reducing the interference due to OBF is also called opportunistic nulling (ONU) [1].

This paper investigates the performance of the cellular opportunistic beamforming in the presence of intercell interference. The investigation is based on the cellular system with full frequency reuse, i.e. all cells are assumed to be operated at the same radio frequency. In addition, time division duplexing (TDD) is used and channel reciprocity is exploited. For comparison, frequency division duplexing (FDD) is also considered in which it is assumed that UL and DL channels are independently fading.

II. System Model

A. Multi-User OFDMA Setup

One OFDM symbol having, N, subcarriers is divided into, D, clusters, where each cluster consists of, L, consecutive subcarriers. Each user transmits on a single cluster where the number of users in the system is, U, such that $U \leq D$.

B. Scheduling for TDD and FDD

Scheduling and cluster selection is done on the DL. The same cluster is then used for UL transmission. Both TDD and FDD are considered in this investigation. It is assumed that UL and DL transmission is within the coherence time of the channel such that the channel can be assumed to be reciprocal in TDD. In FDD, as the UL and DL transmission is on separate channels, the channels fade independently regardless of the coherence time.

C. Opportunistic beamforming and user-scheduling

The frequency selective channels are exploited to obtain multi-user diversity as mentioned before. In the case of flat fading channels, the *transmit diversity* in combination with *OBF* is used to artificially increase the channel fluctuations.

The transmit diversity is done by allowing the BS to use up to, M, different transmitters and the opportunistic beamforming is done by weighting the transmitted, D, clusters by the random complex OWFs,$[W_1, W_2, ..., W_M]$. The OWF power is normalized to one across the antennas at the transmitter such that,

$$\sum_{i=0}^{M} W_i^2 = 1 \ . \quad (1)$$

In this paper, M, is restricted to 2 antennas, and thus the OWF are obtained as follows,

$$W_1 = [w_{11}, w_{11}, ..., w_{1D}],\ W_2 = [w_{21}, w_{21}, ..., w_{2D}]\ , \quad (2)$$

with,

$$w_{1n} = \sqrt{\alpha_n} e^{j\phi_n},\ w_{2n}\sqrt{1-\alpha_n} e^{j\theta_n}\ , \quad (3)$$

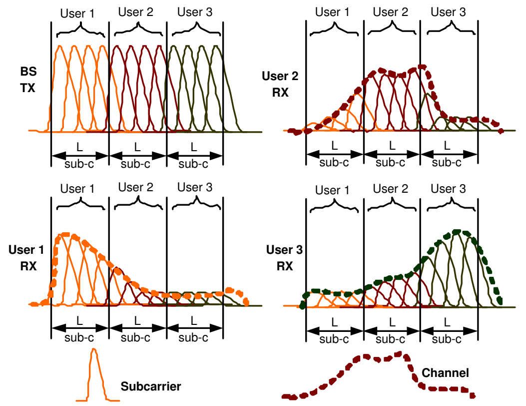

Fig. 1. The induced frequency selectivity is exploited for user scheduling

where α_n is the random magnitude, θ_n and ϕ_n are the random phases of the weighting factor of the n^{th} cluster. W_1 and W_2 are assumed to be constant for, S, OFDM symbols, where $S \leq R$, assuming R is the number of OFDM symbols in the transmission block.

The use of OWFs will create random variations of the resultant channel at the user location. As a consequence, the probability that a high average cluster SINR can be achieved at the user location is increased. The principle mechanism is depicted in Fig. 1.

D. Scheduling

The average SINR of each cluster is estimated by the MS [7]. These SINRs are fedback to the BS for user scheduling. The scheduler works on a table with the maximum dimension equal to the number of users, U, times the number of cluster, D. For each cluster, the scheduler selects those users which report the highest SINRs and blocks the other users for that particular cluster.

It is assumed that the feedback information is transmitted on an error free channel, and that the feedback information can be reduced by using the reduced feedback scheme in [2]. This means that the number of clusters, for which the average SINR is feedback, is restricted to, Z, where $Z \leq D$.

E. Cellular system and opportunistic nulling

The cellular system is implemented assuming a frequency reuse pattern of one. In addition, OBF is applied at the BSs. In the cellular system, OBF in combination with user scheduling, as described before, is equivalent to ONU [1] because of,

1) Transmit diversity: The desired signal power is added coherently, while adding the interfering signal powers incoherently.

2) Scheduling based on SINR: This aims at selecting those clusters with maximum desired signal power and least intercell interference power.

F. Interference

Intercell interference from the first tier of cells is considered. In the DL, the MS of interest is interfered by the BS in the neighbouring cells, while in the UL, all MSs in the neighbouring cells contribute to interference at the BS of interest. The users in the cell of interest are assumed to be uniformly distributed over the cell area and the BS is located at the cell center. Transmissions in the neighbouring cells take place on the entire bandwidth with constant power.

To simulate the performance for different user locations, the MS of interest moves away from the BS towards the cell boundary on a straight line radially from the cell center.

G. Calculation of Throughput

The maximum throughput, C, (in bits/OFDM symbol) for the OFDM system with two transmit antennas is calculated using Shannon capacity equation as described in [2], [4]. This means that perfect channel coding is assumed, and that intercell interference can be approximated as white Gaussian noise. Using the OWF in (3), Shannon capacity can be expressed as,

$$C = \frac{1}{2}\sum_{n}^{D}\log_2\{1+\frac{\rho_n}{M}\sum_{j=1}^{M}|h_{n,j}w_{j,\lfloor n/L\rfloor}|^2\} \quad (4)$$

and,

$$\rho_n = \frac{P_n}{\sigma_z^2 + I_n}, \quad (5)$$

where ρ_n is the ratio of the power on the n^{th} subcarrier, P_n, to the noise variance, σ_z^2, and average interference power I_n; and $h_{n,j}$, is the complex channel transfer factor for the n^{th} subcarrier linked to the j^{th} antenna.

At the transmitter, the power across all subcarriers selected for transmission is normalized to one, where it generally holds that $z \subset N$.

$$\sum_{z\subset N} P_z = P_{max} = 1 \quad (6)$$

where (z/L) is the number of admitted users constrained to $(z/L) \leq U$.

H. Calculation of Outage

Outage is defined as the ratio of the number of users that are permitted into the system, (z/L), to the maximum number of users, U,

$$\text{Outage} = \frac{z/L}{U} = \frac{z}{N} \quad (7)$$

III. Channel Model

A. Channel Fading Model

In this paper, slow fading is considered such that the channel value, $h_{Mk}(t)$, remains constant for all t, where t is time required for transmitting, R, OFDM symbols. The OWF, as well as the scheduling rate, is assumed to be changed every $t/5$.

The multipath effect is simulated by a Rayleigh fading channel with exponential decaying power profile as in [2]. The impulse response from the M^{th} transmitter antenna to the k^{th} user antenna is modeled by

$$h_{Mk}(t) = \sum_{i=0}^{l-1}\beta_i^{Mk}\delta(t - iT_s) \quad (8)$$

where l is the number of channel taps equals to the ratio between the root mean square delay spread, γ, and the sampling period, T_s, [5]. The channel gain, β_i^{Mk}, is an independent complex Gaussian random variables with an exponentially decaying power profile.

B. Pathloss Model

The interference is calculated using the UMTS outdoor pathloss model in [6]. The following equation represents the implemented path-loss model.

$$\text{PL}(d)|_{dB} = K_1 + 10p\log(d) + X_\sigma \quad (9)$$

where p is the pathloss exponent of the cellular model, and equals to 4, d is the distance between the interfering source and the destination antenna in kilometer (km), K_1 is pathloss value at reference distance and X_σ is used to model the shadowing effect. (K_1 and σ^2 values are selected respectively 49 and 10 dB.)

IV. Simulation Results

The proposed system is simulated using MATLAB. The OFDMA simulation parameters used are presented in **??**.

TABLE I
OFDMA SYSTEM PARAMETERS

Parameter	Value
Sampling rate	40 Msps
Symbol interval	4 μsec
Useful symbol part duration	3.2 μsec
Cyclic prefix & max. delay spread	0.8 μsec
Subcarriers spacing	0.3125 MHz
Number of data carriers N	96
Number of carriers per cluster L	6
Number of clusters D	16
Number of feedback clustered Z	3
Cell radius R	3 km

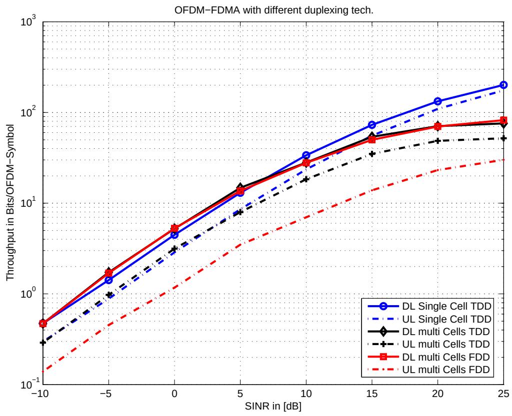

Fig. 2. Maximum throughput of a TDD-OFDMA and FDD-OFDMA cellular system

A. Throughput and Outage Analysis

The proposed system performance is measured using the throughput analysis and the outage ratio. The comparisons between the single cell and the cellular model are done by the following steps,

1) TDD and FDD throughput results: The throughput performance of the TDD and FDD, cellular mode, is evaluated against SINR. Fig. 2 shows the performance degradation due to the cellular model, compared to the single cell model, where the throughput is reduced by 20%m at 15 dB. For the TDD case, the DL:UL throughput ratio is 1.4:1, with a gain of 1.4 for the DL over the UL due to the OWF variation only.

The effect of the user scheduling and OWF, (OBF), can be shown in the difference between the UL throughput of TDD and FDD, where the TDD UL performance is twice better than the FDD UL.

2) Varying the number of users: Using OBF increases the system performance by increasing the number of users in the one hand, on the other hand, the outage ratio increases by increasing the number of users. Fig. 3 is simulated using various number of users, from 2 to 16 users. The transmission power in each case is normalized to one, and equally distruputed over the current users in the system. Fig. 4 shows the outage ratio, the varying users capacity, in the cellular mode. The outage ratio remains constant for all SINR until we have 8 users (half loaded system), then the outage starts to increase gradually for cells with more than 8 users.

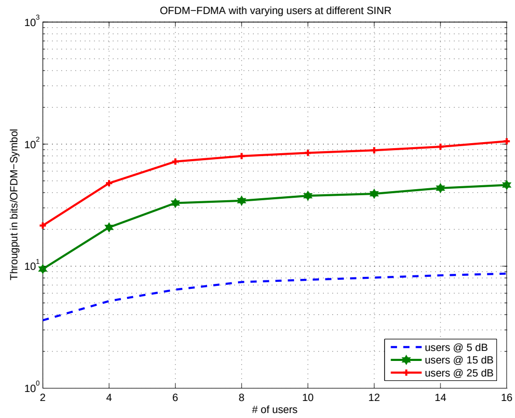

Fig. 3. Varying the number of users in the cell

The previous results need a tradeoff between the required throughput and the number of users in the system, to have acceptable outage ratio for high throughput. For example, keeping the users capacity at half the system load, will give a better outage performance and high throughput capacity.

B. Throughput without user scheduling or OBF

This section compares the proposed system to the normal antenna diversity system without OWF or user scheduling (non-OBF).

1) The system performance with OBF and non-OBF: For the comparison between the system with OBF and with non-OBF, the same cellular implementation is considered. Fig. 5 shows the results for the DL throughput, for the single cell and the cellular mode, with OBF and with non-OBF. These results show that the system with OBF performs 3 times better than the system with non-OBF, also the degradation of performance for the non-OBF, between the cellular system and the single cell, is worse by 1.4 times than the OBF case (which is the gain of the OWF).

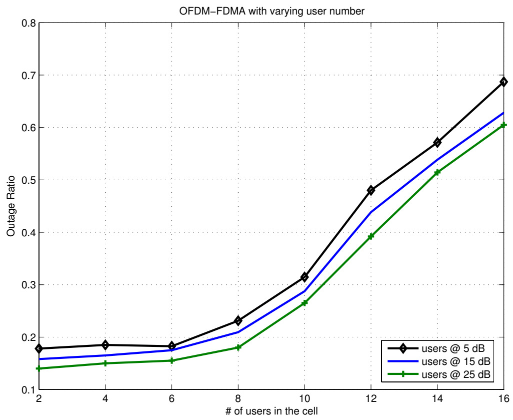

Fig. 4. Outage ratio for varying number of users

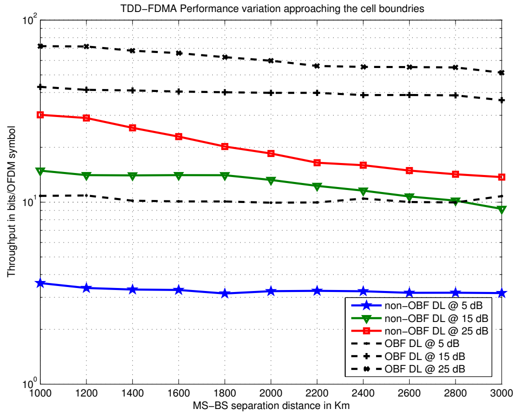

Fig. 6. Varying MS to BS distance

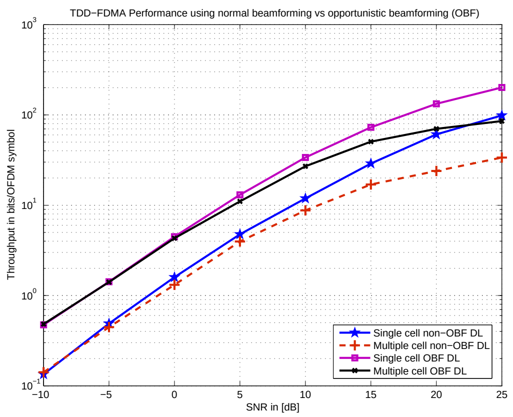

Fig. 5. Varying MS to BS distance

2) MS-to-BS separation distance variation: The OBF, with OWF and user scheduling, increases the spectral efficiency as shown in the previous results. The system performance due to OBF remains constant at any position in cell, from the cell center to the cell boundary. Fig. 6 shows that the throughput remains constant at the lower SINR (5 and 15 dB). The throughput decreases only 15% for SINR higher than 25 dB.

The performance of the non-OBF systems is worse than the OBF case with respect to MS-to-BS distance, where the throughput decreases by 60% for SINR higher than 25 dB and 40% for SINR higher than 15 dB.

V. CONCLUSION

The previous study shows that the ONU due to using OBF (with OWF and users scheduling) gives better performance, in the cellular system with full frequency reuse, than the non-OBF method. The interference is also limited in the UL and DL scenarios in the cellular system. The performance is kept constant along the cell radius even at the cell boundaries. The TDD performance is better than FDD due to channel reciprocity, so that DL:UL ratio is very low by scheduling users during the DL only.

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