3G, HSDPA, HSUPA and FDD Versus TDD Networking:
Smart Antennas and Adaptive Modulation

by

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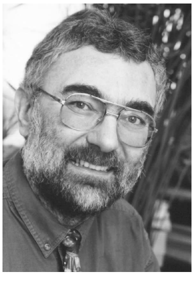

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Other Wiley and IEEE Press Books on Related Topics [1]

- R. Steele, L. Hanzo (Ed): *Mobile Radio Communications: Second and Third Generation Cellular and WATM Systems*, John Wiley and IEEE Press, 2nd edition, 1999, ISBN 07 273-1406-8, 1064 pages

- L. Hanzo, F.C.A. Somerville, J.P. Woodard: *Voice Compression and Communications: Principles and Applications for Fixed and Wireless Channels*; IEEE Press and John Wiley, 2001, 642 pages

- L. Hanzo, P. Cherriman, J. Streit: *Wireless Video Communications: Second to Third Generation and Beyond*, IEEE Press and John Wiley, 2001, 1093 pages

- L. Hanzo, T.H. Liew, B.L. Yeap: *Turbo Coding, Turbo Equalisation and Space-Time Coding*, John Wiley and IEEE Press, 2002, 751 pages

- J.S. Blogh, L. Hanzo: *Third-Generation Systems and Intelligent Wireless Networking: Smart Antennas and Adaptive Modulation*, John Wiley and IEEE Press, 2002, 408 pages

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- L. Hanzo, L-L. Yang, E-L. Kuan, K. Yen: *Single- and Multi-Carrier CDMA: Multi-User Detection, Space-Time Spreading, Synchronisation, Networking and Standards*, John Wiley and IEEE Press, June 2003, 1060 pages

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[1] For detailed contents and sample chapters please refer to http://www-mobile.ecs.soton.ac.uk

- L. Hanzo, T. Keller: *An OFDM and MC-CDMA Primer*, John Wiley and IEEE Press, 2006, 430 pages
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Chapter 5

HSDPA-Style FDD Networking, Adaptive Arrays and Adaptive Modulation

5.1 Introduction

In January 1998, the European standardisation body for third generation mobile radio systems, the European Telecommunications Standards Institute - Special Mobile Group (ETSI SMG), agreed upon a radio access scheme for third generation mobile radio systems, referred to as the Universal Mobile Telecommunication System (UMTS) [11,59]. Although this chapter was detailed in Chapter 1, here we provide a rudimentary introduction to the system, in order to allow readers to consult this chapter directly, without having to read Chapter 1 first. Specifically, the UMTS Terrestrial Radio Access (UTRA) supports two modes of duplexing, namely Frequency Division Duplexing (FDD) , where the uplink and downlink are transmitted on different frequencies, and Time Division Duplexing (TDD) , where the uplink and the downlink are transmitted on the same carrier frequency, but multiplexed in time. The agreement recommends the employment of Wideband Code Division Multiple Access (W-CDMA) for UTRA FDD and Time Division - Code Division Multiple Access (TD-CDMA) for UTRA TDD. TD-CDMA is based on a combination of Time Division Multiple Access (TDMA) and CDMA, whereas W-CDMA is a pure CDMA-based system. The UTRA scheme can be used for operation within a minimum spectrum of 2 x 5 MHz for UTRA FDD and 5 MHz for UTRA TDD. Both duplex or paired and simplex or unpaired frequency bands have been identified in the region of 2 GHz to be used for the UTRA third generation mobile radio system. Both modes of UTRA have been harmonised with respect to the basic system parameters, such as carrier spacing, chip rate and frame length. Thereby, FDD/TDD dual mode operation is facilitated, which provides a basis for the development of low cost terminals. Furthermore, the interworking of UTRA with GSM [11] is ensured.

In UTRA, the different service needs are supported in a spectrally efficient way by a combination of FDD and TDD. The FDD mode is intended for applications in both macro- and micro-cellular environments, supporting data rates of up to 384 kbps and high mobility. The TDD mode, on the other hand, is more suited to micro and pico-cellular environments, as well as for licensed and unlicensed cordless and wireless local loop applications. It makes efficient use of the unpaired spectrum - for example in wireless Internet applications, where much of the teletraffic is in the downlink - and supports data rates of up to 2 Mbps. Therefore, the TDD mode is particularly well suited for environments generating a high traffic density (e.g. in city centres, business areas, airports etc.) and for indoor coverage, where the applications require high data rates and tend to have highly asymmetric traffic again, as in Internet access.

In parallel to the European activities, extensive work has been carried out also in Japan and the USA on third generation mobile radio systems. The Japanese standardisation body known as the Association of Radio Industry and Business (ARIB) also opted for using W-CDMA, and the Japanese as well as European proposals for FDD bear strong similarities. Similar concepts have also been developed by the North-American T1 standardisation body for the pan-American third generation (3G) system known as cdma2000, which was also described in Chapter 1 [11].

In order to work towards a truly global third generation mobile radio standard, the Third Generation Partnership Project (3GPP) was formed in December 1998. 3GPP consists of members of the standardisation bodies in Europe (ETSI), the US (T1), Japan (ARIB), Korea (TTA - Telecommunications Technologies Association), and China (CWTS - China Wireless Telecommunications Standard). 3GPP merged the already well harmonised proposals by the regional standardisation bodies and now works towards a single common third generation mobile radio standard under the terminology UTRA, retaining its two modes, and aiming to operate on the basis of the evolved GSM core network. The Third Generation Partnership Project 2 (3GPP2), on the other hand, works towards a third generation mobile radio standard, which is based on an evolved IS-95 type system which was originally referred to as cdma2000 [11]. In June 1999, major international operators in the Operator Harmonisation Group (OHG) proposed a harmonised G3G (Global Third Generation) concept, which has been accepted by 3GPP and 3GPP2. The harmonised G3G concept is a single standard with the following three modes of operation:

- CDMA direct spread (CDMA-DS), based on UTRA FDD as specified by 3GPP.
- CDMA multi-carrier (CDMA-MC), based on cdma2000 using FDD as specified by 3GPP2.
- TDD (CDMA TDD) based on UTRA TDD as specified by 3GPP.

5.2 Direct Sequence Code Division Multiple Access

A rudimentary introduction to CDMA was provided in Chapter 1 in the context of single-user receivers, while in Chapter 2 the basic concepts of multi-user detection have been introduced. However, as noted earlier, our aim is to allow reader to consult this chapter directly, without having to refer back to the previous chapters. Hence here a brief overview of the undrlying CDMA basics is provided.

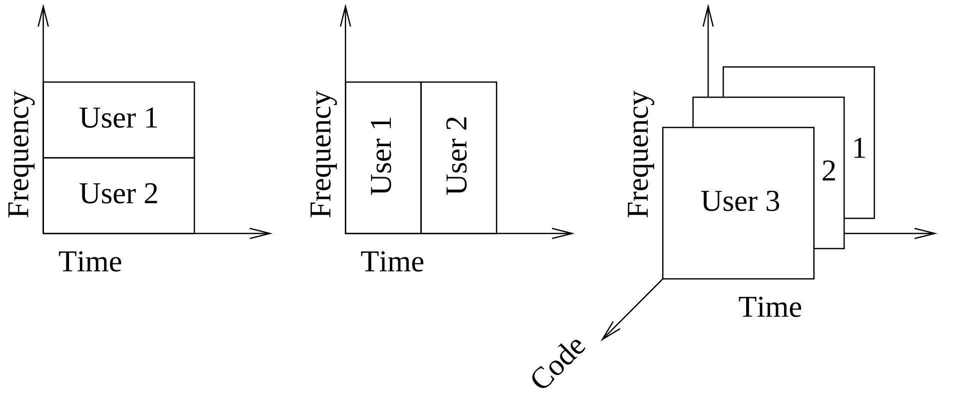


Figure 5.1: Multiple access schemes: FDMA (left), TDMA (middle) and CDMA (right).

Traditional ways of separating signals in time using TDMA and in frequency ensure that the signals are transmitted orthogonal in either time or frequency and hence they are non-interfering. In CDMA different users are separated employing a set of waveforms exhibiting good correlation properties, which are known as spreading codes. Figure 5.1 illustrates the principles of FDMA, TDMA and CDMA. More explicitly, FDMA uses a fraction of the total FDMA frequency band for each communications link for the whole duration of a conversation, while TDMA uses the entire bandwidth of a TDMA channel for a fraction of the TDMA frame, namely for the duration of a time slot. Finally, CDMA uses the entire available frequency band all the time and separates the users with the aid of unique, orthogonal user signature sequences.

In a CDMA digital communications system, such as that shown in Figure 5.2, the data stream is multiplied by the spreading code, which replaces each data bit with a sequence of code chips. A chip is defined as the basic element of the spreading code, which typically assumes binary values. Hence, the spreading process consists of replacing each bit in the original user's data sequence with the complete spreading code. The chip rate is significantly higher than the data rate, hence causing the bandwidth of the user's data to be spread, as shown in Figure 5.2.

At the receiver, the composite signal containing the spread data of multiple users is multiplied by a synchronised version of the spreading code of the wanted user. The specific auto-correlation properties of the codes allow the receiver to identify and recover each delayed, attenuated and phase-rotated replica of the transmitted signal, provided that the signals are separated by more than one chip period and the receiver has the capability of tracking each significant path. This is achieved using a Rake receiver [5] that can process multiple delayed received signals. Coherent combination of these transmitted signal replicas allows the original signal to be recovered. The unwanted signals of the other simultaneous users remain wideband, having a bandwidth equal to that of the noise, and appear as additional noise with respect to the wanted signal. Since the bandwidth of the despread wanted signal is reduced relative to this noise, the signal-to-noise ratio of the wanted signal is enhanced by the despreading process in proportion to the ratio of the spread and despread bandwidths, since

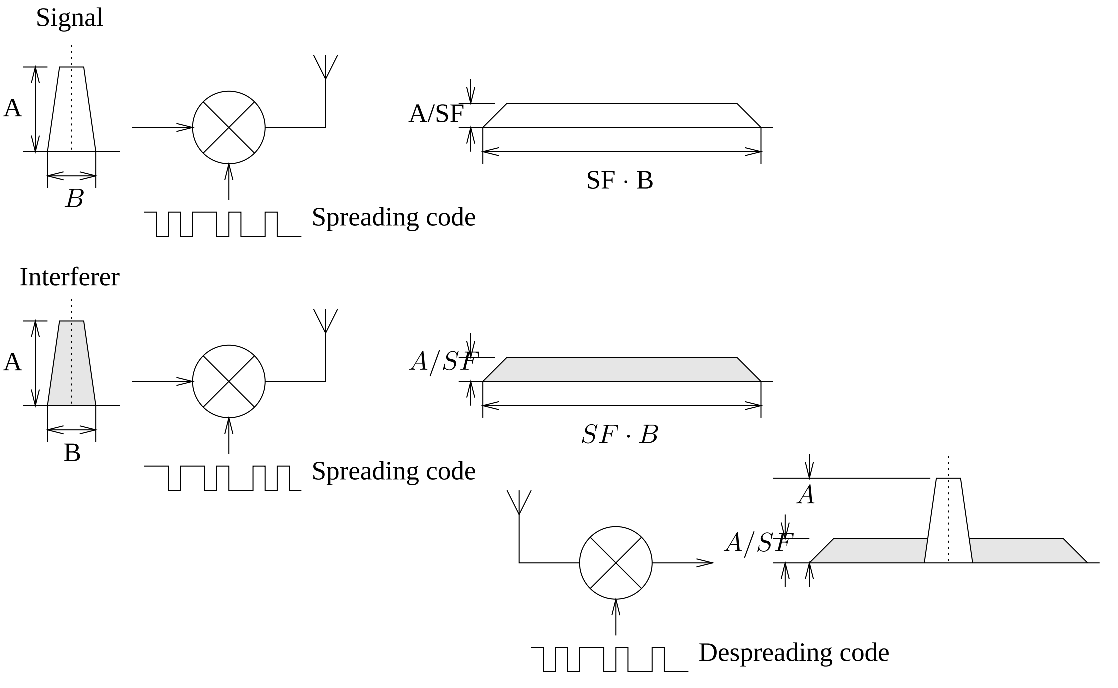


Figure 5.2: CDMA Spreading and Despreading Processes

the noise power outside the useful despread signal's bandwidth can be removed by a low-pass filter. This bandwidth ratio is equal to the ratio of the chip rate to the data rate, which is known as the Processing Gain (PG). For this process to work efficiently, the signals of all of the users should be received at or near the same power at the receiver. This is achieved with the aid of power control, which is one of the critical elements of a CDMA system. The performance of the power control scheme directly affects the capacity of the CDMA network.

5.3 UMTS Terrestrial Radio Access

A bandwidth of 155 MHz has been allocated for UMTS services in Europe in the frequency region of 2.0 GHz. The paired bands of 1920-1980 MHz (uplink) and 2110-2170 MHz (downlink) have been set aside for FDD W-CDMA systems, and the unpaired frequency bands of 1900-1920 MHz and 2010-2025 MHz for TDD CDMA systems.

A UTRA Network (UTRAN) consists of one or several Radio Network Sub-systems (RNSs), which in turn consist of base stations (referred to as Node Bs) and Radio Network Controllers (RNCs). A Node B may serve one or multiple cells. Mobile stations are known as User Equipment (UE), which are expected to support multi-mode operation in order to enable handovers between the FDD and TDD modes and, prior to complete UTRAN coverage, also to GSM. The key parameters of UTRA have been defined as in Table 5.1.

Duplex scheme	FDD	TDD
Multiple access scheme	W-CDMA	TD-CDMA
Chip rate	3.84 Mchip/s	3.84 Mchip/s
Spreading factor range	4-512	1-16
Frequency bands	1920-1980 MHz (UL)	1900-1920 MHz
	2110-2170 MHz (DL)	2010-2025 MHz
Modulation mode	4-QAM/QPSK	4-QAM/QPSK
Bandwidth	5 MHz	5 MHz
Nyquist pulse shaping	0.22	0.22
Frame length	10 ms	10 ms
Number of timeslots per frame	15	15

Table 5.1: Key UTRA Parameters.

5.3.1 Spreading and Modulation

As usual, the uplink is defined as the transmission path from the mobile station to the base station, which receives the unsynchronised channel impaired signals from the network's mobiles. The base station has the task of extracting the wanted signal from the received signal contaminated by both intra- and inter-cell interference. However, as described in Section 5.2, some degree of isolation between interfering users is achieved due to employing unique orthogonal spreading codes, although their orthogonality is destroyed by the hostile mobile channel.

The spreading process consists of two operations. The first one is the channelisation operation, which transforms every data symbol into a number of chips, thus increasing the bandwidth of the signal, as seen in Figure 5.2 of Section 5.2. The channelisation codes in UTRA are Orthogonal Variable Spreading Factor (OVSF) codes [11] that preserve the orthogonality between a given user's different physical channels, which are also capable of supporting multirate operation. These codes will be further discussed in the context of Figure 5.4. The second operation related to the spreading, namely the 'scrambling' process then multiplies the resultant signals separately on the I- and Q-branches by a complex-valued scrambling code, as shown in Figure 5.3. The scrambling codes may be one of either 2^{24} different 'long' codes or 2^{24} 'short' uplink scrambling codes.

The Dedicated Physical Control CHannel (DPCCH) [11, 386] is spread to the chip rate by the channelisation code C_c, while the n^{th} Dedicated Physical Data CHannel (DPDCH), namely DPDCH$_n$, is spread to the chip rate by the channelisation code $C_{d,n}$. One DPCCH and up to six parallel DPDCHs can be transmitted simultaneously, i.e. $1 \leq n \leq 6$ as seen in Figure 5.3). However, it is beneficial to transmit with the aid of a single DPDCH, if the required bit-rate can be provided by a single DPDCH for reasons of terminal amplifier efficiency. This is because multi-code transmissions increase the peak-to-average ratio of the transmission, which reduces the efficiency of the terminal's power amplifier [59]. The maximum user data rate achievable with the aid of a single code is derived from the maximum channel bit rate, which is 960 kbps using a spreading factor of four without channel coding in the 1999 version of the UTRA standard. However, at the time of writing a spreading factor of one is being considered by the standardisation body. With channel coding the maximum

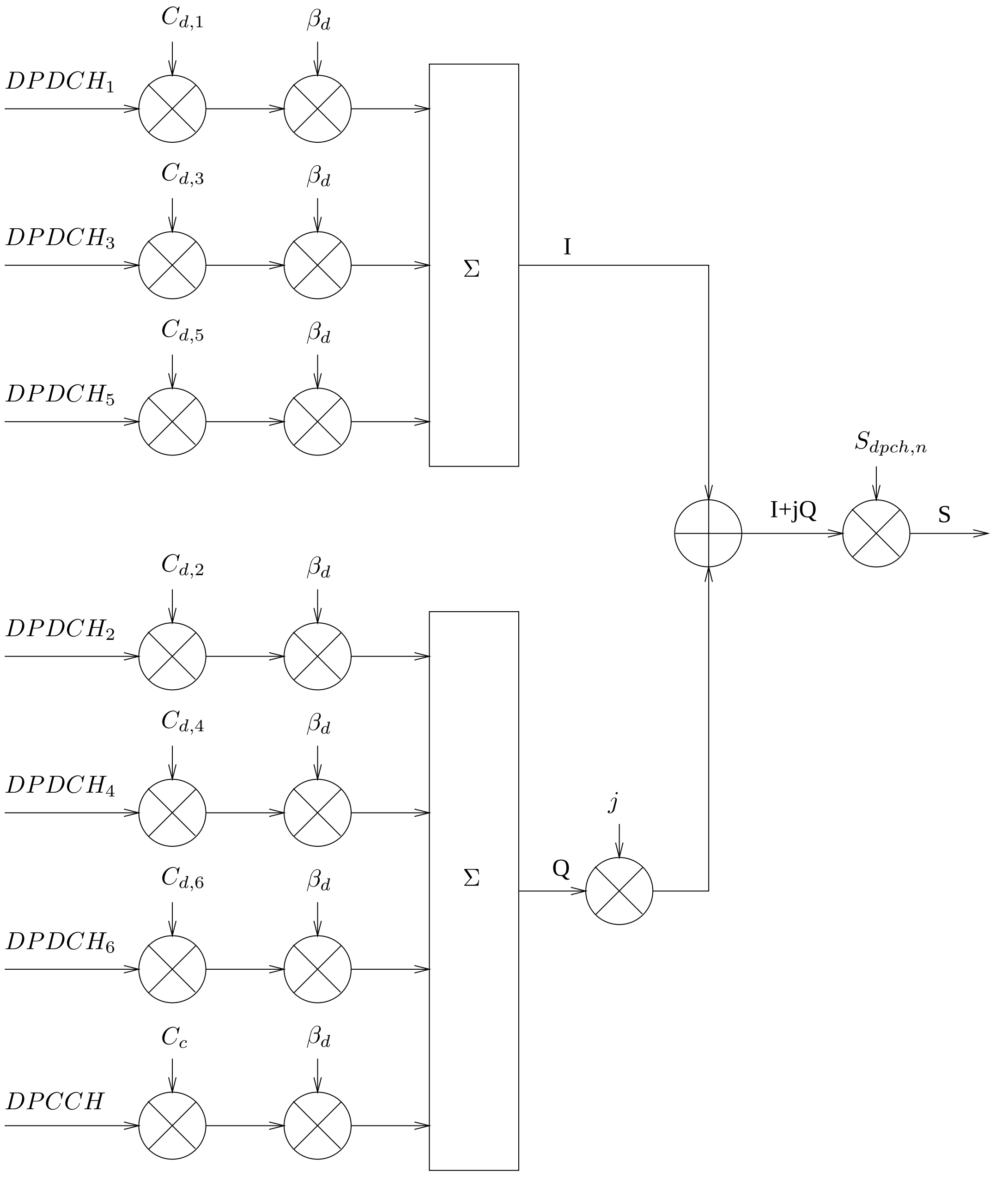


Figure 5.3: Spreading for uplink DPCCH and DPDCHs

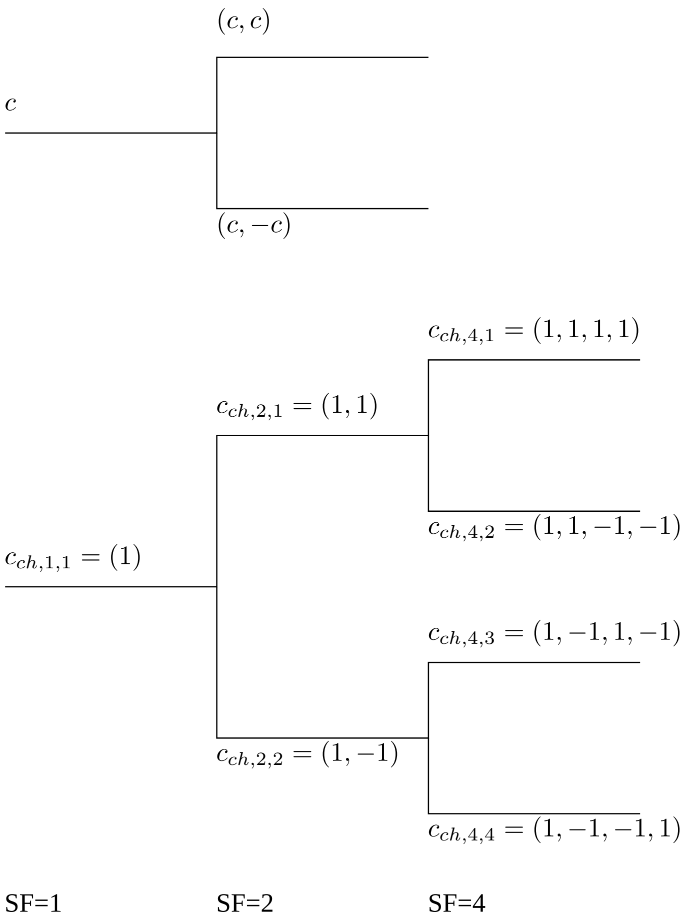


Figure 5.4: Code tree for the generation of Orthogonal Variable Spreading Factor (OVSF) codes

practical user data rate for single code transmission is of the order of 400-500 kbps. For achieving higher data rates parallel multi-code channels are used. This allows up to six parallel codes to be used, increasing the achievable channel bit rate up to 5740 kbps, which can accommodate a 2 Mbps user data rate or even higher data rates, when the channel coding rate is $1/2$.

The OVSF codes [130] can be defined using the code tree of Figure 5.4. In Figure 5.4, the channelisation codes are uniquely described by $C_{ch,SF,k}$, where SF is the spreading factor of the codes, and k is the code index where $0 \leq k \leq SF - 1$. Each level in the code tree defines spreading codes of length SF, corresponding to a particular spreading factor of SF. The number of codes available for a particular spreading factor is equal to the spreading factor itself. All the codes of the same level in the code tree constitute a set and they are orthogonal to each other. Any two codes of different levels are also orthogonal to each other, as long as one of them is not the mother of the other code. For example, the codes $c_{15}(2)$,

$c_7(1)$ and $c_3(1)$ are all the mother codes of $c_{31}(3)$ and hence are not orthogonal to $c_{31}(3)$, where the number in the round bracket indicates the code index. Thus not all the codes within the code tree can be used simultaneously by a mobile station. Specifically, a code can be used by an MS if and only if no other code on the path from the specific code to the root of the tree, or in the sub-tree below the specific node is used by the same MS.

For the DPCCH and DPDCHs the following applies:

- The PDCCH is always spread by code $C_c = C_{ch,256,0}$.
- When only one DPDCH is to be transmitted, DPDCH_1 is spread by the code $C_{d,1} = C_{ch,SF,k}$, where SF is the spreading factor of DPDCH_1 and $k = SF/4$.
- When more than one DPDCHs have to be transmitted, all DPDCHs have spreading factors equal to four. Furthermore, DPDCH_n is spread by the code $C_{d,n} = C_{ch,4,k}$, where $k = 1$ if $n \subset \{1, 2\}$, $k = 3$ if $n \subset \{3, 4\}$, and $k = 2$ if $n \subset \{5, 6\}$.

A fundamental difference between the uplink and the downlink is that in the downlink synchronisation is common to all users and channels of a given cell. This enables us to exploit the cross-correlation properties of the OVSF codes, which were originally proposed in [130]. These codes offer perfect cross-correlation in an ideal channel, but there is only a limited number of these codes available. The employment of OVSF codes allows the spreading factor to be changed and orthogonality between the spreading codes of different lengths to be maintained. The codes are selected from the code tree, which is illustrated in Figure 5.4. As illustrated above, there are certain restrictions as to which of the channelisation codes can be used for transmission from a single source. Another physical channel may invoke a certain code from the tree, if no other physical channel to be transmitted employing the same code tree is using a code on an underlying branch, since this would be equivalent to using a higher spreading factor code generated from the spreading code to be used, which are not orthogonal to each other on the same branch of the code tree. Neither can a smaller spreading factor code on the path to the root of the tree be used. Hence, the number of available codes depends on the required transmission rate and spreading factor of each physical channel.

In the UTRA downlink a part of the multi-user interference can be orthogonal - apart from the channel effects. The users within the same cell share the same scrambling code, but use different channelisation/OVSF codes. In a non-dispersive downlink channel, all intra-cell users are synchronised and therefore they are perfectly orthogonal. Unfortunately, in most cases the channel will be dispersive, implying that non-synchronised interference will be suppressed only by a factor corresponding to the processing gain, and thus they will interfere with the desired signal. The interference from other cells which is referred to as inter-cell interference, is non-orthogonal, due to employing different scrambling but possibly the same channelisation codes. Therefore inter-cell interference is also suppressed by a factor corresponding to the processing gain.

The channelisation code used for the Primary Common PIlot CHannel (CPICH) is fixed to $C_{ch,256,0}$, while the channelisation code for the Primary Common Control Physical CHannel (CCPCH) is fixed to $C_{ch,256,1}$ [386]. The channelisation codes for all other physical channels are assigned by the UTRAN [386].

A total of $2^{18} - 1 = 262143$ scrambling codes, numbered as $0 \ldots 262142$ can be generated. However, not all of the scrambling codes are used. The scrambling codes are divided into 512 sets, each consisting of a primary scrambling code and 15 secondary scrambling codes [386].

More specifically, the primary scrambling codes consist of scrambling codes $n = 16 * i$, where $i = 0 \ldots 511$. The i^{th} set of secondary scrambling codes consists of scrambling codes $16 * i + k$ where $k = 1 \ldots 15$. There is a one-to-one mapping between each primary scrambling code and the associated 15 secondary scrambling codes in a set, such that the i^{th} primary scrambling code uniquely identifies the i^{th} set of secondary scrambling codes. Hence, according to the above statement, scrambling codes $k = 0 \ldots 8191$ are used. Each of these codes is associated with a left alternative scrambling code and a right alternative scrambling code, that may be used for the so-called compressed frames. Specifically, compressed frames are shortened duration frames transmitted right before a handover, in order to create an inactive period during which no useful data is transmitted. This allows the transceivers to carry out operations necessary for the handover to be successful. The left alternative scrambling code associated with scrambling code k is the scrambling code $k + 8192$, while the corresponding right alternative scrambling code is scrambling code $k + 16384$. In compressed frames, the left alternative scrambling code is used, if $n < SF/2$ and the right alternative scrambling code is used, if $n \geq SF/2$, where $C_{ch,SF,n}$ is the channelisation code used for non-compressed frames.

The set of 512 primary scrambling codes is further divided into 64 scrambling code groups, each consisting of 8 primary scrambling codes. The j^{th} scrambling code group consists of primary scrambling codes $16 * 8 * j + 16 * k$, where $j = 0 \ldots 63$ and $k = 0 \ldots 7$.

Each cell is allocated one and only one primary scrambling code. The primary CCPCH and primary CPICH are always transmitted using this primary scrambling code. The other downlink physical channels can be spread and transmitted with the aid of either the primary scrambling code or a secondary scrambling code from the set associated with the primary scrambling code of the cell.

5.3.2 Common Pilot Channel

The Common PIlot CHannel (CPICH) is an unmodulated downlink code channel, which is scrambled with the aid of the cell-specific primary scrambling code. The function of the downlink CPICH is to aid the Channel Impulse Response (CIR) estimation necessary for the detection of the dedicated channel at the mobile station and to provide the CIR estimation reference for the demodulation of the common channels, which are not associated with the dedicated channels.

UTRA has two types of common pilot channels, namely the primary and secondary CPICHs. Their difference is that the primary CPICH is always spread by the primary scrambling code defined in Section 5.3.1. More explicitly, the primary CPICH is associated with a fixed channelisation code allocation and there is only one such channel and channelisation code for a cell or sector. The secondary CPICH may use any channelisation code of length 256 and may use a secondary scrambling code as well. A typical application of secondary CPICHs usage would be in conjunction with narrow antenna beams intended for service provision at specific teletraffic ‘hot spots’ or places exhibiting a high traffic density [59].

An important application of the primary common pilot channel is during the collection of channel quality measurements for assisting during the handover and cell selection process. The measured CPICH reception level at the terminal can be used for handover decisions.

Furthermore, by adjusting the CPICH power level the cell load can be balanced between different cells, since reducing the CPICH power level encourages some of the terminals to handover to other cells, while increasing it invites more terminals to handover to the cell, as well as to make their initial access to the network in that cell.

5.3.3 Power Control

Agile and accurate power control is perhaps the most important aspect in W-CDMA, in particular on the uplink, since a single high-powered rogue mobile can cause serious performance degradation to other users in the cell. The problem is referred to as the 'near-far effect' and occurs when, for example, one mobile is near the cell edge, and another is near the cell centre. In this situation, the mobile at the cell edge is exposed to a significantly higher pathloss, say 70 dB higher, than that of the mobile near the cell centre. If there were no power control mechanisms in place, the mobile near the base station could easily 'overpower' the mobile at the cell edge, and thus may block a large part of the cell. The optimum strategy in the sense of maximising the system's capacity is to equalise the received power per bit of all mobile stations at all times.

A so-called open-loop power control mechanism [59] attempts to make a rough estimate of the expected pathloss by means of a downlink beacon signal, but this method can be highly inaccurate. The prime reason for this is that the fast fading is essentially uncorrelated between the uplink and downlink, due to the large frequency separation of the uplink and downlink band of the W-CDMA FDD mode. Open-loop power control is however, used in W-CDMA, but only to provide a coarse initial power setting of the mobile station at the beginning of a connection.

A better solution is to employ fast closed-loop power control [59]. In closed-loop power control in the uplink, the base station performs frequent estimates of the received SIR and compares it to the target SIR. If the measured SIR is higher than the target SIR, the base station commands the mobile station to reduce the power, while if it is too low it will instruct the MS to increase its power. Since each 10 ms UTRA frame consists of 15 time slots, each corresponding to one power control power adjustment period, this procedure takes place at a rate of 1500 Hz. This is far faster than any significant change of pathloss, including street corner effects, and indeed faster than the speed of Rayleigh fading for low to moderate mobile speeds. The street corner effect occurs when a mobile turns the street corner and hence the received signal power drops markedly. Therefore the mobile responds by rapidly increasing its transmit power, which may inflict sever interference upon other closely located base stations. In response, the mobiles using these base stations increase their transmit powers in an effort to maintain their communications quality. This is undesirable, since it results in a high level of co-channel interference, leading to excessive transmission powers and to a reduction of the battery recharge period.

The same closed-loop power control technique is used on the downlink, although the rationale is different. More specifically, there is no near-far problem due to the one-to-many distributive scenario, i.e. all the signals originate from the single base station to all mobiles. It is, however, desirable to provide a marginal amount of additional power to mobile stations near the cell edge, since they suffer from increased inter-cell interference. Hence, the closed loop power control in CDMA systems ensures that each mobile transmits just sufficient power to satisfy the outer-loop power control scheme's SIR target. The SIR target is controlled by an outer-loop power control process that adjusts the required SIR in order to meet the Bit Error Ratio (BER) requirements of a particular service. At higher mobile speeds typically a higher SIR is necessary for attaining a given BER/FER.

5.3.3.1 Uplink Power Control

The uplink's inner-loop power control adjusts the mobile's transmit power in order to maintain the received uplink SIR at the given SIR target, namely at SIR_{target}. The base stations that are communicating with the mobile generate Transit Power Control (TPC) commands and transmit them, once per slot, to the mobile. The mobile then derives from the TPC commands of the various base stations, a single TPC command, TPC_cmd, for each slot, combining multiple received TPC commands if necessary. In [387] two algorithms were defined for the processing of TPC commands and hence for deriving TPC_cmd.

Algorithm 1: [387]

When not in soft-handover, i.e. when the mobile communicates with a single base station, only one TPC command will be received in each slot. Hence, for each slot, if the TPC command is equal to 0 ($SIR > SIR_{target}$) then $TPC\_cmd = -1$, otherwise, if the TPC command is 1 ($SIR < SIR_{target}$) then $TPC\_cmd = 1$, which implies powering down or up, respectively.

When in soft handover, multiple TPC commands are received in each slot from the different base stations in the active base station set. If all of the base station's TPC commands are identical, then they are combined to form a single TPC command, namely TPC_cmd. However, if the TPC commands of the different base stations differ, then a soft decision W_i is generated for each of the TPC commands, TPC_i, where $i = 1, 2, \ldots, N$, and N is the number of TPC commands. These N soft decisions are then used to form a combined TPC command TPC_cmd according to:

$$TPC\_cmd = \gamma(W_1, W_2, \ldots, W_N) \tag{5.1}$$

where TPC_cmd is either -1 or +1 and $\gamma()$ is the decision function combining the soft values, $W_1, \ldots, W_N$.

If the N TPC commands appear to be uncorrelated, and have a similar probability of being 0 or 1, then function $\gamma()$ should be defined such that the probability that the output of the function $\gamma()$ is equal to 1, is greater than or equal to 1/2^N, and the probability that the output of $\gamma()$ is equal to -1, shall be greater than or equal to 0.5 [387]. Alternatively, the function $\gamma()$ should be defined such that $P(\gamma() = 1) \geq 1/2^N$ and $P(\gamma() = -1) \geq 0.5$.

Algorithm 2: [387]

When not in soft handover, only one TPC command will be received in each slot, and the mobile will process the maximum 15 TPC commands in a five-slot cycle, where the sets of five slots are aligned with the frame boundaries and the sets do not overlap. Therefore, when not in soft handover, for the first four slots of a five-slot set $TPC\_cmd = 0$ is used for indicating that no power control adjustments are made. For the fifth slot of a set the mobile performs hard decisions on all five of the received TPC commands. If all five hard decisions result in a binary 1, then we set $TPC\_cmd = 1$. In contrast, if all five hard decisions yield a binary 0, then $TPC\_cmd = -1$ is set, else $TPC\_cmd = 0$.

When the mobile is in soft handover, multiple TPC commands will be received in each slot from each of the base stations in the set of active base stations. When the TPC commands of the active base stations are identical, then they can be combined into a single TPC command. However, when the received TPC commands are different, the mobile makes a hard decision concerning the value of each TPC command for three consecutive slots, resulting in N hard decisions for each of the three slots, where N is the number of base stations within the active set. The sets of three slots are aligned to the frame boundaries and do not overlap. Then $TPC\_cmd = 0$ is set for the first two slots of the three-slot set, and then TPC_cmd is determined for the third slot as follows.

The temporary command TPC_temp_i is determined for each of the N sets of three TPC commands of the consecutive slots by setting $TPC\_temp_i = 1$ if all three TPC hard decisions are binary 1. In contrast, if all three TPC hard decisions are binary 0, $TPC\_temp_i = -1$ is set, otherwise we set $TPC\_temp_i = 0$. These temporary TPC commands are then used to determine the combined TPC command for the third slot invoking the decision function $\gamma(TPC\_temp_1, TPC\_temp_2, \ldots, TPC\_temp_N)$ defined as:

$$\begin{aligned} TPC\_cmd &= 1 && \text{if } \frac{1}{N}\sum_{i=1}^{N} TPC\_temp_i > 0.5 \\ TPC\_cmd &= -1 && \text{if } \frac{1}{N}\sum_{i=1}^{N} TPC\_temp_i < -0.5 \\ TPC\_cmd &= 0 && \text{otherwise.} \end{aligned} \tag{5.2}$$

5.3.3.2 Downlink Power Control

The downlink transmit power control procedure simultaneously controls the power of both the DPCCH and its corresponding DPDCHs, both of which are adjusted by the same amount, and hence the relative power difference between the DPCCH and DPDCHs remains constant.

The mobile generates TPC commands for controlling the base station's transmit power and sends them in the TPC field of the uplink DPCCH. When the mobile is not in soft handover, the TPC command generated is transmitted in the first available TPC field using the uplink DPCCH. In contrast, when the mobile is in soft handover, it checks the downlink power control mode (DPC_MODE) before generating the TPC command. If $DPC\_MODE = 0$, the mobile sends a unique TPC command in the first available TPC field in the uplink DPCCH. If however, $DPC\_MODE = 1$, the mobile repeats the same TPC command over three consecutive slots of the same frame and the new TPC command is transmitted to the base station in an effort the control its power at the beginning of the next frame. The minimum required transmit power step size is 1 dB, with a smaller step size of 0.5 dB being optional. The power control step size can be increased from 1 dB to 2 dB, thus allowing a 30 dB correction range during the 15 slots of a 10 ms frame. The maximum transmit powers are +21 dBm and +24 dBm, although it is likely that in the first phase of network deployment most terminals will belong to the 21 dBm power class [59].

5.3.4 Soft Handover

Theoretically, the ability of CDMA to despread the interfering signals, and thus adequately operate at low signal-to-noise ratios, allows a CDMA network to have a frequency reuse factor of one [59]. Traditionally, non-CDMA based networks have required adjacent cells to have different carrier frequencies, in order to reduce the co-channel interference to acceptable levels. Therefore, when a mobile hands over from one cell to another, it has to re-tune its synthesiser to the new carrier frequency, i.e. it performs an inter-frequency handover. This process is a ‘break-before-make’ procedure, known as a hard handover, and hence call disruption or interruption is possible. However, in a CDMA based network, having a frequency reuse factor of one, so-called soft handovers may be performed, which is a ‘make-before-break’ process, potentially allowing for a smoother handover between cells. During a soft handover a mobile is connected to two or more base stations simultaneously, thus utilising more network resources and transmitting more signals, which interfere with other users. Therefore, it is in the network operator’s interests to minimise the number of users in soft handover, whilst maintaining a satisfactory quality of service. In soft handover, each connected base station receives and demodulates the user’s data, and selection diversity is performed between the base stations, i.e. the best version of the uplink frame is selected. In the downlink, the mobile station performs maximal ratio combining [5] of the signal received from the multiple base stations. This diversity combining improves the coverage in regions of previously low-quality service provision, but at the expense of increased backhaul connections.

The set of base stations engaged in soft handover is known as the *active set*. The mobile station continuously monitors the received power level of the PIlot CHannels (PICHs) transmitted by its neighbouring base stations. The received pilot power levels of these base stations are then compared to two thresholds, the acceptance threshold, T_{acc} and the dropping threshold T_{drop}. Therefore, as a mobile moves away from base station 1, and towards base station 2, the pilot signal strength received from base station 2 increases. When the pilot strength exceeds the *acceptance threshold*, T_{acc}, the mobile station enters the soft handover state, as shown in Figure 5.5. As the mobile continues to move away from base station 1, its pilot strength decreases, until it falls below the *drop threshold*. After a given time interval, T_{drop}, during which the signal strength from base station 1 has not exceeded the drop threshold, base station 1 is removed from the active set.

5.3.5 Signal-to-Interference plus Noise Ratio Calculations

5.3.5.1 Downlink

The interference received at the mobile can be divided into interference due to the signals transmitted to other mobiles from the same base station, which is known as intra-cell interference, and that received due to the signals transmitted to other mobiles from other base stations, which is termed inter-cell interference. In an ideal case, the intra-cell interference would be zero, since all the signals from the base station are subjected to the same channel conditions, and orthogonal channelisation codes are used for separating the users. However, after propagation through a dispersive multipath channel, this orthogonality is eroded. The intra-cell and inter-cell interference values are always non-zero when in a single-user scenario due to the inevitable interference inflicted by the common pilot channels.

The instantaneous SINR is obtained by dividing the received signal powers by the total interference plus thermal noise power, and then by multiplying this ratio by the spreading factor, SF, yielding

$$SINR_{DL} = \frac{SF \cdot S}{(1-\alpha)I_{Intra} + I_{Inter} + N_0}, \tag{5.3}$$

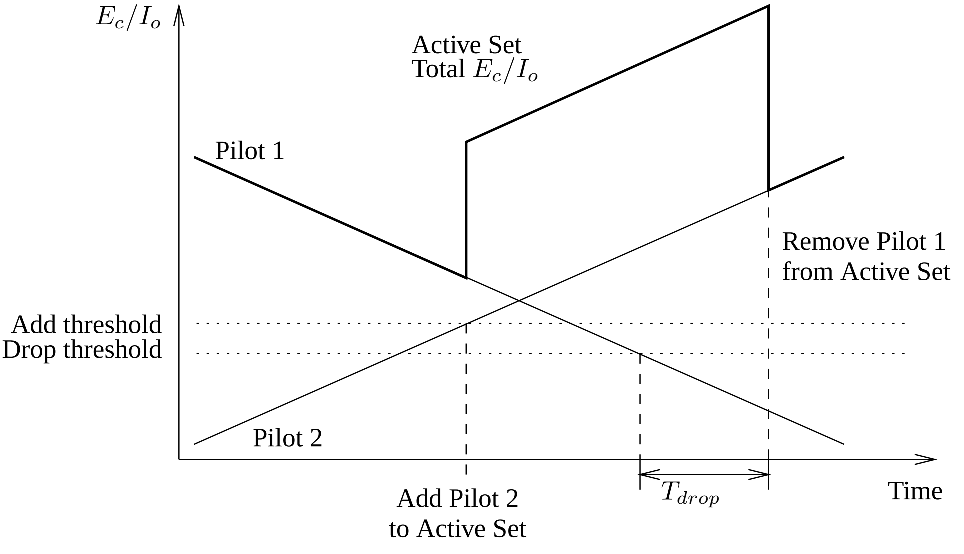


Figure 5.5: The soft handover process showing the process of adding and dropping base stations from the active set.

where $\alpha = 1$ corresponds to the ideal case of perfectly orthogonal intra-cell interference, and $\alpha = 0$ is for completely asynchronous intra-cell interference. Furthermore, N_0 is the thermal noise's power spectral density, S is the received signal power, I_{Intra} is the intra-cell interference and I_{Inter} is the inter-cell interference. Again, the interference plus noise power is scaled by the spreading factor, SF, since after the low-pass filtering the noise bandwidth is reduced by a factor of SF during the despreading process.

When in soft handover, the maximum ratio combining is performed on the N received signals of the N active base stations. Therefore, provided that the active base stations' received signals are independent, the SINR in this situation is:

$$SINR_{DL} = SINR_{DL_1} + SINR_{DL_2} + \ldots + SINR_{DL_N}. \tag{5.4}$$

5.3.5.2 Uplink

The uplink differs from the downlink in that the multiple access interference is asynchronous in the uplink due to the un-coordinated transmissions of the mobile stations, whereas it may remain quasi-synchronous in the downlink. Therefore, the intra-cell uplink interference is not orthogonal. A possible solution for mitigating this problem is employing Multi-User Detectors (MUDs) [93] at the base stations.

Thus, we define β as the MUD's efficiency, which effectively gives the percentage of the intra-cell interference that is removed by the MUD. Setting $\beta = 0.0$ implies 0% efficiency, when the intra-cell interference is not reduced by the MUD, whereas $\beta = 1.0$ results in the perfect suppression of all the intra-cell interference. Therefore, the expression for the uplink

SINR is:

$$SINR_{UL} = \frac{SF \cdot S}{(1-\beta)I_{Intra} + I_{Inter} + N_0}. \quad (5.5)$$

When in soft handover, selection diversity is performed on the N received signals at each of the active base stations. Therefore, the SINR in this situation becomes:

$$SINR_{UL} = \max(SINR_{UL_1}, SINR_{UL_2}, \ldots, SINR_{UL_N}). \quad (5.6)$$

5.3.6 Multi-User Detection

Multiple access communications using DS-CDMA is interference limited due to the Multiple Access Interference (MAI) generated by the users transmitting simultaneously within the same bandwidth. The signals received from the users are separated with the aid of the despreader using spreading sequences that are unique to each user. Again, these spreading sequences are usually non-orthogonal. Even if they are orthogonal, the asynchronous uplink transmissions of the users or the time-varying nature of the mobile radio channel may partially destroy this orthogonality. The non-orthogonal nature of the codes results in residual MAI, which degrades the performance of the system. The frequency selective mobile radio channel also gives rise to Inter-Symbol Interference (ISI) due to dispersive multipath propagation. This is exacerbated by the fact that the mobile radio channel is time-varying.

Conventional CDMA detectors - such as the matched filter [5, 388] and the RAKE combiner [389] - are optimised for detecting the signal of a single desired user. RAKE combiners exploit the inherent multi-path diversity in CDMA, since they essentially consist of matched filters combining each resolvable path of the multipath channel. The outputs of these matched filters are then coherently combined according to a diversity combining technique, such as maximal ratio combining [309], equal gain combining or selective diversity combining . These conventional single-user detectors are inefficient, because the interference is treated as noise, and our knowledge concerning the CIR of the mobile channel, or that of the spreading sequences of the interferers is not exploited. The efficiency of these detectors is dependent on the cross-correlation (CCL) between the spreading codes of all the users. The higher the cross-correlation, the higher the MAI. This CCL-induced MAI is exacerbated by the effects of the dispersive multi-path channel and asynchronous transmissions. The utilisation of these conventional receivers results in an interference-limited system. Another weakness of the above-mentioned conventional CDMA detectors is the phenomenon known as the 'near-far effect' [390, 391]. For conventional detectors to operate efficiently, the signals received from all the users have to arrive at the receiver with approximately the same power. A signal that has a significantly weaker signal strength compared to the other signals will be 'swamped' by the relatively higher powers of the other signals and the quality of the weaker signal at the output of the conventional receiver will be severely degraded. Therefore, stringent power control algorithms are needed to ensure that the signals arrive at similar powers at the receiver, in order to achieve a similar quality of service for different users [391, 392]. Using conventional detectors to detect a signal corrupted by MAI, while encountering a hostile channel results in an irreducible BER, even if the E_s/N_0 ratio is increased. This is because at high E_s/N_0 values the probability of errors due to thermal noise is insignificant compared to the errors caused by the MAI and the channel. Therefore, detectors that can reduce or remove the effects of MAI and ISI are needed in order to achieve user capacity gains. These detectors also have to be ‘near-far resistant’, in order to avoid the need for stringent power control requirements. In order to mitigate the problem of MAI, Verdú [93] proposed the optimum multi-user detector for asynchronous Gaussian multiple access channels. This optimum detector significantly outperforms the conventional detector and it is near-far resistant, but unfortunately its complexity increases exponentially according to the order of $O(2^{NK})$, where N is the number of overlapping asynchronous bits considered in the detector’s window, and K is the number of interfering users. In order to reduce the complexity of the receiver and yet to provide an acceptable BER performance, significant research efforts have been invested in the field of sub-optimal CDMA multiuser receivers [93, 393].

In summary, multi-user detectors reduce the error floor due to MAI and this translates into user capacity gains for the system. These multi-user detectors are also near-far resistant to a certain extent and this results in less stringent power control requirements. However, multi-user detectors are more complex than conventional detectors. Coherent detectors require the explicit knowledge of the channel impulse response estimates, which implies that a channel estimator is needed in the receiver, and hence training sequences have to be included in the transmission frames. Training sequences are specified in the TDD mode of the UTRA standard and enable the channel impulse response of each simultaneously communicating user to be derived, which is necessary for the multi-user detectors to be able to separate the signals received from each user. These multi-user detectors also exhibit an inherent latency, which results in delayed reception. Multi-user detection is more suitable for the uplink receiver since the base station has to detect all users’ signals anyway and it can tolerate a higher complexity. In contrast, a hand-held mobile receiver is required to be compact and lightweight, imposing restrictions on the available processing power. Recent research into blind MUDs has shown that data detection is possible for the desired user without invoking the knowledge of the spreading sequences and channel estimates of other users. Hence using these detectors for downlink receivers is becoming feasible.

5.4 Simulation Results

This section presents simulation results obtained for an FDD mode UMTS type CDMA cellular network, investigating the applicability of various soft handover metrics when subjected to different propagation conditions. This is followed by performance curves obtained using adaptive antenna arrays, when subjected to both non-shadowed as well as shadowed propagation conditions. The performance of adaptive modulation techniques used in conjunction with adaptive antenna arrays in a shadow faded environment is then characterised.

5.4.1 Simulation Parameters

Simulations of an FDD mode UMTS type CDMA based cellular network were conducted for various scenarios and algorithms in order to study the interactions of the processes involved in such a network. As in the standard, the frame length was set to 10 ms, containing 15 power control timeslots. The power control target SINR was chosen to give a Bit Error Ratio (BER) of 1×10^{-3}, with a low quality outage occurring at a BER of 5×10^{-3} and an outage taking place at a BER of 1×10^{-2}. The received SINRs at both the mobile and the base stations were required for each of the power control timeslots, and hence the outage and low quality outage statistics were gathered. If the received SINR was found to be below the outage SINR for 75 consecutive power control timeslots, corresponding to 5 consecutive transmission frames or 50 ms, the call was dropped. The post despreading SINRs necessary for obtaining the target BERs were determined with the aid of physical-layer simulations using a 4-QAM modulation scheme, in conjunction with $1/2$ rate turbo coding and joint detection over a COST 207 seven-path Bad Urban channel [394]. For a spreading factor of 16, the post-de-spreading SINR required to give a BER of 1×10^{-3} was 8.0 dB, for a BER of 5×10^{-3} it was 7.0 dB, and for a BER of 1×10^{-2} was about 6.6 dB. These values can be seen along with the other system parameters in Table 5.2. The-pre de-spreading SINR is related to E_b/N_o and to the spreading factor by :

$$SINR = (E_b/N_o)/SF, \tag{5.7}$$

where the spreading factor $SF = W/R$, with W being the chip rate and R the data rate. A receiver noise figure of 7 dB was assumed for both the mobile and the base stations [59]. Thus, in conjunction with a thermal noise density of -174 dBm/Hz and a noise bandwidth of 3.84 MHz, this resulted in a receiver noise power of -100 dBm. The power control algorithm used was relatively simple, and unrelated to the previously introduced schemes of Section 5.3.3. Furthermore, since it allowed a full transmission power change of 15 dB within a 15-slot UTRA data frame, the power control scheme advocated is unlikely to limit the network's capacity.

Specifically, for each of the 15 timeslots per transmitted frame, both the mobile and base station transmit powers were adjusted such that the received SINR was greater than the target SINR, but less than the target SINR plus 1 dB of hysteresis. When in soft handover, a mobile's transmission power was only increased if all of the base stations in the Active Base station Set (ABS) requested a power increase, but was it decreased if any of the base stations in the ABS had an excessive received SINR. In the downlink, if the received SINR at the mobile was insufficiently high then all of the active base stations were commanded to increase their transmission powers. Similarly, if the received SINR was unnecessarily high, then the active base stations would reduce their transmit powers. The downlink intra-cell interference orthogonality factor, α, as described in Section 5.3.5, was set to 0.5 [395–397]. Due to the frequency reuse factor of one, with its associated low frequency reuse distance, it was necessary for both the mobiles and the base stations, when initiating a new call or entering soft handover, to increase their transmitted power gradually. This was required to prevent sudden increases in the level of interference, particularly on links using the same base station. Hence, by gradually increasing the transmit power to the desired level, the other users of the network were capable of compensating for the increased interference by increasing their transmit powers, without encountering undesirable outages. In an FDMA/TDMA network this effect is less noticeable due to the significantly higher frequency reuse distance.

Since a dropped call is less desirable from a user's viewpoint than a blocked call, two resource allocation queues were invoked, one for new calls and the other - higher priority - queue, for handovers. By forming a queue of the handover requests, which have a higher priority during contention for network resources than new calls, it is possible to reduce the number of dropped calls at the expense of an increased blocked call probability. A further advantage of the Handover Queueing System (HQS) is that during the time a handover is in the queue, previously allocated resources may become available, hence increasing the probability of a successful handover. However, in a CDMA based network the capacity is not hard-limited by the number of frequency/timeslot combinations available, like in

Parameter	Value	Parameter	Value
Frame length	10 ms	Timeslots per frame	15
Target E_b/N_o	8.0 dB	Outage E_b/N_o	6.6 dB
Low Quality (LQ) Outage E_b/N_o	7.0 dB	BS Pilot Power	-5 dBm
BS/MS Minimum TX Power	-44 dBm	BS Antenna Gain	11 dBi
BS/MS Maximum TX Power	+21 dBm	MS Antenna Gain	0 dBi
Attenuation at 1 m reference point	39 dB	Pathloss exponent	-3.5
Power control SINR hysteresis	1 dB	Cell radius	150 m
Downlink scrambling codes per BS	1	Modulation scheme	4-QAM
Downlink OVSF codes per BS	Variable	Max new-call queue-time	5 s
Uplink scrambling codes per BS	Variable	Average inter-call time	300 s
Uplink OVSF codes per BS	Variable	Average call length	60 s
Spreading factor	Variable	Data/voice bit rate	Variable
Remove BS from ABS threshold	Variable	Add BS to ABS threshold	Variable
User speed	1.34 m/s	Noisefloor	-100 dBm
	(3 mph)	Size of ABS	2

Table 5.2: Simulation parameters of the UTRA-type CDMA based cellular network.

an FDMA/TDMA based network, such as GSM. The main limiting factors are the number of available spreading and OVSF codes, where the number of the available OVSF codes is restricted to the spreading factor minus one, since an OVSF code is reserved for the pilot channel. This is because, although the pilot channel has a spreading factor of 256, it removes an entire branch of the OVSF code generation tree. Other limiting factors are the interference levels in conjunction with the restricted maximum transmit power, resulting in excessive call dropping rates. New call allocation requests were queued for up to 5 s, if they could not be immediately satisfied, and were blocked if the request had not been completed successfully within the 5 s.

Similarly to our TDMA-based investigations portrayed in Chapter 4, several network performance metrics were used in order to quantify the quality of service provided by the cellular network, namely the:

- New Call Blocking probability, P_B,
- Call Dropping or Forced Termination probability, P_{FT},
- Probability of low quality connection, P_{low},
- Probability of Outage, P_{out},
- Grade Of Service, GOS.

The new call blocking probability, P_B, is defined as the probability that a new call is denied access to the network. In an FDMA/TDMA based network, such as GSM, this may occur because there are no available physical channels at the desired base station or the available channels are subject to excessive interference. However, in a CDMA based network this does not occur, provided that no interference level based admission control is performed and hence the new call blocking probability is typically low.

The call dropping probability, P_{FT}, is the probability that a call is forced to terminate prematurely. In a GSM type network, an insufficiently high SINR, which inevitably leads to dropped calls, may be remedied by an intra- or inter-cell handover. However, in CDMA either the transmit power must be increased, or a soft handover must be performed in order to exploit the available diversity gain.

Again, the probability of a low quality connection is defined as:

$$\begin{aligned} P_{low} &= P\{SINR_{uplink} < SINR_{req} \text{ or } SINR_{downlink} < SINR_{req}\} \\ &= P\{min(SINR_{uplink}, SINR_{downlink}) < SINR_{req}\}. \end{aligned} \tag{5.8}$$

The GOS was defined in [317] as:

$$\begin{aligned} GOS &= P\{\text{unsuccessful or low-quality call access}\} \\ &= P\{\text{call is blocked}\} + P\{\text{call is admitted}\} \times \\ &\quad P\{\text{low signal quality and call is admitted}\} \\ &= P_B + (1 - P_B)P_{low}, \end{aligned} \tag{5.9}$$

and is interpreted as the probability of unsuccessful network access (blocking), or low quality access, when a call is admitted to the system.

In our forthcoming investigations, in order to compare the network capacities of different networks, similarly to our TDMA-based investigations in Chapter 4, it was decided to use two scenarios defined as :

- A *conservative scenario*, where the maximum acceptable value for the new call blocking probability, P_B, is 3%, the maximum call dropping probability, P_{FT}, is 1%, and P_{low} is 1%.
- A *lenient scenario*, where the maximum acceptable value for the new call blocking probability, P_B, is 5%, the maximum call dropping probability, P_{FT}, is 1%, and P_{low} is 2%.

In the next section we consider the network's performance considering both fixed and normalised soft handover thresholds using both received pilot power and received pilot power versus interference threshold metrics. A spreading factor of 16 was used, corresponding to a channel data rate of 3.84 Mbps/16 = 240 kbps with no channel coding, or 120 kbps when using $1/2$ rate channel coding. It must be noted at this stage that the results presented in the following sections are network capacities obtained using a spreading factor of 16. The network capacity results presented in the previous chapter, which were obtained for an FDMA/TDMA GSM-like system, were achieved for speech-rate users. Here we assumed that the channel coded speech-rate was 15 kbps, which is the lowest possible Dedicated Physical Data CHannel (DPDCH) rate. Speech users having a channel coded rate of 15 kbps may be supported by invoking a spreading factor of 256. Hence, subjecting the channel data rate of 15 kbps to $1/2$ rate channel coding gives a speech-rate of 7.5 kbps, or if protected by a $2/3$ rate code the speech-rate becomes 10 kbps, which are sufficiently high for employing the so-called Advanced MultiRate (AMR) speech codec [398–400] capable of operating at rates between 4.7 kbps and 12.2 kbps. Therefore, by multiplying the resultant network capacities according to a factor of 256/16=16, it is possible to estimate the number of speech users supported by a speech-rate network. However, with the aid of our exploratory simulations, conducted using a spreading factor of 256, which are not presented here, we achieved network capacities higher than 30 times the network capacity supported in conjunction with a spreading factor of 16. Therefore, it would appear that the system is likely to support more than 16 times the number of 240 kbps data users, when communicating at the approximately 16 times lower speech-rate, employing a high spreading factor of 256. Hence, using the above-mentioned scaling factor of 16 we arrive at the lower bound of network capacity. A mobile speed of 3 mph was used in conjunction with a cell size of 150 m radius, which was necessarily small in order to be able to support the previously assumed 240 kbps high target data rate. The performance advantages of using both adaptive beamforming and adaptive modulation assisted networks are also investigated.

5.4.2 The Effect of Pilot Power on Soft Handover Results

In this section we consider the settings of the soft handover thresholds, for an IS-95 type handover algorithm [58], where the handover decisions are based on downlink pilot power measurements. Selecting inappropriate values for the soft handover thresholds, namely for the *acceptance threshold* and the *drop threshold*, may result in an excessive number of blocked and dropped calls in certain parts of the simulation area. For example, if the *acceptance threshold* that has to be exceeded by the signal level for a base station to be added to the active set is too high (Threshold B in Figure 5.6), then a user may be located within a cell, but it would be unable to add any base stations to its active base station set. Hence this user is unable to initiate a call. Figure 5.6 illustrates this phenomenon and shows that the *acceptance thresholds* must be set sufficiently low for ensuring that at least one base station covers every part of the network.

Another consequence of setting the *acceptance threshold* to an excessively high value, is that soft handovers may not be completed. This may occur when a user leaving the coverage area of a cell, since the pilot signal from that cell drops below the *drop threshold*, before the signal from the adjacent cell becomes sufficiently strong for it to be added to the active base station set. However, if the *acceptance threshold*, in conjunction with the *drop threshold*, is set correctly, then new calls and soft handovers should take place as required, so long as the availability of network resources allows it. Care must be taken however, not to set the soft handover threshold too low, otherwise the mobiles occupy additional network resources and create extra interference, due to initiating unnecessary soft-handovers.

5.4.2.1 Fixed Received Pilot Power Thresholds without Shadowing

Figure 5.7 shows the new call blocking probability of a network using a spreading factor of 16, in conjunction with fixed received pilot signal strength based soft handover thresholds without imposing any shadowing effects. The figure illustrates that reducing both the acceptance and the dropping soft handover thresholds results in an improved new call blocking performance. Reducing the threshold at which further base stations may be added to the Active Base station Set (ABS) increases the probability that base stations exist within the ABS, when a new call request is made. Hence, as expected, the new call blocking probability is reduced, when the acceptance threshold is reduced. Similarly, dropping the threshold at which base stations are removed from the ABS also results in an improved new call blocking probability, since a base station is more likely to be retained in the ABS as a mobile moves away from it. Therefore, should a mobile attempt to initiate a call in this situation, there is a

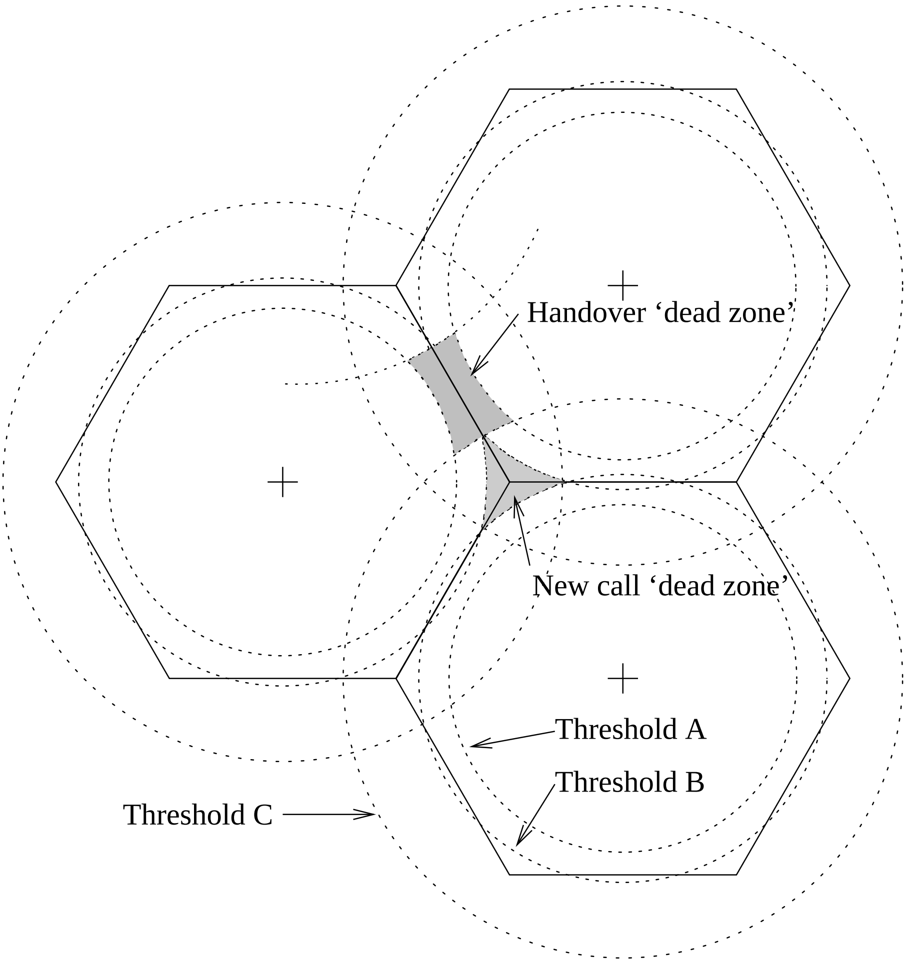


Figure 5.6: This figure indicates that using inappropriate soft handover thresholds may lead to blocked and dropped calls due to insufficient pilot coverage of the simulation area. Threshold A is the drop threshold, which when combined with the acceptance threshold C can fail to cover the simulation area sufficiently well, thus leading to soft handover failure. When combining threshold A with the acceptance threshold B, users located in the ‘new call dead zone’ may become unable to initiate calls.

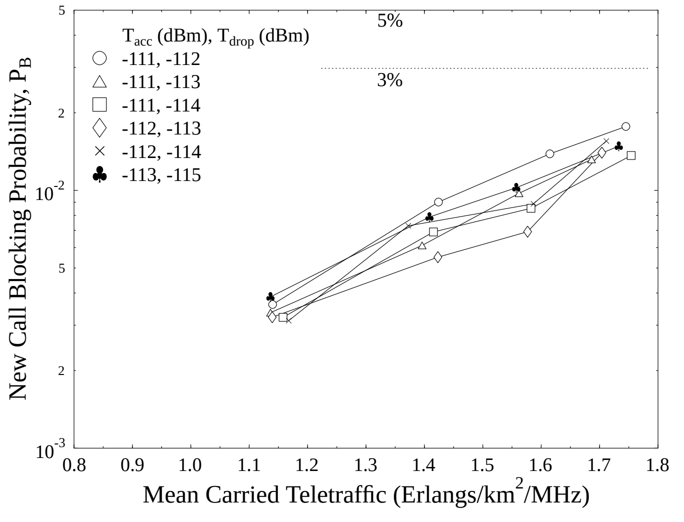


Figure 5.7: New call blocking probability versus mean carried traffic of a CDMA based cellular network using **fixed received pilot power** based soft handover thresholds **without shadowing** for SF=16.

greater chance that the ABS will contain a suitable base station.

The associated call dropping probability is depicted in Figure 5.8, indicating that reducing the soft handover thresholds, and thus increasing the time spent in soft handover, improved the performance up to a certain point. However, above this point the additional interference inflicted by the soft handover process led to a degraded performance. For example, in this figure the performance associated with $T_{acc} = -111$ dBm improved, when T_{drop} was decreased from -112 dBm to -113 dBm. However, at high traffic levels the performance degraded when T_{drop} was decreased further, to -114 dBm. The call dropping probability obtained using T_{acc}=-113 dBm and T_{drop}=-115 dBm was markedly lower for the lesser levels of traffic carried due to the extra diversity gain provided by the soft handover process. However, since these soft handover thresholds resulted in a greater proportion of time spent in soft handover, the levels of interference were increased, and thus at the higher traffic levels the performance degraded rapidly, as can be seen in Figure 5.8. Hence, the call dropping performance is based on a trade-off between the diversity gain provided by the soft handover process and the associated additional interference.

The probability of low quality access (not explicitly shown) was similar in terms of its character to the call dropping probability, since reducing T_{drop} improved the performance to a certain point, after which it degraded.

The mean number of base stations in the ABS is shown in Figure 5.9, illustrating that reducing the soft handover thresholds leads, on average, to a higher number of base stations in the ABS. Therefore, a greater proportion of call time is spent in soft handover. The associated diversity gain improves the link quality of the reference user but additional co-channel interference is generated by the diversity links, thus ultimately reducing the call quality, as

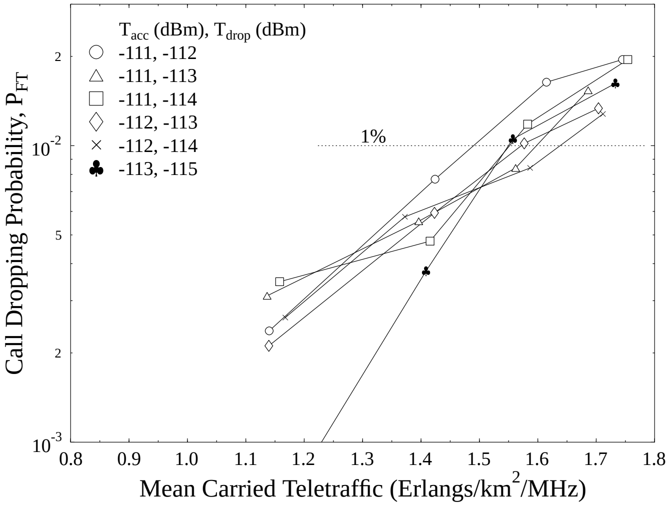


Figure 5.8: Call dropping probability versus mean carried traffic of a CDMA based cellular network using **fixed received pilot power** based soft handover thresholds **without shadowing** for SF=16.

shown in Figure 5.8. Additionally, this extra co-channel interference required more transmission power for maintaining the target SINR as depicted in Figure 5.10. This figure shows that when lower soft handover thresholds are used, and thus a greater proportion of time is spent in soft handover, greater levels of co-channel interference are present, and thus the required mean transmission powers became higher. It is interesting to note that for the highest soft handover thresholds employed in Figure 5.10, the downlink transmission power required for maintaining the target SINR is lower than the uplink transmission power, whereas for the lower soft handover thresholds, the required mean uplink transmission power is lower than the downlink transmission power. The required downlink transmission power was, in general, lower than the uplink transmission power due to the mobile stations' ability to perform maximal ratio combining when in soft handover. This was observed despite the absence of the pilot interference in the uplink, and despite the base stations' ability to perform selective diversity which offers less diversity gain when compared to maximal ratio combining. However, reducing the soft handover thresholds to the lowest levels shown in Figure 5.10, led to increased co-channel interference on the downlink, thus requiring higher base station transmission powers, as clearly seen in the figure.

In summary, as seen by comparing Figures 5.7-5.10 the maximum capacity of the network using fixed received pilot power based soft handover thresholds was limited by the call dropping probability. The new call blocking probability remained below the 3% limit, thanks to the appropriate choice of thresholds used, whilst the probability of low quality access was constantly below the 1% mark. Therefore, the maximum normalised teletraffic load was 1.64 Erlangs/km^2/MHz, corresponding to a total network capacity of 290 users, while satisfying both quality of service constraints, was achieved with the aid of an acceptance threshold

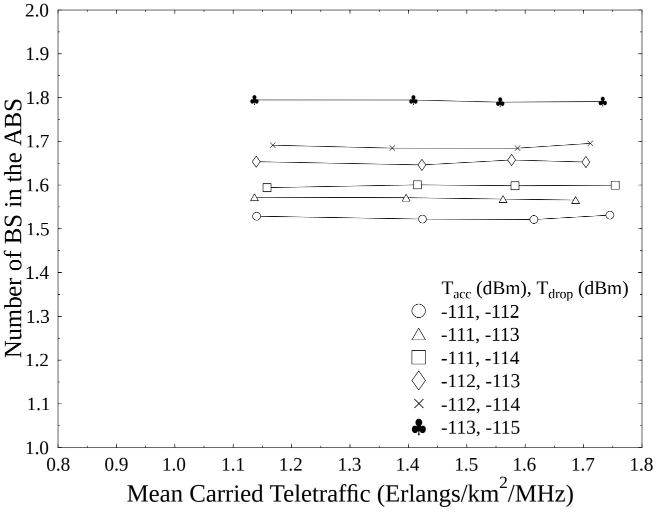


Figure 5.9: Mean number of base stations in the active base station set versus mean carried traffic of a CDMA based cellular network using **fixed received pilot power** based soft handover thresholds **without shadowing** for SF=16.

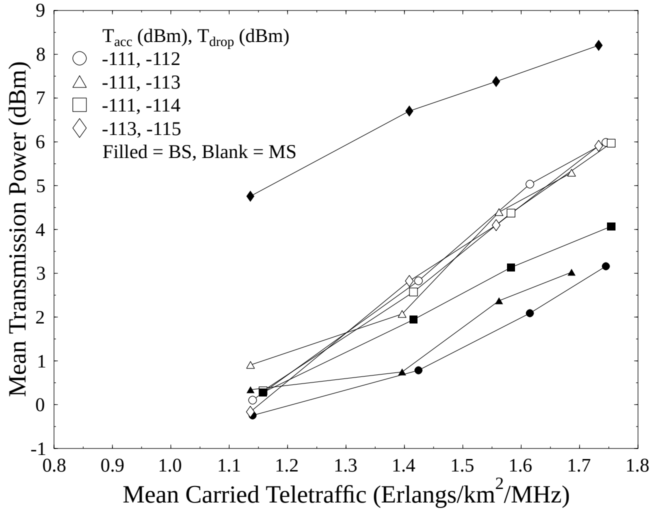


Figure 5.10: Mean transmission power versus mean carried traffic of a CDMA based cellular network using **fixed received pilot power** based soft handover thresholds **without shadowing** for SF=16.

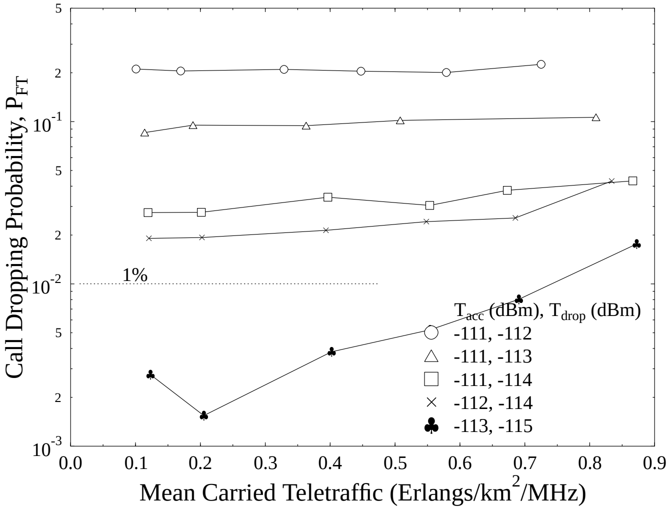


Figure 5.11: Call dropping probability versus mean carried traffic of a CDMA based cellular network using **fixed received pilot power** based soft handover thresholds in conjunction **with 0.5 Hz shadowing having a standard deviation of 3 dB** for SF=16.

of -112 dBm and a dropping threshold of -114 dBm. A mean ABS size of 1.7 base stations was registered at this traffic level, and both the mobile and base stations exhibited a mean transmission power of 5.1 dBm.

5.4.2.2 Fixed Received Pilot Power Thresholds with 0.5 Hz Shadowing

In this section we examine the achievable performance, upon using fixed received pilot power based soft handover thresholds when subjected to log-normal shadow fading having a standard deviation of 3 dB and a maximum frequency of 0.5 Hz.

The call dropping results of Figure 5.11 suggested that the network's performance was poor when using fixed received pilot power soft handover thresholds in the above mentioned shadow fading environment. The root cause of the problem is that the fixed thresholds must be set such that the received pilot signals, even when subjected to shadow fading, are retained in the active set. Therefore, setting the thresholds too high results in the base stations being removed from the active set, thus leading to an excessive number of dropped calls. However, if the thresholds are set too low, in order to counteract this phenomenon, then the base stations can be in soft handover for too high a proportion of time, and thus an unacceptable level of low quality accesses is generated due to the additional co-channel interference inflicted by the high number of active base stations. Figure 5.11 shows that reducing the soft handover thresholds improved the network's call dropping probability, but Figure 5.12 illustrates that reducing the soft handover thresholds engendered an increase in the probability of a low quality access.

The network cannot satisfy the quality requirements of the conservative scenario, namely

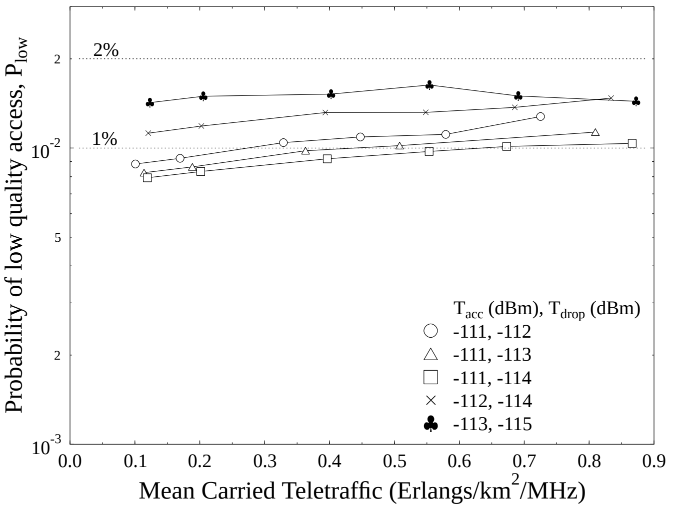


Figure 5.12: Probability of low quality access versus mean carried traffic of a CDMA based cellular network using **fixed received pilot power** based soft handover thresholds in conjunction **with 0.5 Hz shadowing having a standard deviation of 3 dB** for SF=16.

that of maintaining a call dropping probability of 1% combined with a maximum probability of low quality access below 1%. However, the entire network supported 127 users, whilst meeting the lenient scenario's set of criteria, which consists of a maximum call dropping probability of 1% and a probability of low quality access of below 2%, using the thresholds of T_{acc}=-113 dBm and T_{drop}=-115 dBm.

5.4.2.3 Fixed Received Pilot Power Thresholds with 1.0 Hz Shadowing

This section presents results obtained using fixed receiver pilot power based soft handover thresholds in conjunction with log-normal shadow fading having a standard deviation of 3 dB and a maximum fading frequency of 1.0 Hz.

The corresponding call dropping probability is depicted in Figure 5.13, showing that using fixed thresholds in a propagation environment exposed to shadow fading resulted in a very poor performance. This was due to the shadow fading induced fluctuations of the received pilot signal power, which resulted in removing base stations from the ABS mid-call, which ultimately engendered dropped calls. Hence, lowering the fixed thresholds significantly reduced the call dropping probability. However, this led to a deterioration of the low quality access probability, as shown in Figure 5.14. The probability of low quality access was also very poor due to the rapidly fluctuating interference-limited environment. This was shown particularly explicitly in conjunction with T_{acc}=-113 dBm and T_{drop}=-115 dBm, where reducing the number of users resulted in a degradation of the low quality access performance due to the higher deviation of the reduced number of combined sources of interference. In contrast, adding more users led to a near-constant level of interference that varied less dra-

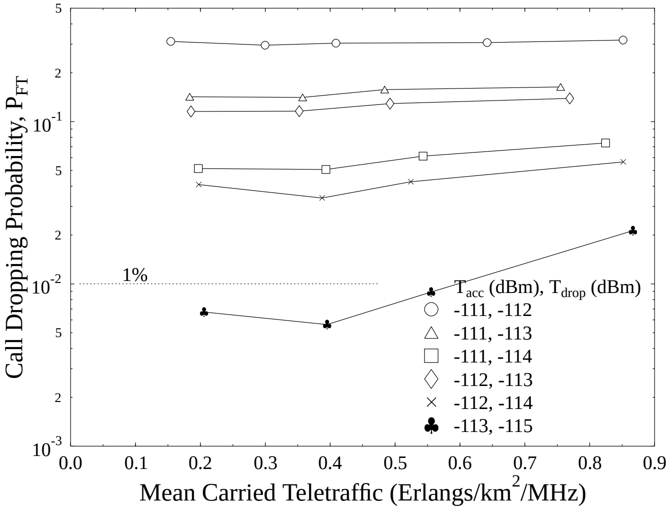


Figure 5.13: Call dropping probability versus mean carried traffic of a CDMA based cellular network using **fixed received pilot power** based soft handover thresholds in conjunction **with 1 Hz shadowing having a standard deviation of 3 dB** for SF=16.

matically.

It was found that the network was unable to support any users at the required service quality, since using the thresholds that allowed the maximum 1% call dropping probability restriction to be met, led to a greater than 2% probability of a low quality outage occurring.

5.4.2.4 Summary

In summary of our findings in the context of Figure 5.7-5.14, a disadvantage of using fixed soft handover thresholds is that in some locations all pilot signals may be weak, whereas in other locations, all of the pilot signals may be strong due to the localised propagation environment or terrain. Hence, using relative or normalised soft handover thresholds is expected to be advantageous in terms of overcoming this limitation. An additional benefit of using dynamic thresholds is confirmed within a fading environment, where the received pilot power may drop momentarily below a fixed threshold, thus causing unnecessary removals and additions to/from the ABS. However, these base stations may have been the only base stations in the ABS, thus ultimately resulting in a dropped call. When using dynamically controlled thresholds this scenario would not have occurred. Hence, in the next section we considered the performance of using relative received pilot power based soft handover thresholds under both non-shadowing and shadowing impaired propagation conditions.

To summarise, using fixed received pilot power thresholds in a non-shadowing environment resulted in a total network capacity of 290 users for both quality of service scenarios, namely for both the conservative and lenient scenarios considered. However, this performance was severely degraded in a shadow fading impaired propagation environment, where

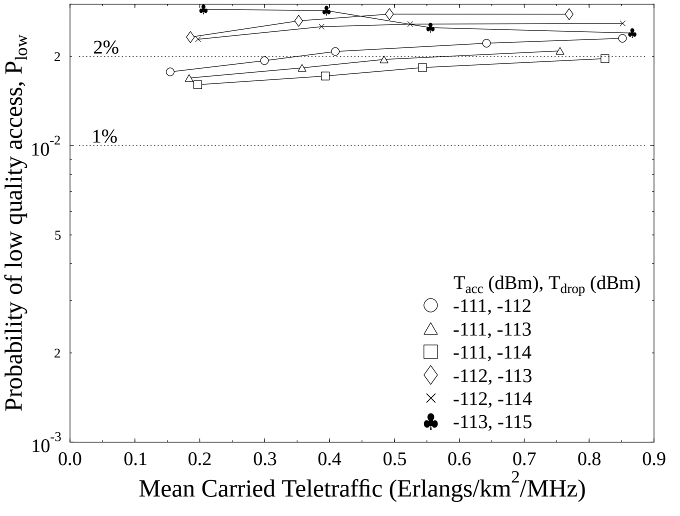


Figure 5.14: Probability of low quality access versus mean carried traffic of a CDMA based cellular network using **fixed received pilot power** based soft handover thresholds in conjunction **with 1 Hz shadowing having a standard deviation of 3 dB** for SF=16.

a total network capacity of 127 users was supported in conjunction with a maximum shadow fading frequency of 0.5 Hz. Unfortunately, the network capacity could not be evaluated when using a maximum shadow fading frequency of 1.0 Hz due to the contrasting characteristics of the dropped call and low quality access probability results.

5.4.2.5 Relative Received Pilot Power Thresholds without Shadowing

Employing relative received pilot power thresholds is important in realistic propagation environments exposed to shadow fading. More explicitly, in contrast to the previously used thresholds, which were expressed in terms of dBm, i.e. with respect to 1 mW, in this section the thresholds T_{acc} and T_{drop} are expressed in terms of dB relative to the received pilot strength of the base stations in the ABS. Their employment also caters for situations, where the absolute pilot power may be too low for use in conjunction with fixed thresholds, but nonetheless sufficiently high for reliable communications. Hence, in this section we examine the performance of relative received pilot power based soft handover thresholds in a non-shadow faded environment.

The call dropping performance is depicted in Figure 5.15, which shows that reducing the soft handover thresholds, and thus increasing the time spent in soft handover, improved the call dropping performance. It was also found in the cases considered here, that simultaneously the probability of a low quality access decreased, as illustrated by Figure 5.16. However, it was also evident in both figures, that reducing the soft handover thresholds past a certain point resulted in degraded performance due to the extra interference incurred during the soft handover process.

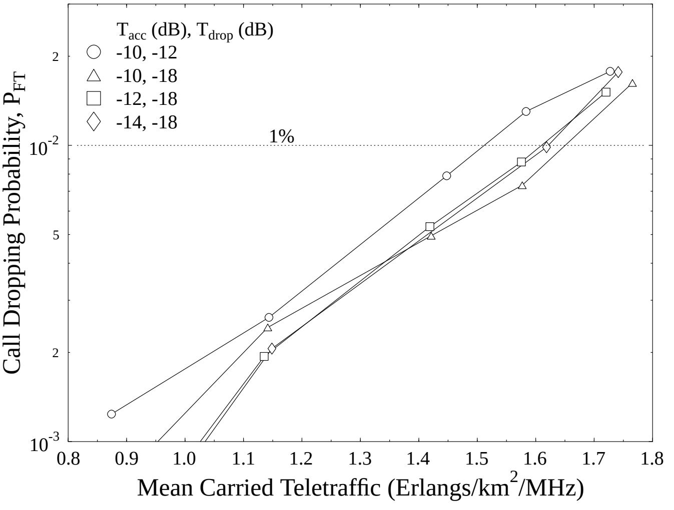


Figure 5.15: Call dropping probability versus mean carried traffic of a CDMA based cellular network using **relative received pilot power** based soft handover thresholds **without shadowing** for SF=16.

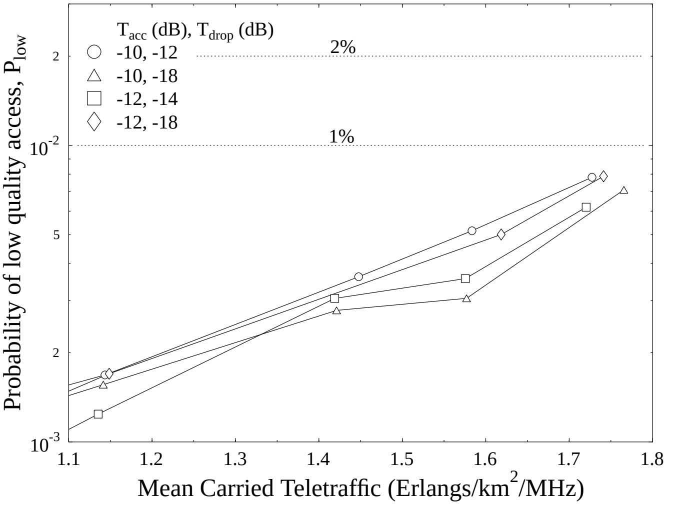


Figure 5.16: Probability of low quality access versus mean carried traffic of a CDMA based cellular network using **relative received pilot power** based soft handover thresholds **without shadowing** for SF=16.

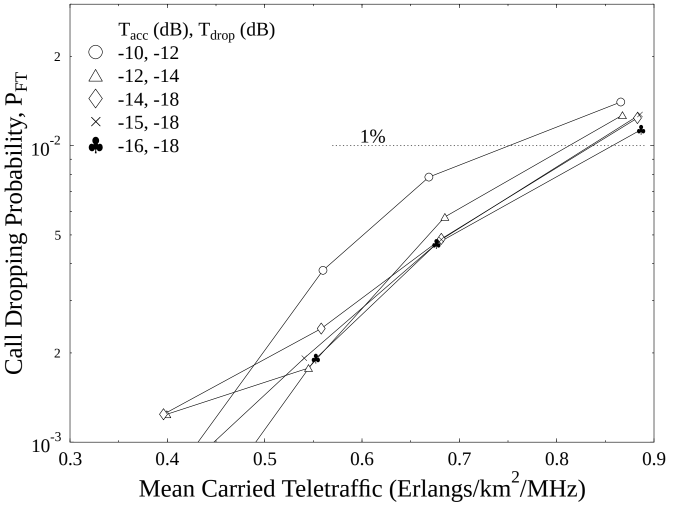


Figure 5.17: Call dropping probability versus mean carried traffic of a CDMA based cellular network using **relative received pilot power** based soft handover thresholds in conjunction **with 0.5 Hz shadowing and a standard deviation of 3 dB** for SF=16.

Since the probability of low quality access was under the 1% threshold, the network capacity for both the lenient and conservative scenarios were the same, namely 1.65 Erlangs / km^2 / MHz or a total of 288 users over the entire simulation area of 2.86 km^2. The mean ABS size was 1.7 base stations, with a mean mobile transmission power of 4.1 dBm and an average base station transmit power of 4.7 dBm.

5.4.2.6 Relative Received Pilot Power Thresholds with 0.5 Hz Shadowing

In this section we present results obtained using relative received pilot power based soft handover thresholds in a shadowing-impaired propagation environment. The maximum shadow fading frequency was 0.5 Hz and the standard deviation of the log-normal shadowing was 3 dB.

Figure 5.17 depicts the call dropping probability for several relative thresholds and shows that by reducing both the thresholds, the call dropping performance is improved. This enables the mobile to add base stations to its ABS earlier on during the soft handover process, and to relinquish them at a much later stage than in the case of using higher handover thresholds. Therefore, using lower relative soft handover thresholds results in a longer period of time spent in soft handover, as can be seen in Figure 5.18, which shows the mean number of base stations in the ABS.

The probability of low quality access is shown in Figure 5.19, illustrating that, in general, as the relative soft handover thresholds were reduced, the probability of low quality access increased. This demonstrated that spending more time in soft handover generated more co-channel interference and thus degraded the network's performance. However, the difference

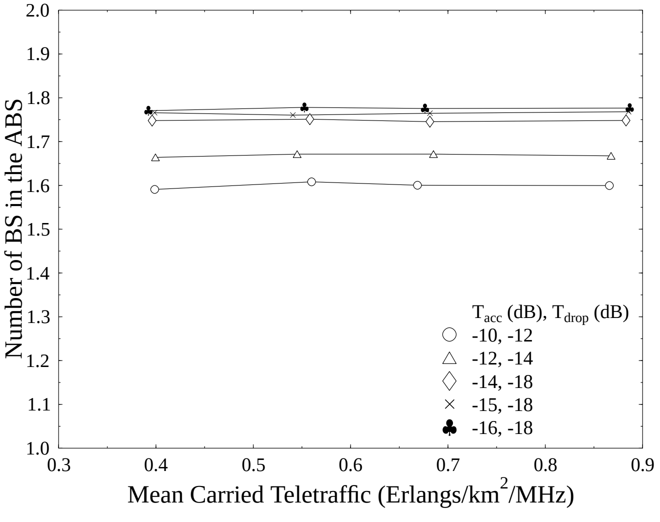


Figure 5.18: Mean number of base stations in the active base station set versus mean carried traffic of a CDMA based cellular network using **relative received pilot power** based soft handover thresholds in conjunction **with 0.5 Hz shadowing and a standard deviation of 3 dB** for SF=16.

between the two thresholds must also be considered. For example, the probability of low quality access is higher in conjunction with $T_{acc} = -16$ dB and T_{drop}=-18 dB, than using T_{acc}=-16 dB and T_{drop}=-20 dB, since the latter scenario has a higher mean number of base stations in its ABS. Therefore, there is a point at which the soft handover gain experienced by the desired user outweighs the detrimental effects of the extra interference generated by base stations' transmissions to users engaged in the soft handover process.

Figure 5.20 shows the mean transmission powers of both the mobiles and the base stations. The mobiles are required to transmit at a lower power than the base stations, because the base stations are not subjected to downlink pilot power interference and to soft handover interference. Furthermore, the mobiles are not affected by the level of the soft handover thresholds, because only selective diversity is performed in the uplink, and hence the mobile transmits as if not in soft handover. As the soft handover thresholds were reduced, the time spent in soft handover increased and thus the mean base transmission power had to be increased in order to overcome the additional downlink interference.

The maximum network capacity of 0.835 Erlangs/km^2/MHz, or 144 users over the entire simulation area, was achieved using the soft handover thresholds of T_{acc}=-14 dB and T_{drop}=-18 dB for the conservative scenario. The mean ABS size was 1.77 base stations, while the mean mobile transmit power was -1.5 dBm and 0.6 dBm for the base stations. In the lenient scenario a maximum teletraffic load of 0.865 Erlangs / km^2 / MHz, corresponding to a total network capacity of 146 users was maintained using soft handover thresholds of T_{acc}=-16 dB and T_{drop}=-18 dB. The mean number of base stations in the ABS was 1.78, with an average transmit power of -1.5 dBm for the mobile handset, and 1.3 dBm for the base station.

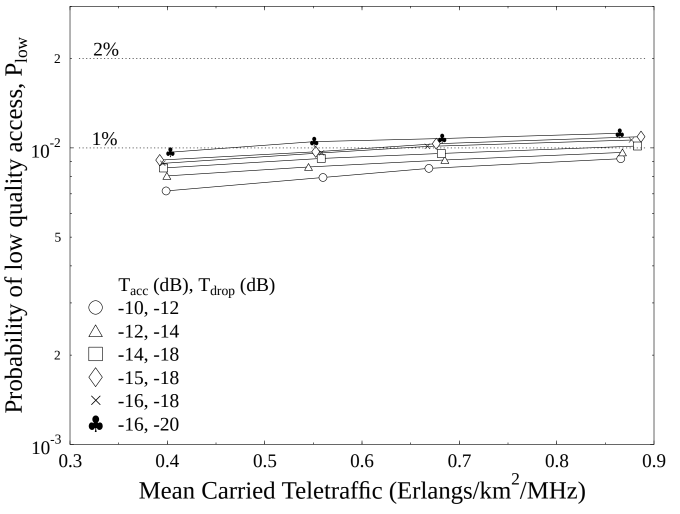


Figure 5.19: Probability of low quality access versus mean carried traffic of a CDMA based cellular network using **relative received pilot power** based soft handover thresholds in conjunction **with 0.5 Hz shadowing and a standard deviation of 3 dB** for SF=16.

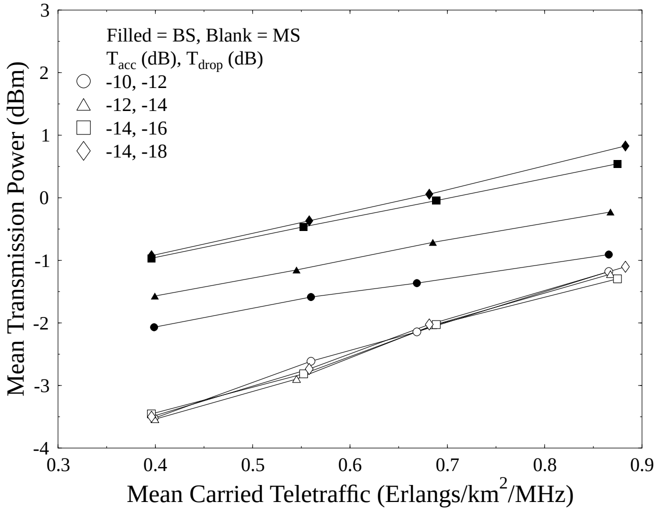


Figure 5.20: Mean transmission power versus mean carried traffic of a CDMA based cellular network using **relative received pilot power** based soft handover thresholds in conjunction **with 0.5 Hz shadowing and a standard deviation of 3 dB** for SF=16.

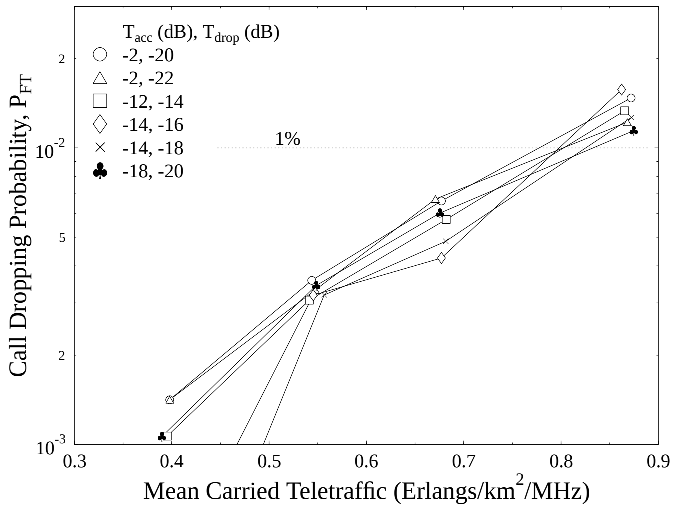


Figure 5.21: Call dropping probability versus mean carried traffic of a CDMA based cellular network using **relative received pilot power** based soft handover thresholds in conjunction **with 1 Hz shadowing and a standard deviation of 3 dB** for SF=16.

5.4.2.7 Relative Received Pilot Power Thresholds with 1.0 Hz Shadowing

In this section we present further performance results obtained using relative received pilot power based soft handover thresholds in a shadowing propagation environment. The maximum shadow fading frequency was 1.0 Hz and the standard deviation of the log-normal shadowing was 3 dB.

On comparing the call dropping probability curves seen in Figure 5.21 with the call dropping probability obtained for a maximum shadow fading frequency of 0.5 Hz in Figure 5.17 it was found that the performance of the 1.0 Hz frequency shadowing scenario was slightly worse. However, the greatest performance difference was observed in the probability of low quality access, as can be seen in Figure 5.22.

Using the soft handover thresholds which gave a good performance for a maximum shadow fading frequency of 0.5 Hz resulted in significantly poorer low quality access performance for a maximum shadowing frequency of 1.0 Hz. In order to obtain a probability of low quality access of below 1% it was necessary to use markedly different soft handover thresholds, which reduced the time spent in soft handover and hence also the size of the ABS, as illustrated in Figure 5.23.

For the conservative scenario, where the maximum probability of low quality access, P_{low}, was set to 1%, the maximum network capacity was found to be 0.69 Erlangs/km^2/MHz, equivalent to a total network capacity of 127 users, obtained using T_{drop}=-2 dB and T_{acc}=-16 dB. In contrast, in the lenient scenario, where the P_{low} limit was 2%, the maximum number of users supported was found to be 144, or 0.825 Erlangs/km^2/MHz, in conjunction with T_{acc}=-14 dB and T_{drop}=-18 dB.

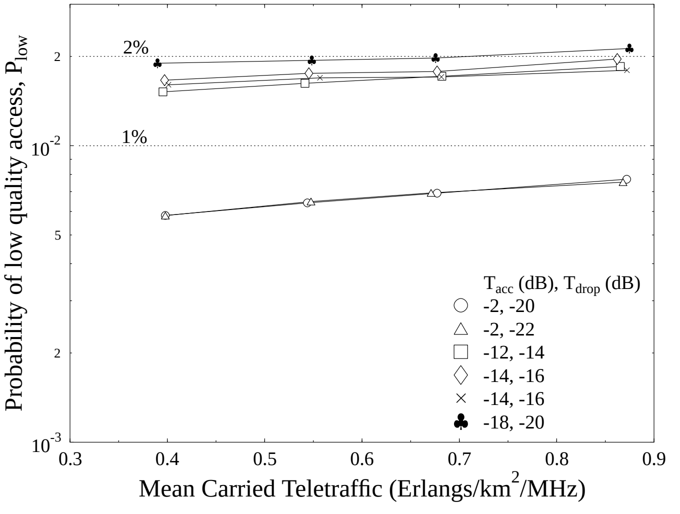


Figure 5.22: Probability of low quality access versus mean carried traffic of a CDMA based cellular network using **relative received pilot power** based soft handover thresholds in conjunction **with 1 Hz shadowing and a standard deviation of 3 dB** for SF=16.

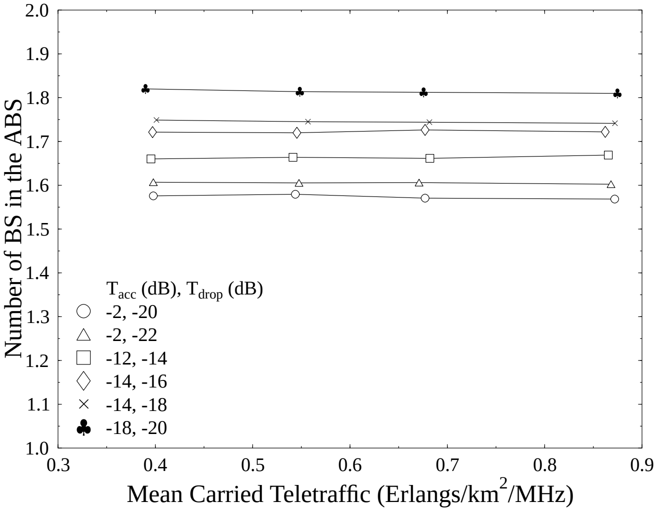


Figure 5.23: Mean number of base stations in the active base station set versus mean carried traffic of a CDMA based cellular network using **relative received pilot power** based soft handover thresholds in conjunction **with 1 Hz shadowing and a standard deviation of 3 dB** for SF=16.

5.4.2.8 Summary

In summary, using relative received pilot power as a soft handover metric has resulted in a significantly improved performance in comparison to that of the fixed received pilot power based results in a shadow fading environment. In the non-shadowed environment the network capacity was approximately the same as when using the fixed threshold algorithm, albeit with a slightly improved mean transmission power. Due to the time varying nature of the received signals subjected to shadow fading, using relative thresholds has been found to be more amenable to employment in a realistic propagation environment, than using fixed thresholds. In conclusion, without shadow fading the network supported a total of 288 users, whilst with a maximum shadow fading frequency of 0.5 Hz, approximately 145 users were supported by the entire network, for both the conservative and lenient scenarios. However, different soft handover thresholds were required for each situation, for achieving these capacities. At a maximum shadowing frequency of 1.0 Hz, a total of 127 users were supported in the conservative scenario, and 144 in the lenient scenario. However, again, different soft handover thresholds were required in each scenario in order to maximise the network capacity.

5.4.3 E_c/I_o Power Based Soft Handover Results

An alternative soft handover metric used to determine 'cell ownership' is the pilot to downlink interference ratio of a cell, which was proposed for employment in the 3rd generation systems [59]. The pilot to downlink interference ratio, or E_c/I_o, may be calculated thus as [401]:

$$\frac{E_c}{I_o} = \frac{P_{pilot}}{P_{pilot} + N_0 + \sum_{k=1}^{N_{cells}} P_k T_k}, \tag{5.10}$$

where P_k is the total transmit power of cell k, T_k is the transmission gain, which includes the antenna gain and pathloss as well as shadowing, N_0 is the power spectral density of the thermal noise and N_{cells} is the number of cells in the network. The advantage of using such a scheme is that it is not an absolute measurement that is used, but the ratio of the pilot power to the interference power. Thus, if fixed thresholds were used a form of admission control may be employed for new calls if the interference level became too high. A further advantage is that it takes into account the time-varying nature of the interference level in a shadowed environment.

5.4.3.1 Fixed E_c/I_o Thresholds without Shadowing

The new call blocking probability obtained when using fixed E_c/I_o soft handover thresholds without any form of shadow fading is shown in Figure 5.24, which suggests that in general, lowering the soft handover thresholds reduced the probability of a new call attempt being blocked. However, it was found that in conjunction with $T_{drop} = -40$ dB, dropping the threshold T_{acc} from -20 dB to -24 dB actually increased the new call blocking probability. This was attributed to the fact that the lower threshold precipitated a higher level of co-channel interference, since there was a higher mean number of base stations in the ABS, as evidenced by Figure 5.25. Therefore, since the mean level of interference present in the network is higher, when using a lower threshold, and the threshold determines the value of

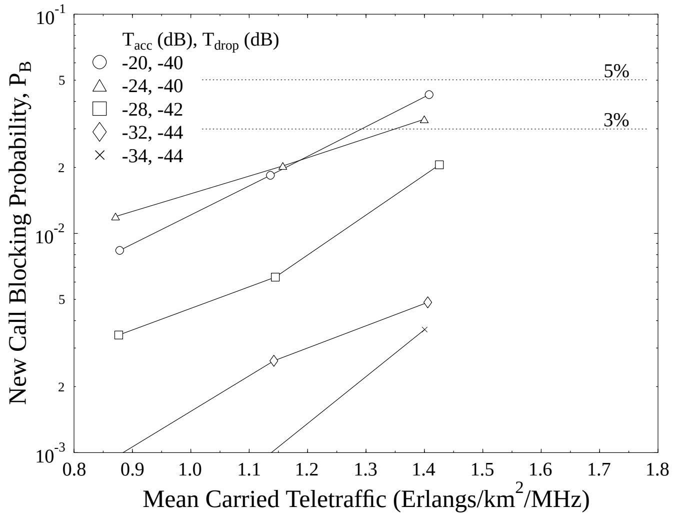


Figure 5.24: New call blocking probability versus mean carried traffic of a CDMA based cellular network using **fixed** E_c/I_o based soft handover thresholds **without shadowing** for SF=16.

the pilot to downlink interference ratio at which base stations may be added to the ABS, a more frequent blocking of calls occurs. Alternatively, a lower threshold resulted in a higher level of downlink interference due to the additional interference inflicted by supporting the mobiles in soft handover, which prevented base stations from being included in the ABS due to insufficient pilot to interference 'head-room'. This then ultimately led to blocked calls due to the lack of base stations in the ABS.

Again, the mean number of base stations in the ABS is given in Figure 5.25, which illustrates that as expected, reducing the soft handover thresholds increased the proportion of time spent in soft handover, and thus reduced the mean number of base stations in the ABS. The average size of the ABS was found to decrease, as the network's traffic load increased. This was a consequence of the increased interference levels associated with the higher traffic loads, which therefore effectively reduced the pilot to interference ratio at a given point, and hence base stations were less likely to be in soft handover and in the ABS.

Figure 5.26 depicts the mean transmission powers for both the uplink and the downlink, for a range of different soft handover thresholds. These results show similar trends to the results presented in previous sections, with the required average downlink transmission power increasing, since a greater proportion of call time is spent in soft handover. Again, the mean uplink transmission power varied only slightly, since the selection diversity technique of the base stations only marginally affected the received interference power at the base stations.

Figure 5.27 shows the call dropping performance, indicating that lowering the soft handover thresholds generally improved the call dropping performance. However, reducing the soft handover thresholds too much resulted in a degradation of the call dropping probability due to the increased levels of co-channel interference inherent when a higher proportion of the call time is spent in soft handover. This is explicitly illustrated by Figure 5.28, which

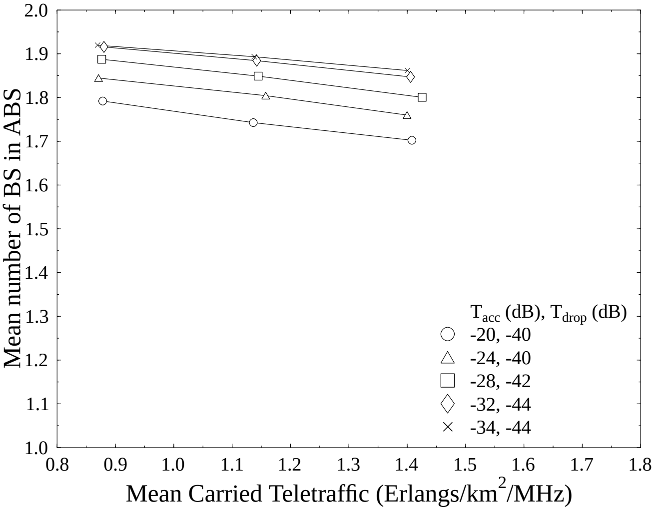


Figure 5.25: Mean number of base stations in the active base station set versus mean carried traffic of a CDMA based cellular network using **fixed** E_c/I_o based soft handover thresholds **without shadowing** for SF=16.

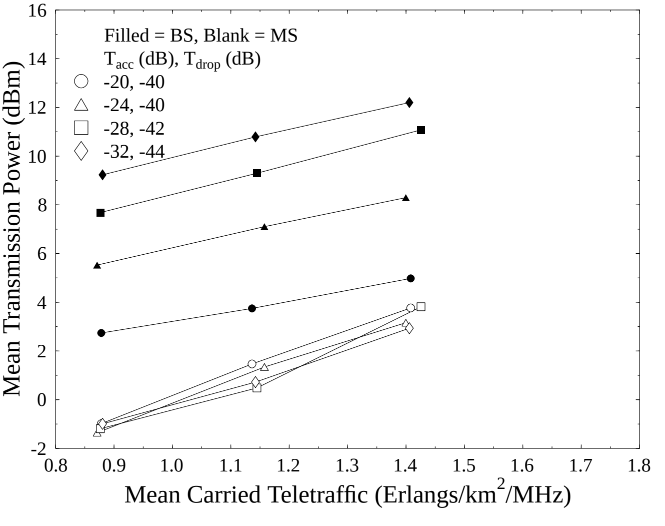


Figure 5.26: Mean transmission power versus mean carried traffic of a CDMA based cellular network using **fixed received** E_c/I_o based soft handover thresholds **without shadowing** for SF=16.

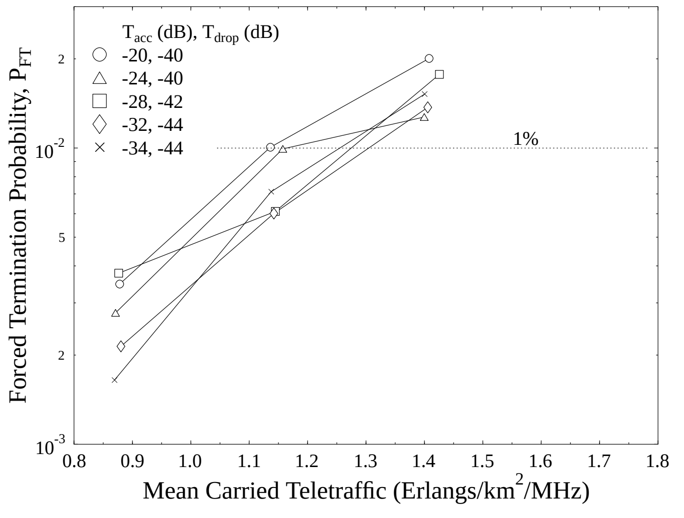


Figure 5.27: Call dropping probability versus mean carried traffic of a CDMA based cellular network using **fixed received** E_c/I_o based soft handover thresholds **without shadowing** for SF=16.

indicates that reducing the soft handover thresholds caused a significant degradation in the probability of low quality access. This was a consequence of the additional co-channel interference associated with the soft handover process. The figure also shows that there is a point where the diversity gain of the mobiles obtained with the advent of the soft handover procedure outweighs the extra interference that it generates.

On the whole, the capacity of the network when using fixed E_c/I_o soft handover thresholds was lower than when using fixed received pilot power based soft handover thresholds. This can be attributed to the fact that the E_c/I_o thresholds are related to the interference level of the network, which changes with the network load and propagation conditions. Hence using a fixed threshold is sub-optimal. In the conservative scenario, the network capacity was 1.275 Erlangs/km^2/MHz, corresponding to a total network capacity of 223 users. In the lenient scenario, this increased to 1.305 Erlangs/km^2/MHz, or 231 users. In contrast, when using fixed received pilot power thresholds the entire network supported 290 users.

5.4.3.2 Fixed E_c/I_o Thresholds with 0.5 Hz Shadowing

In this section we consider fixed pilot to downlink interference ratio based soft handover thresholds in a propagation environment exhibiting shadow fading in conjunction with a maximum fading frequency of 0.5 Hz and a standard deviation of 3 dB.

Examining Figure 5.29, which shows the call dropping probability, we see, again, that reducing the soft handover thresholds typically resulted in a lower probability of a dropped call. However, since the handover thresholds are dependent upon the interference level, there was some interaction between the handover thresholds and the call dropping rate. For exam-

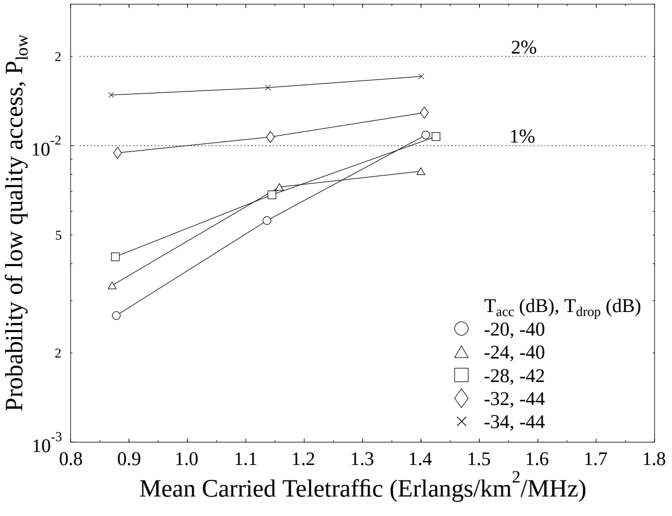


Figure 5.28: Probability of low quality access versus mean carried traffic of a CDMA based cellular network using **fixed received** E_c/I_o based soft handover thresholds **without shadowing** for SF=16.

ple, it can be seen in the figure that when $T_{drop} = -40$ dB, the call dropping probability fell as T_{acc} was reduced from -20 dB to -24 dB. However, on lowering T_{acc} further, to -26 dB, the call dropping rate at low traffic loads became markedly higher. A similar phenomenon was observed in Figure 5.30, which shows the probability of low quality outage.

It is explicitly seen from Figures 5.29 and 5.30 that the performance of the fixed E_c/I_o soft handover threshold based scheme clearly exceeded that of the fixed received pilot power threshold based system in a shadow fading environment. The network supported a teletraffic load of 0.7 Erlangs/km^2/MHz or a total of 129 users in the conservative scenario, which rose to 0.78 Erlangs/km^2/MHz, or 140 users, in the lenient scenario. These network capacities were achieved with the aid of a mean number of active base stations in the ABS, which were 1.88 and 1.91, respectively. In order to achieve the total network capacity of 129 users in the conservative scenario, a mean mobile transmit power of -2.4 dBm was required, while the mean base station transmission power was 7 dBm. For the lenient scenario, these figures were -2.4 dBm and 8.7 dBm, respectively.

5.4.3.3 Fixed E_c/I_o Thresholds with 1.0 Hz Shadowing

Increasing the maximum shadow fading frequency from 0.5 Hz to 1.0 Hz resulted in an increased call dropping probability and a greater probability of low quality access, for a given level of carried teletraffic. This is clearly seen by comparing Figures 5.31 and 5.32 with Figures 5.29 and 5.30. Explicitly, Figure 5.31 and 5.32 show that reducing the soft handover threshold, T_{acc} from -20 dB to -24 dB led to both an increased call dropping probability and an increased probability of low quality access. This can be attributed to the extra co-channel

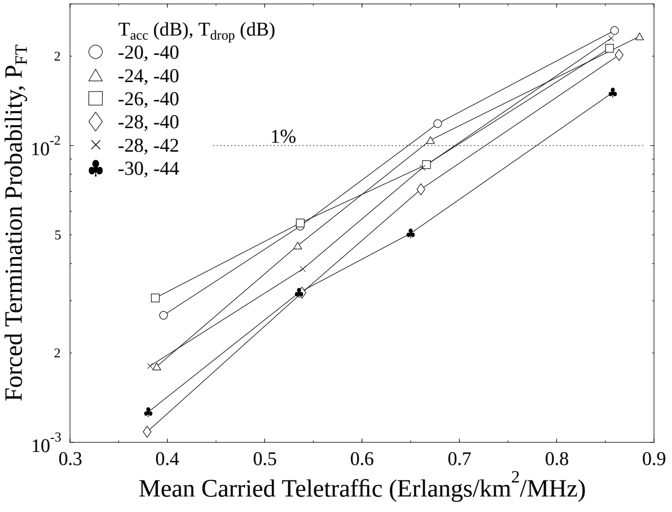


Figure 5.29: Call dropping probability versus mean carried traffic of a CDMA based cellular network using **fixed received** E_c/I_o based soft handover thresholds in conjunction **with 0.5 Hz shadowing and a standard deviation of 3 dB** for SF=16.

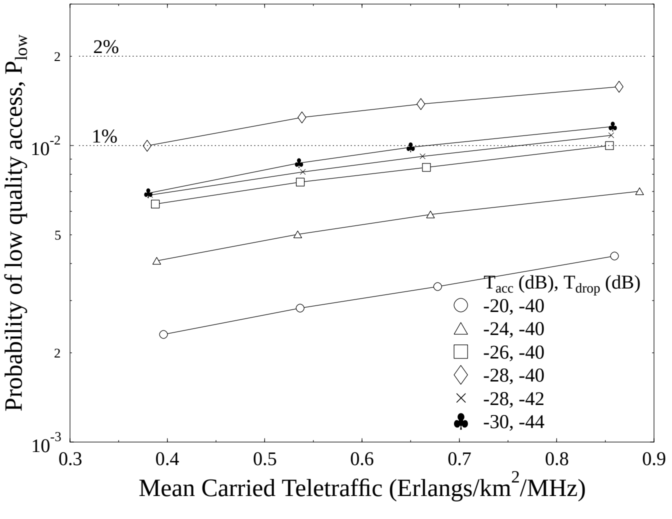


Figure 5.30: Probability of low quality access versus mean carried traffic of a CDMA based cellular network using **fixed received** E_c/I_o based soft handover thresholds in conjunction **with 0.5 Hz shadowing and a standard deviation of 3 dB** for SF=16.

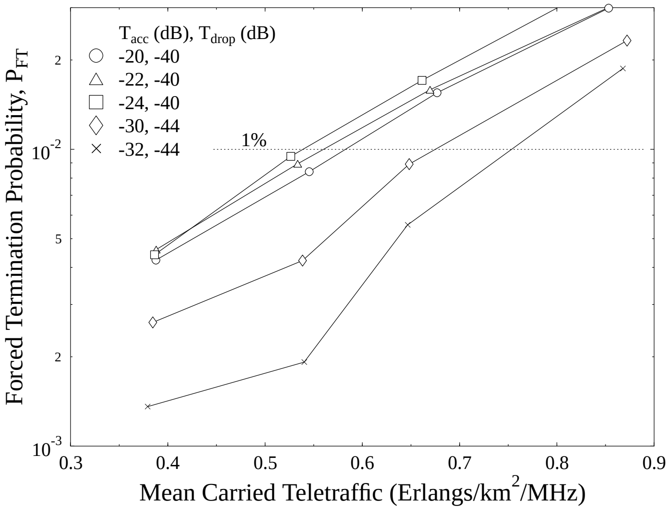


Figure 5.31: Call dropping probability versus mean carried traffic of a CDMA based cellular network using **fixed received** E_c/I_o based soft handover thresholds in conjunction **with 1.0 Hz shadowing and a standard deviation of 3 dB** for SF=16.

interference generated by the greater proportion of call time being spent in soft handover. This is also confirmed by the increased probability of low quality access observed in Figure 5.32 for lower soft handover thresholds T_{acc} and T_{drop}.

The network capacity of the conservative scenario was 0.583 Erlangs/km^2/MHz, giving an entire network capacity of 107 users. In the lenient scenario the network supported a total of 128 users or a traffic load of 0.675 Erlangs/km^2/MHz was carried. The 107 users were serviced in conjunction with a mean ABS size of 1.86, a mean mobile transmit power of -3 dBm and a mean base station transmit power of 4.5 dBm. The 128 users supported in the lenient scenario necessitated an average mobile transmit power of -3 dBm and an average base station transmit power of 9.5 dBm. The mean number of base stations in the ABS was 1.91.

5.4.3.4 Summary

In summary, a maximum network capacity of 290 users was obtained when employing the fixed E_c/I_o soft handover thresholds. This capacity was equal to that when using fixed received pilot power thresholds in the lenient scenario without shadow fading. However, in the conservative scenario the network capacity was reduced from 290 to 231 users. Nevertheless, when a realistic shadowed propagation environment was considered, using the pilot power to interference ratio based soft handover metric improved the network capacity significantly. This was particularly evident in conjunction with the maximum shadow fading frequency of 1.0 Hz, when using the fixed received pilot power thresholds no users could be supported whilst maintaining the desired call quality. In contrast, using the fixed E_c/I_o soft handover

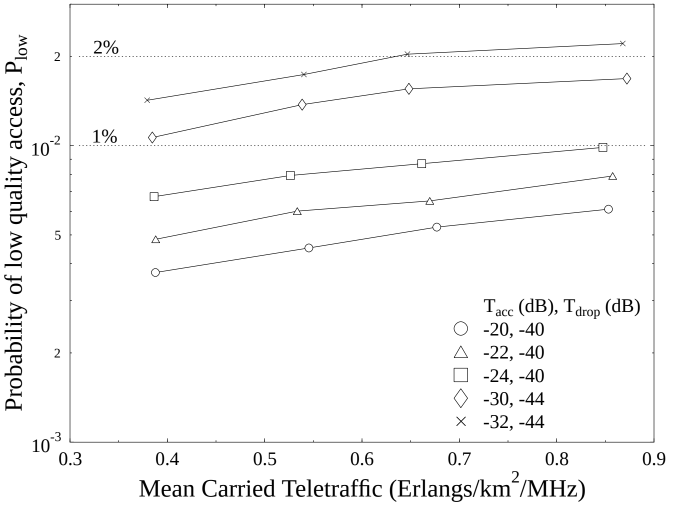


Figure 5.32: Probability of low quality access versus mean carried traffic of a CDMA based cellular network using **fixed received** E_c/I_o based soft handover thresholds in conjunction **with 1.0 Hz shadowing and a standard deviation of 3 dB** for SF=16.

thresholds led to a total network capacity of between 107 and 128 users, for the conservative and lenient scenarios, respectively. This capacity increase was the benefit of the more efficient soft handover mechanism, which was capable of taking into account the interference level experienced, leading to a more intelligent selection of base stations supporting the call. At a maximum shadow fading frequency of 0.5 Hz the network had a maximum capacity of 129 and 140 users, for the conservative and lenient scenario, respectively, when using the fixed E_c/I_o soft handover thresholds.

5.4.3.5 Relative E_c/I_o Thresholds without Shadowing

In this section we combined the benefits of using the received E_c/I_o ratio and relative soft handover thresholds, thus ensuring that variations in both the received pilot signal strength and interference levels were monitored in the soft handover process.

The call dropping performance is shown in Figure 5.33, illustrating that reducing the soft handover thresholds improved the probability of dropped calls, in particular at higher traffic loads. This phenomenon is also evident in Figure 5.34, which shows the probability of a low quality outage. However, in some cases it was evident that excessive reduction of the thresholds led to increasing the co-channel interference, and hence to a greater probability of outage associated with low quality. Again, this was the consequence of supporting an excessive number of users in soft handover, which provided a beneficial diversity gain for the mobiles but also increased the amount of downlink interference inflicted by the base stations supporting the soft handovers.

The entire network supported a total of 256 users employing soft handover thresholds of

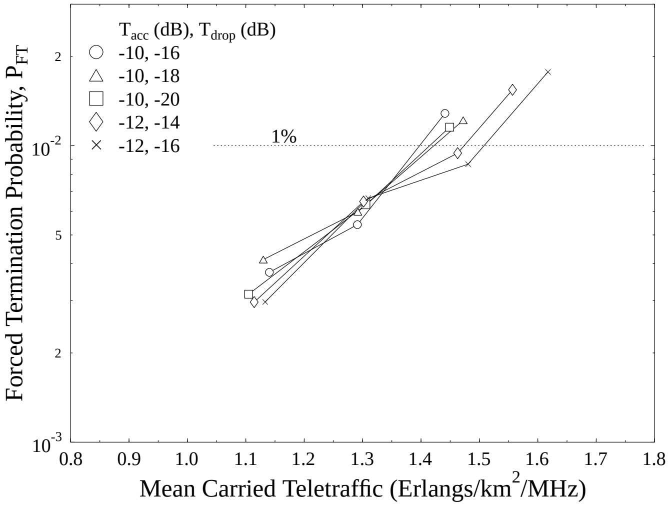


Figure 5.33: Call dropping probability versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds **without shadowing** for SF=16.

T_{acc}=-12 dB and T_{drop}=-16 dB. The mean number of base stations in the active set was 1.68, and the mean mobile transmit power was 3.1 dBm. The average base station transmit power was 2.7 dBm.

5.4.3.6 Relative E_c/I_o Thresholds with 0.5 Hz Shadowing

Examining the call dropping probability graphs in Figure 5.35 shows that the probability of a dropped call was significantly lower than that of the other soft handover algorithms considered for the same propagation environment. This was because the handover algorithm was capable of taking the current interference levels into account when deciding whether to initiate a handover, additionally, the employment of the relative thresholds minimised the chances of making an inappropriate soft handover decision concerning the most suitable base station to use. The superiority of this soft handover algorithm was further emphasised by the associated low probability of a low quality access, as illustrated in Figure 5.36, which was an order of magnitude lower than that achieved using the alternative soft handover algorithms.

When T_{acc} was set to -10 dB the ultimate capacity of the network was only marginally affected by changing T_{drop}, although some variation could be observed in the call dropping probability. Furthermore, the probability of low quality access increased for the lowest values of T_{drop}. This degradation of the probability of low quality access was due to the higher proportion of time spent in soft handover, as indicated by the correspondingly increased ABS size in Figure 5.37, which was a consequence of the associated increased co-channel interference levels.

The mean transmit power curves of Figure 5.38 exhibited a different characteristic in

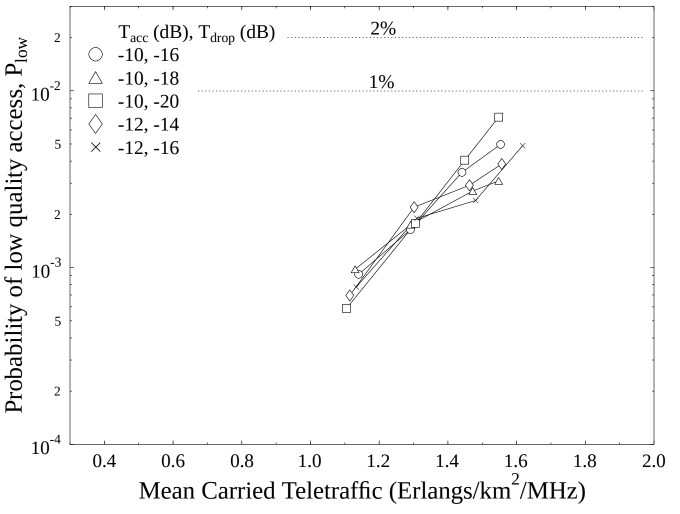


Figure 5.34: Probability of low quality access versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds **without shadowing** for SF=16.

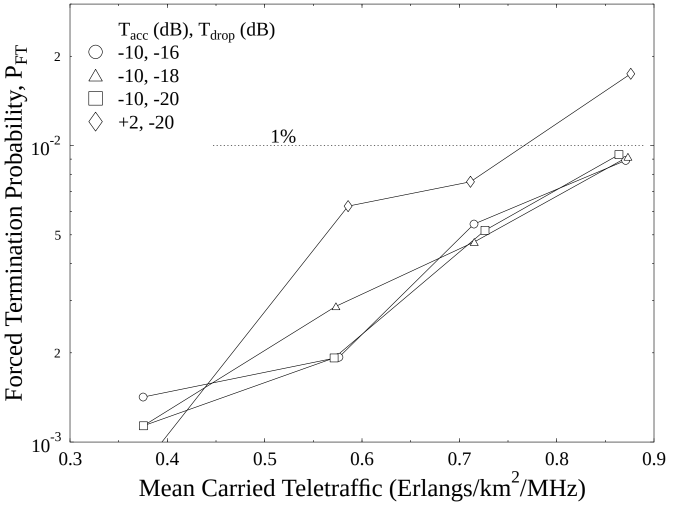


Figure 5.35: Call dropping probability versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds in conjunction **with 0.5 Hz shadowing and a standard deviation of 3 dB** for SF=16.

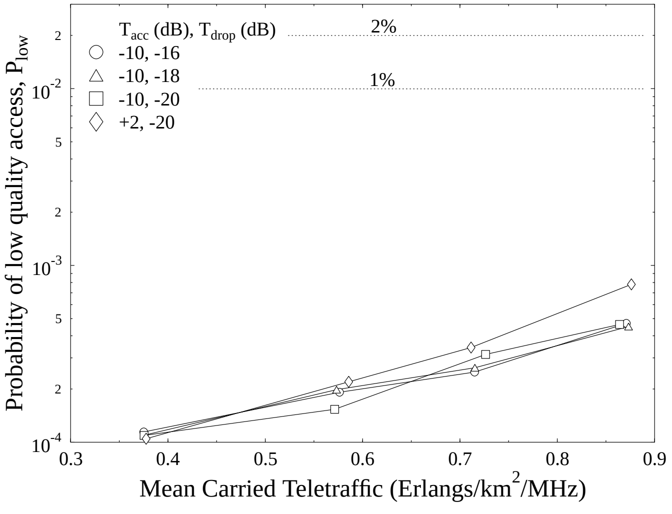


Figure 5.36: Probability of low quality access versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds in conjunction **with 0.5 Hz shadowing and a standard deviation of 3 dB** for SF=16.

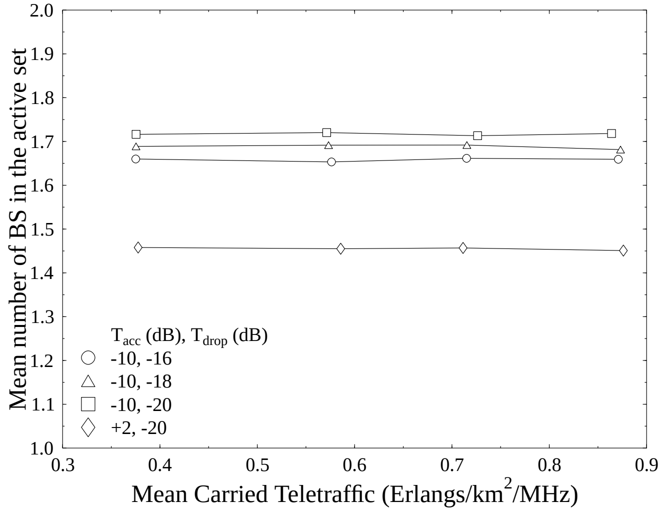


Figure 5.37: Mean number of base stations in the active base station set versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds in conjunction **with 0.5 Hz shadowing and a standard deviation of 3 dB** for SF=16.

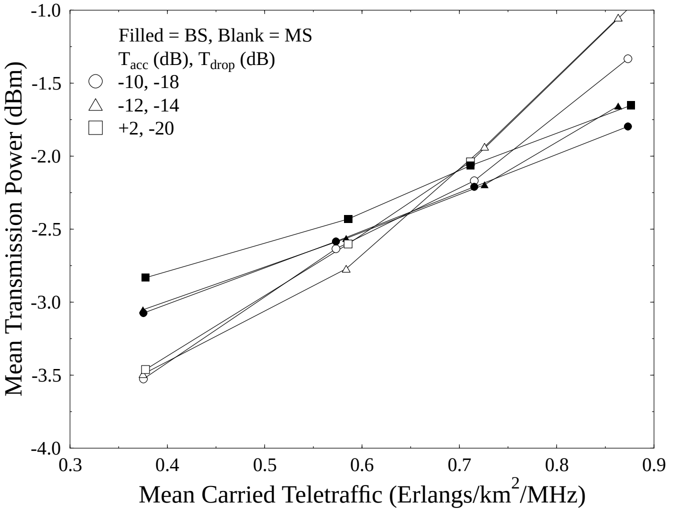


Figure 5.38: Mean transmission power versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds in conjunction **with 0.5 Hz shadowing and a standard deviation of 3 dB** for SF=16.

comparison to that observed for the other soft handover algorithms. Specifically, at low traffic loads the mean mobile transmit power was less than that of the base stations, whereas at the higher traffic loads, the mobile transmit power was greater than that of the base stations. Although, comparing this graph with Figure 5.20 revealed that the spread and the rate of change of the mobile transmit power versus the traffic load was similar in both scenarios, the mean base station transmission power was lower in Figure 5.38. This reduced base station transmission power, again demonstrated the superiority of this soft handover algorithm, which manifested itself in its more efficient use of resources.

Since the probability of low quality access fell well below the 1% threshold, both the conservative and lenient scenarios exhibited the same total network capacity, which was slightly above 150 users for the entire network. This was achieved on average with the aid of 1.65 base stations, at a mean mobile transmit power of -1.2 dBm and at a mean base station transmit power of -1.7 dBm.

5.4.3.7 Relative E_c/I_o Thresholds with 1.0 Hz Shadowing

The call dropping probability shown in Figure 5.39 is slightly worse than that obtained in Figure 5.35 for a maximum shadow fading frequency of 0.5 Hz, with a greater performance difference achieved by altering T_{drop}. A similar performance degradation was observed for the probability of low quality access in Figure 5.40, with an associated relatively low impact due to varying the soft handover thresholds. Although not explicitly shown, we found that the mean transmission powers were similar to those required for a maximum shadow fading frequency of 0.5 Hz.

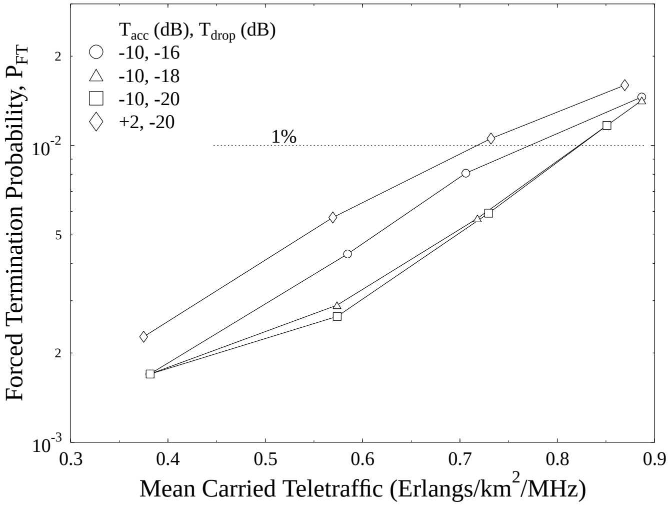


Figure 5.39: Call dropping probability versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds in conjunction **with 1.0 Hz shadowing and a standard deviation of 3 dB** for SF=16.

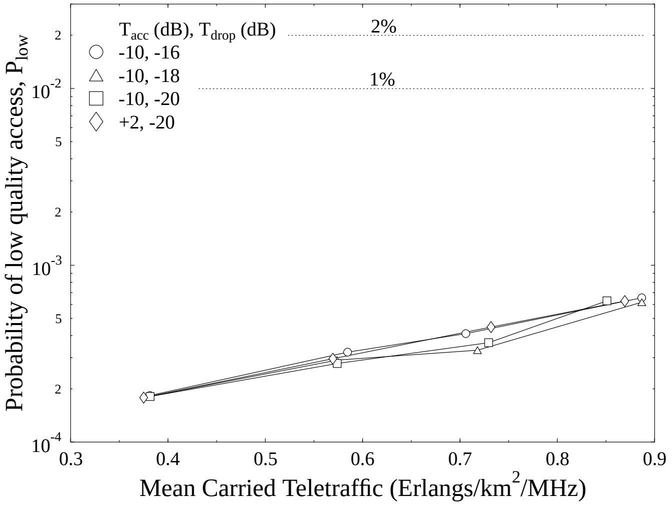


Figure 5.40: Probability of low quality access versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds in conjunction **with 1.0 Hz shadowing and a standard deviation of 3 dB** for SF=16.

5.4.3.8 Summary

In summary, the employment of relative E_c/I_o soft handover thresholds resulted in a superior network performance and capacity under all the propagation conditions investigated. This was achieved whilst invoking the lowest average number of base stations and the minimum mean base station transmit power. A further advantage of this handover scheme is that the same soft handover thresholds excelled in all of the propagation environments studied, unlike the previously considered algorithms, which obtained their best results at different thresholds for different conditions. The entire network capacity was 256 users without shadow fading, with a mean ABS size of 1.68. At a maximum shadowing frequency of 0.5 Hz the network supported just over a total of 150 users, whilst 144 users were served by the entire network, when a maximum shadow fading frequency of 1.0 Hz was encountered.

5.4.4 Overview of Results

		Conservative scenario P_{FT}=1%, P_{low}=1%				Lenient scenario P_{FT}=1%, P_{low}=2%			
				Power (dBm)				Power (dBm)	
Soft handover algorithm	Shadowing	Users	ABS	MS	BS	Users	ABS	MS	BS
Fixed pilot pwr.	No	290	1.7	5.1	5.1	290	1.7	5.1	5.1
Fixed pilot pwr.	0.5 Hz, 3 dB	-	-	-	-	127	1.83	-2.0	6.5
Fixed pilot pwr.	1.0 Hz, 3 dB	-	-	-	-	-	-	-	-
Delta pilot pwr.	No	288	1.7	4.1	4.7	288	1.7	4.1	4.1
Delta pilot pwr.	0.5 Hz, 3 dB	144	1.77	-1.5	0.6	146	1.78	-1.5	1.3
Delta pilot pwr.	1.0 Hz, 3 dB	127	1.5	-2.4	-1.9	144	1.72	-1.5	0.8
Fixed E_c/I_o	No	223	1.83	2.0	10.0	231	1.86	2.0	10.3
Fixed E_c/I_o	0.5 Hz, 3 dB	129	1.88	-2.4	7.0	140	1.91	-2.4	8.7
Fixed E_c/I_o	1.0 Hz, 3 dB	107	1.86	-3.0	4.5	128	1.91	-3.0	9.5
Delta E_c/I_o	No	256	1.68	3.1	2.7	256	1.68	3.1	2.7
Delta E_c/I_o	0.5 Hz, 3 dB	$\approx$150	1.65	-1.2	-1.7	$\approx$150	1.65	-1.2	-1.7
Delta E_c/I_o	1.0 Hz, 3 dB	144	1.65	-1.1	-1.6	144	1.65	-1.1	-1.6

Table 5.3: Maximum number of mobile users that can be supported by the network, for different soft handover metrics/algorithms whilst meeting the preset quality constraints. The mean number of base stations in the Active Base station Set (ABS) is also presented, along with the mean mobile and mean base station transmit powers.

Table 5.3 summarises the results obtained for the various soft handover algorithms over the three different propagation environments considered. The fixed receiver pilot power based algorithm performed the least impressively overall, as expected due to its inherent inability to cope with shadow fading. However, it did offer a high network capacity in a non-shadowed environment. Using the relative received pilot power based soft handover algorithm improved the performance under shadow fading, but different fading rates required different thresholds to meet the conservative and lenient quality criteria. The performance of the fixed E_c/I_o based soft handover algorithm also varied significantly, when using the same thresholds for the two different fading rates considered. However, the maximum network capacity achieved under the different shadow fading conditions was significantly higher, than that of the fixed received pilot power based algorithm. This benefit resulted from the inclusion of the interference levels in the handover process, which thus took into account the fading of both the signal and the co-channel interference. Combining the relative threshold based scheme with using E_c/I_o thresholds allowed us to support the highest number of users under the shadow fading conditions investigated. Whilst its performance was not the highest in the non-shadowed environment, this propagation environment is often unrealistic, and hence the relative received E_c/I_o based soft handover algorithm was chosen as the basis for our future investigations, while using the soft handover thresholds of T_{acc}=-10 dB and T_{drop}=-18 dB. The advantages of this handover algorithm were its reduced fraction of time spent in soft handover, and its ability to perform well under both shadow fading conditions evaluated, whilst utilising the same soft handover thresholds. Since the constraining factor of these network capacity results was the probability of a dropped call, P_{FT}, which was the same for both scenarios, further network capacity results were only shown for the conservative scenario.

5.4.5 Performance of Adaptive Antenna Arrays in a High Data Rate Pedestrian Environment

In our previous investigations we endeavoured to identify the soft handover algorithm, which supports the greatest number of users, at the best call quality, regardless of the propagation conditions. In this section we study the impact of adaptive antenna arrays on the network's performance. The investigations were conducted using the relative E_c/I_o based soft handover algorithm in conjunction with T_{acc}=-10 dB and T_{drop}=-18 dB, using a spreading factor of 16. Given that the chip rate of UTRA is 3.84 Mchips/sec, this spreading factor corresponds to a channel data rate of 3.84$\times 10^6$/16=240 kbps. Applying $1/2$ rate error correction coding would result in an effective data throughput of 120 kbps, whereas utilising a $2/3$ rate error correction code would provide a useful throughput of 160 kps. As in the previous simulations, a cell radius of 150 m was assumed and a pedestrian walking velocity of 3 mph was used. In our previous results investigations employing adaptive antenna arrays at the base station and using a FDMA/TDMA based network, as in Chapter 4, we observed quite significant performance gains as a direct result of the interference rejection capabilities of the adaptive antenna arrays invoked. Since the CDMA based network considered here has a frequency reuse of 1, the levels of co-channel interference are significantly higher, and hence the adaptive antennas may be able to null the interference more effectively. However, the greater number of interference sources may limit the achievable interference rejection.

Network performance results were obtained using two and four element adaptive antenna arrays, both in the absence of shadow fading, and in the presence of 0.5 Hz and 1.0 Hz frequency shadow fading exhibiting a standard deviation of 3 dB. The adaptive beamforming algorithm used was the Sample Matrix Inversion (SMI) algorithm, as described in Chapter 3 and used in the FDMA/TDMA network simulations of Chapter 4. The specific adaptive beamforming implementation used in the CDMA based network was identical to that used in the FDMA/TDMA network simulations. Briefly, one of the eight possible 8-bit BPSK reference signals was used to identify the desired user, and the remaining interfering users were assigned the other seven 8-bit reference signals. The received signal's autocorrelation matrix was then calculated, and from the knowledge of the desired user's reference signal, the receiver's optimal antenna array weights were determined with the aid of the SMI algorithm. The reader is referred to Section 4.6.1 for further details. Since this implementation of the algorithm only calculated the receiver's antenna array weights, i.e. the antenna arrays

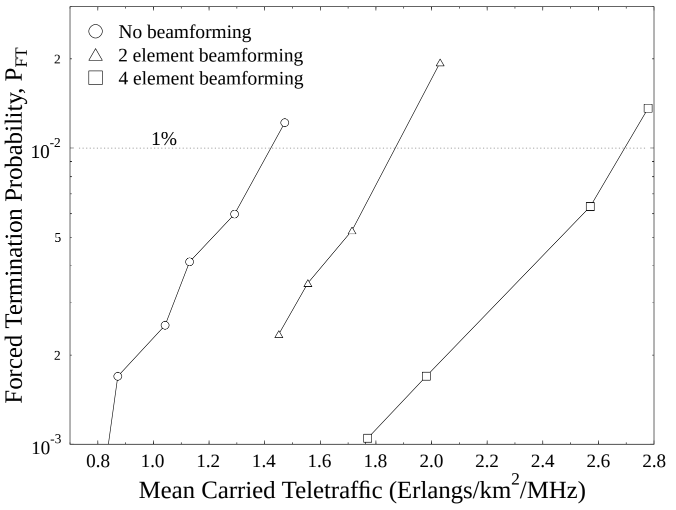


Figure 5.41: Call dropping probability versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds **with and without beamforming and without shadowing** for SF=16.

weights used by the base station in the uplink, these weights may not be suitable for use in the downlink, when independent up/downlink shadow fading is experienced. Hence, further investigations were conducted, where the uplink and downlink channels were identical, in order to determine the potential performance gain that may be achieved by separately calculating the antenna array weights to be used in the downlink. The antenna array weights were re-calculated for every power control step, i.e. 15 times per UTRA data frame, due to the potential significant changes in terms of the desired signal and interference powers that may occur during one UTRA frame as a result of the possible 15 dB change in power transmitted by each user.

Figure 5.41 shows the significant reduction in the probability of a dropped call, i.e. the probability of forced termination P_{FT}, achieved by employing adaptive antenna arrays in a non-shadowed propagation environment. The figure has demonstrated that, even with only two antenna elements, the adaptive antenna arrays have considerably reduced the levels of co-channel interference, leading to a reduced call dropping probability. This has been achieved in spite of the numerous sources of co-channel interference resulting from the frequency reuse factor of one, which was remarkable in the light of the limited number of degrees of freedom of the two element array. Without employing antenna arrays at the base stations the network capacity was limited to 256 users, or to a teletraffic load of approximately 1.4 Erlangs/km^2/MHz. However, with the advent of two element adaptive antenna arrays at the base stations the number of users supported by the network rose by 27% to 325 users, or almost 1.9 Erlangs/km^2/MHz. Replacing the two element adaptive antenna arrays with four element arrays led to a further rise of 48%, or 88% with respect to the capacity of the network using no antenna arrays. This is associated with a network capacity of 480 users,

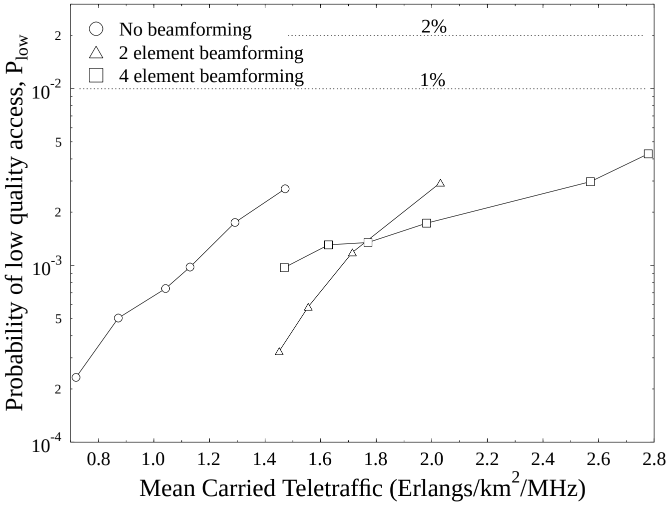


Figure 5.42: Probability of low quality access versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds **with and without beamforming and without shadowing** for SF=16.

or 2.75 Erlangs/km^2/MHz. A summary of the network capacities achieved under different conditions is given in Table 5.4.

The probability of low quality outage, presented in Figure 5.42 also exhibited a substantial improvement with the advent of two element adaptive antenna arrays. However, the performance gains obtained when invoking four element adaptive antenna arrays were more involved. It can be seen from the figure that higher traffic loads were carried with at a sufficiently low probability of a low quality occurring, and at higher traffic loads the probability of a low quality access was lower than that achieved using a two element array. However, at lower traffic loads the performance was worse than that obtained when using two element arrays, and the gradient of the performance curve was significantly lower. Further in-depth analysis of the results suggested that the vast majority of the low quality outages were occurring when new calls started. When a user decided to commence communications with the base station, the current interference level was measured, and the target transmission power was determined in order to reach the target SINR necessary for reliable communications. However, in order to avoid disrupting existing calls the transmission power was ramped up slowly, until the target SINR was reached. A network using no adaptive antenna arrays, i.e. employing omnidirectional antennas, can be viewed as offering equal gain to all users of the network, which we assumed to be 1.0, or 0 dB. Thus, when a new call is initiated, the level of interference rises gradually, and the power control algorithm ensures that the existing users compensate for the increased level of co-channel interference by increasing their transmission power. In a network using adaptive antenna arrays, the adaptive antenna arrays are used to null the sources of interference, and in doing so the array may reduce the antenna gain in the direction of the desired user, in order to maximise the SINR. Hence a user starting a new

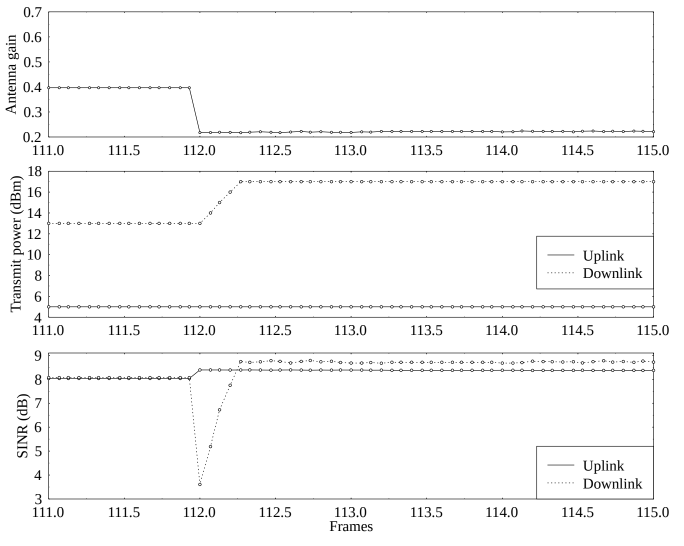


Figure 5.43: The changes in the antenna array gain, versus time, in the direction of the desired user, the up and downlink transmission powers, and the up- and downlink received SINRs, when a new call starts using four element adaptive antenna arrays without shadowing in conjunction with the **original power ramping** algorithm and SF=16.

call, even if it has low transmission power, can alter the antenna array's response, and thus the antenna gain experienced by the existing users. This phenomenon is more marked when using four element arrays since their directivity, and thus sensitivity to interfering signals, is greater.

Figure 5.43 illustrates this phenomenon, where another user starts a new call at frame 112 suddenly reducing the antenna gain in the direction of the desired user from 0.4 to just above 0.2, a drop of 3 dB. As can be seen from the figure, the downlink SINR falls sharply below the low quality outage threshold of 7.0 dB, resulting in several consecutive outages, until the downlink transmission power is increased sufficiently. The impact of reducing the initial transmission power, in order to ensure that the power ramping takes place more gently, is depicted in Figure 5.44. In this figure it can be seen that the antenna gain falls much more gently, over a prolonged period of time, thus reducing the number of low quality outages, as the downlink transmission power is increased in an effort to compensate for the lower antenna gain. It is of interest to note how the received SINR varies as the antenna gain and the power control algorithm interact, in order to maintain the target SINR.

Even though the employment of adaptive antenna arrays can result in the attenuation of the desired signal, this is performed in order to maximise the received SINR, and thus the levels of interference are attenuated more strongly, ultimately leading to the reduction of the mean transmission power, as emphasised by Figure 5.45. This figure clearly shows the lower levels of transmission power, required in order to maintain an acceptable performance, whilst using adaptive antenna arrays at the base stations. A reduction of 3 dB in the mean mobile transmission power was achieved by invoking two element antenna arrays, and a further re-

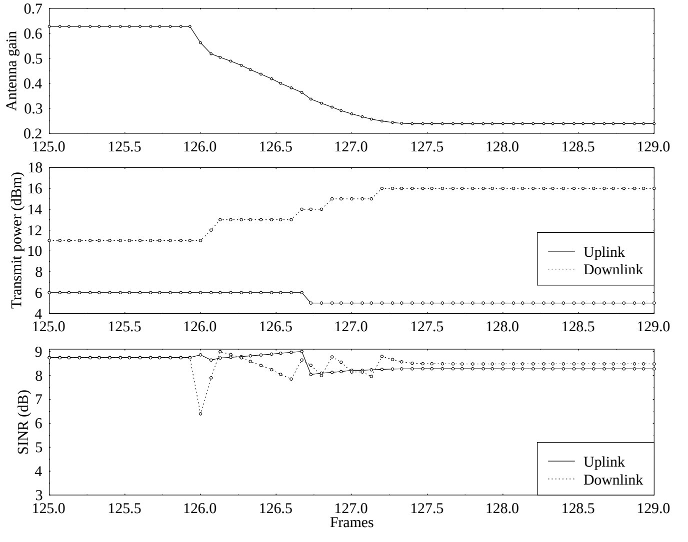


Figure 5.44: The changes in the antenna array gain, versus time, in the direction of the desired user, the up and downlink transmission powers, and the up and downlink received SINRs, when a new call starts using four element adaptive antenna arrays without shadowing in conjunction with a **slower power ramping** algorithm and SF=16.

duction of 1.5 dB resulted from using four element arrays. These power budget savings were obtained in conjunction with reduced levels of co-channel interference, leading to superior call quality, as illustrated in Figures 5.41 and 5.42. A greater performance advantage was evident in the uplink scenario, suggesting that the selective base station diversity techniques employed in the uplink are amenable to amalgamation with adaptive antenna arrays. In contrast, the maximum ratio combining performed at the mobile inherently reduces the impact of co-channel interference, and hence benefits to a lesser extent from the employment of adaptive antenna arrays.

The impact of adaptive antenna arrays in a propagation environment subjected to shadow fading was then investigated. The associated call dropping performance is shown in Figure 5.46. This figure illustrates the substantial network capacity gains achieved with the aid of both two and four element adaptive antenna arrays under shadow fading propagation conditions. Simulations were conducted in conjunction with log-normal shadow fading having a standard deviation of 3 dB, and maximum shadowing frequencies of both 0.5 Hz and 1.0 Hz. As expected the network capacity was reduced at the faster fading frequency. The effect of performing independent up- and down-link beamforming, as opposed to using the base station's receive antenna array weights in the downlink was also studied, and a small, but not insignificant call dropping probability reduction can be seen in the Figure 5.46. The network supported just over 150 users, and 144 users, when subjected to 0.5 Hz and 1.0 Hz frequency shadow fading, respectively. With the application of two element adaptive antenna arrays, re-using the base station's uplink receiver weights on the downlink, these capacities increased by 35% and 40%, to 203 users and 201 users. Performing independent up- and

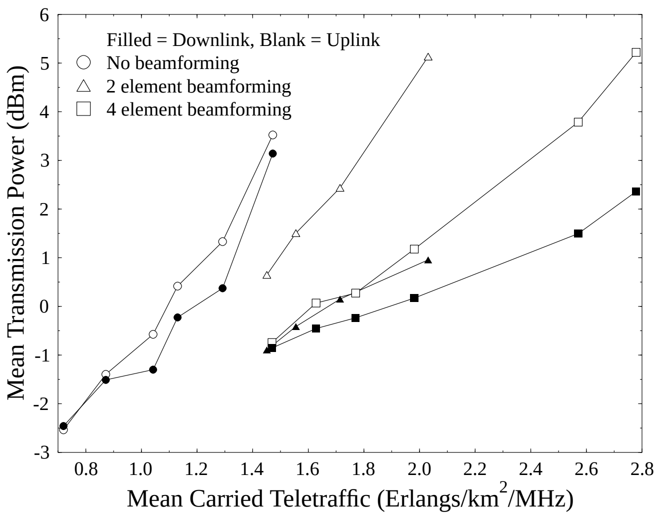


Figure 5.45: Mean transmission power versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds **with and without beamforming and without shadowing** for SF=16.

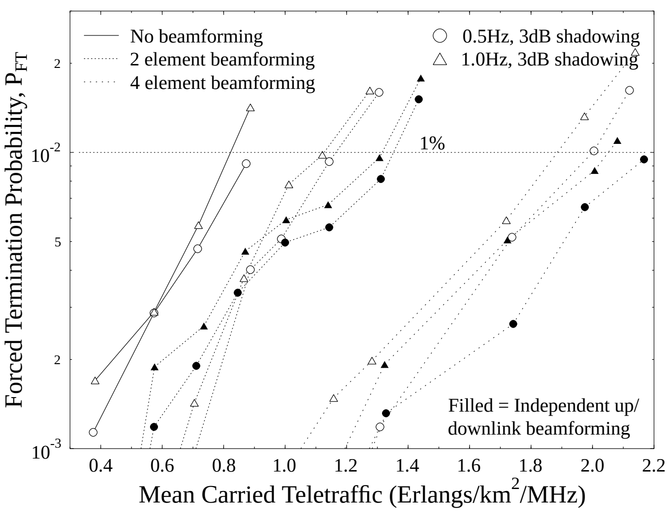


Figure 5.46: Call dropping probability versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds **with and without beamforming and with shadowing having a standard deviation of 3 dB** for SF=16.

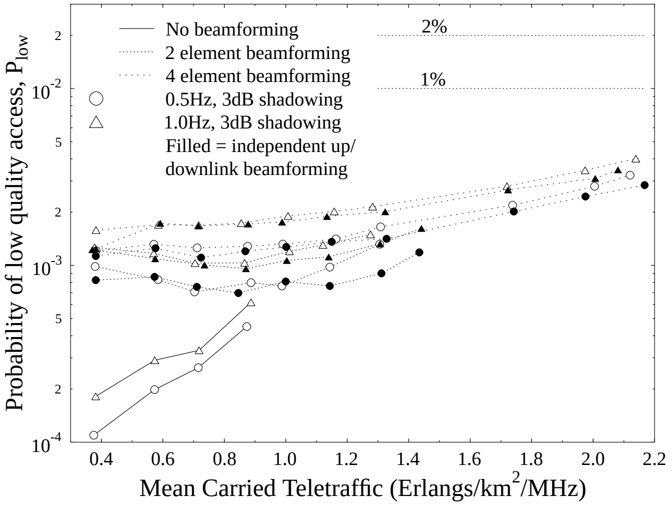


Figure 5.47: Probability of low quality access versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds **with and without beamforming and with shadowing having a standard deviation of 3 dB** for SF=16.

down-link beamforming resulted in a mean further increase of 13% in the network capacity. The implementation of four element adaptive antenna arrays led to a network capacity of 349 users at a 0.5 Hz shadowing frequency, and 333 users at a 1.0 Hz shadowing frequency. This corresponded to relative gains of 133% and 131% over the capacity provided without beamforming. Invoking independent up- and down-link beamforming gave another boost of 7% and 10% to network capacity for 0.5 Hz and 1.0 Hz frequency shadowing environments, respectively, giving final network capacities of just over 375 users and 365 users.

Similar trends were observed regarding the probability of low quality outage to those found in the non-shadowing scenarios. However, the trend was much more prevalent under shadowing, due to greater variation of the received signal strengths, as a result of the shadow fading, as shown in Figure 5.47. The figure indicates that the trend is also evident, when using two element adaptive antenna arrays in conjunction with shadow fading. As expected, the performance deteriorated as the number of antenna elements increased, and when the maximum shadow fading frequency was increased from 0.5 Hz to 1.0 Hz. It should be noted, however that the probability of low quality access always remained below the 1% constraint of the conservative scenario, and the call dropping probability was considerably reduced by the adaptive antenna arrays.

The mean transmission power performance is depicted in Figure 5.48, suggesting that as for the non-shadowing scenario of Figure 5.45, the number of antenna elements had only a limited impact on the base stations' transmission power, although there was some reduction in the mobile stations' mean transmission power. The mean transmission powers required when using independent up- and down-link beamforming are not explicitly shown, but were slightly less than those presented here, with a mean reduction of about 0.4 dB.

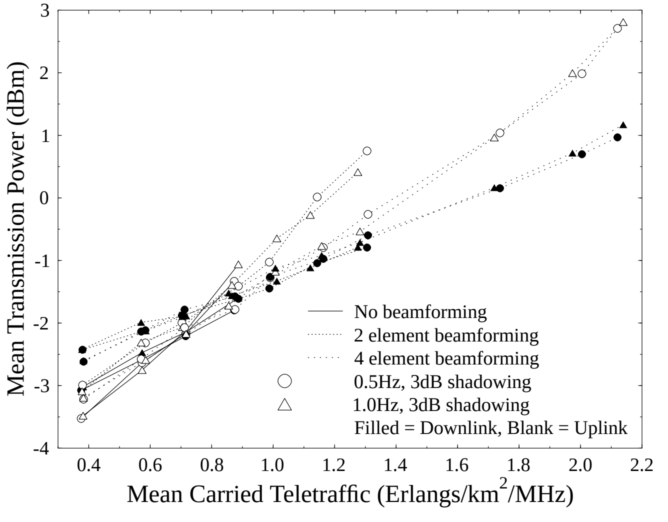


Figure 5.48: Mean transmission power versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds **with and without beamforming and shadowing having a standard deviation of 3 dB** for SF=16.

A summary of the maximum network capacities of the networks considered in this section both with and without shadowing, employing beamforming using two and four element arrays is given in Table 5.4, along with the teletraffic carried and the mean mobile and base station transmission powers required.

The lower bounds of the maximum network capacities obtained under identical scenarios in conjunction with a spreading factor of 256, are also presented in Table 5.5, leading to a bit rate of 15 kbps, which is suitable for use by speech-rate users. The network capacity calculations were performed by scaling the number of users supported, as presented in Table 5.4, by the ratio of their spreading factors, i.e. 256/16=16. Further interesting user capacity figures can be inferred for a variety of target bit rates by comparing Tables 5.4, 5.5, 5.7 and 5.8 and applying the appropriate spreading factor related scaling mentioned in the context of estimating the number of 15 kbps speech users supported.

5.4.6 Performance of Adaptive Antenna Arrays and Adaptive Modulation in a High Data Rate Pedestrian Environment

In this section we build upon the results presented in the previous section by applying Adaptive Quadrature Amplitude Modulation (AQAM) techniques. The various scenarios and channel conditions investigated were identical to those of the previous section, except for the application of AQAM. Since in the previous section an increased network capacity was achieved due to using independent up- and down-link beamforming, this procedure was invoked in these simulations. AQAM involves the selection of the appropriate modulation mode in order to maximise the achievable data throughput over a channel, whilst minimis-

Shadowing	Beamforming:	independent up/downlink	Conservative scenario, P_{FT}=1%, P_{low}=1% Users	Traffic (Erlangs /km^2/MHz)	Power (dBm) MS	BS
No	No	-	256	1.42	3.1	2.7
No	2 elements	-	325	1.87	3.75	0.55
No	4 elements	-	480	2.75	4.55	1.85
0.5 Hz, 3 dB	No	-	≈150	0.87	-1.2	-1.7
0.5 Hz, 3 dB	2 elements	No	203	1.16	0.1	-1.1
0.5 Hz, 3 dB	4 elements	No	349	2.0	2.0	0.65
0.5 Hz, 3 dB	2 elements	Yes	233	1.35	0.2	-0.8
0.5 Hz, 3 dB	4 elements	Yes	≈375	2.2	2.15	0.85
1.0 Hz, 3 dB	No	-	144	0.82	-1.1	-1.6
1.0 Hz, 3 dB	2 elements	No	201	1.12	-0.3	-1.1
1.0 Hz, 3 dB	4 elements	No	333	1.88	1.6	0.5
1.0 Hz, 3 dB	2 elements	Yes	225	1.31	0.1	-0.9
1.0 Hz, 3 dB	4 elements	Yes	365	2.05	1.65	0.6

Table 5.4: Maximum mean carried traffic and maximum number of mobile users that can be supported by the network, whilst meeting the conservative quality constraints. The carried traffic is expressed in terms of normalised Erlangs (Erlang/km^2/MHz) for the network described in Table 5.2 both **with and without beamforming (as well as with and without independent up/down-link beamforming), and also with and without shadow fading having a standard deviation of 3 dB** for SF=16.

Shadowing	Beamforming:	independent up/down-link	Users when SF=256	Traffic (Erlangs /km^2/MHz)
No	No	-	4096	22.7
No	2 elements	-	5200	29.9
No	4 elements	-	7680	44.0
0.5 Hz, 3 dB	No	-	2400	13.9
0.5 Hz, 3 dB	2 elements	No	3248	18.6
0.5 Hz, 3 dB	4 elements	No	5584	32.0
0.5 Hz, 3 dB	2 elements	Yes	3728	21.6
0.5 Hz, 3 dB	4 elements	Yes	6000	35.2
1.0 Hz, 3 dB	No	-	2304	13.1
1.0 Hz, 3 dB	2 elements	No	3216	17.9
1.0 Hz, 3 dB	4 elements	No	5328	30.1
1.0 Hz, 3 dB	2 elements	Yes	3600	21.0
1.0 Hz, 3 dB	4 elements	Yes	5840	32.8

Table 5.5: A lower bound estimate of the maximum mean traffic and the maximum number of mobile **speech-rate** users that can be supported by the network, whilst meeting the **conservative quality constraints**. The carried traffic is expressed in terms of normalised Erlangs (Erlang/km^2/MHz) for the network described in Table 5.2 both **with and without beamforming (as well as with and without independent up/down-link beamforming), and also with and without shadow fading having a standard deviation of 3 dB** for SF=256. The number of users supported in conjunction with a spreading factor of 256 was calculated by multiplying the capacities obtained in Table 5.4 by 256/16=16.

ing the Bit Error Ratio (BER). More explicitly, the philosophy behind adaptive modulation is the most appropriate selection of a modulation mode according to the instantaneous radio channel quality experienced [12, 13]. Therefore, if the SINR of the channel is high, then a high-order modulation mode may be employed, thus exploiting the temporal fluctuation of the radio channel's quality. Similarly, if the channel is of low quality, exhibiting a low SINR, a high-order modulation mode would result in an unacceptably high BER or FER, and hence a more robust, but lower throughput modulation mode would be employed. Therefore, adaptive modulation combats the effects of time-variant channel quality, while also attempting to maximise the achieved data throughput, and maintaining a given BER or FER. In the investigations conducted, the modulation modes of the up and downlink were determined independently, thus taking advantage of the lower levels of co-channel interference on the uplink, or of the potentially greater transmit power of the base stations.

The particular implementation of AQAM used in these investigations is illustrated in Figure 5.49. This figure describes the algorithm in the context of the downlink, but the same implementation was used also in the uplink. The first step in the process was to establish the current modulation mode. If the user was invoking 16-QAM and the SINR was found to be below the Low Quality (LQ) outage SINR threshold after the completion of the power control iterations, then the modulation mode for the next data frame was 4-QAM. Alternatively, if the SINR was above the LQ outage SINR threshold, but any of the base stations in the ABS were using a transmit power within 15 dB of the maximum transmit power - which is the maximum possible power change range during a 15-slot UTRA frame - then the 4-QAM modulation mode was selected. This 'headroom' was introduced in order to provide a measure of protection, since if the interference conditions degrade, then at least 15 dB of increased transmit power would be available in order to mitigate the consequences of the SINR reduction experienced.

A similar procedure was invoked when switching to other legitimate AQAM modes from the 4-QAM mode. If the SINR was below the 4-QAM target SINR and any one of the base stations in the ABS was within 15 dB (the maximum possible power change during a 15-slot UTRA data frame) of the maximum transmit power, then the BPSK modulation mode was employed for the next data frame. However, if the SINR exceeded the 4-QAM target SINR and there would be 15 dB of headroom in the transmit power budget in excess of the extra transmit power required for switching from 4-QAM to 16-QAM, then the 16-QAM modulation mode was invoked.

And finally, when in the BPSK mode, the 4-QAM modulation mode was selected if the SINR exceeded the BPSK target SINR, and the transmit power of any of the base stations in the ABS was less than the power required to transmit reliably using 4-QAM, while being at least 15 dB below the maximum transmit power. The algorithm was activated at the end of each 15-slot UTRA data frame, after the power control algorithm had performed its 15 iterations per data frame, and thus the AQAM mode selection was performed on a UTRA transmission frame-by-frame basis. When changing from a lower-order modulation to a higher-order modulation mode, the lower-order mode was retained for an extra frame in order to ramp up the transmit power to the required level, as shown in Figure 5.50(a). Conversely, when changing from a higher-order modulation mode to a lower-order modulation mode, the lower-order modulation mode was employed whilst ramping the power down, in order to avoid excessive outages in the higher-order modulation mode due to the reduction of the transmit power, as illustrated in Figure 5.50(b).

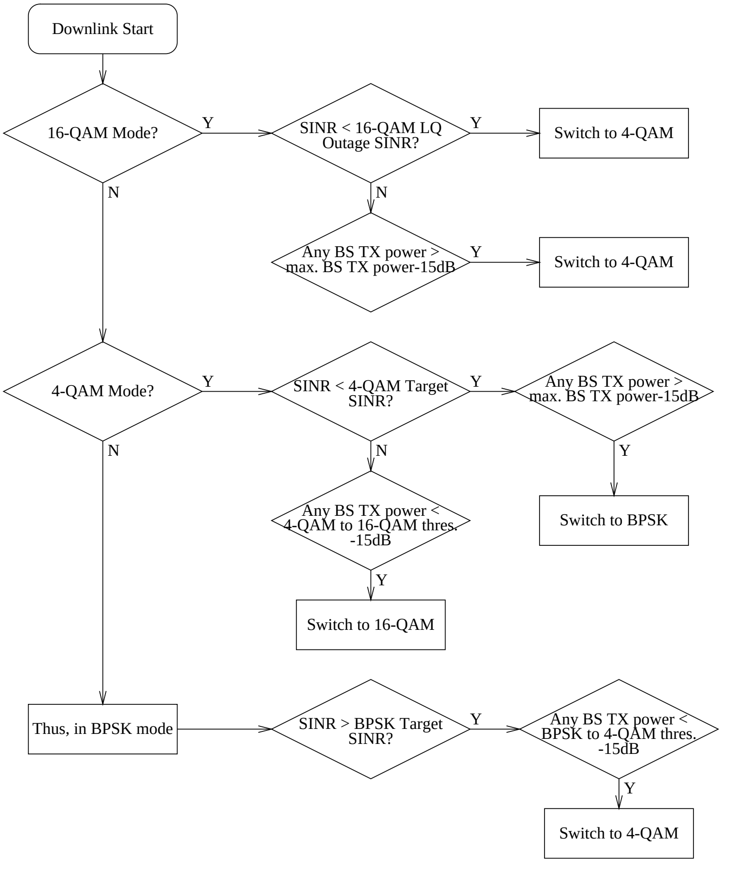
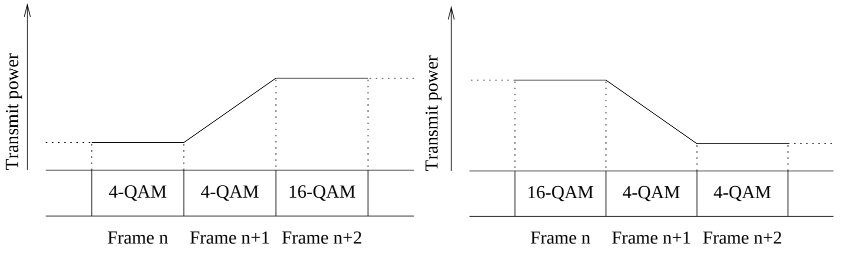


Figure 5.49: The AQAM mode switching algorithm used in the downlink of the CDMA based cellular network.

Table 5.6 gives the BPSK, 4-QAM and 16-QAM SINR thresholds used in the simulations. The BPSK SINR thresholds were 4 dB lower than those necessary when using 4-QAM, while the 16-QAM SINR thresholds were 5.5 dB higher [394]. In other words, in moving from the BPSK modulation mode to the 4-QAM modulation mode, the target SINR, low quality outage SINR and outage SINR all increased by 4 dB. When switching to the 16-QAM mode from the 4-QAM mode, the SINR thresholds increased by 5.5 dB. However, setting the BPSK to 4-QAM and the 4-QAM to 16-QAM mode switching thresholds to a value 7 dB higher than the SINR required for maintaining the target BER/FER was necessary in order to prevent excessive outages due to sudden dramatic channel-induced variations in the SINR levels.

Performance results were obtained both with and without beamforming in a log-normal shadow fading environment, at maximum fading frequencies of 0.5 Hz and 1.0 Hz, and a standard deviation of 3 dB. A pedestrian velocity of 3 mph, a cell radius of 150 m and a spreading factor of 16 were used, as in our previous investigations.

Figure 5.51 shows the significant reduction in the probability of a dropped call, achieved



(a) Ramping up the transmit power whilst remaining in the lower order modulation mode.
(b) Ramping down the transmit power whilst switching to the lower order modulation mode.

Figure 5.50: Power ramping requirements whilst switching modulation modes.

SINR Threshold	BPSK	4-QAM	16-QAM
Outage SINR	2.6 dB	6.6 dB	12.1 dB
Low Quality Outage SINR	3.0 dB	7.0 dB	12.5 dB
Target SINR	4.0 dB	8.0 dB	13.5 dB

Table 5.6: The target SINR, low quality outage SINR and outage SINR thresholds used for the BPSK, 4-QAM and 16-QAM modulation modes of the adaptive modem.

by employing adaptive antenna arrays in conjunction with adaptive modulation in a log-normal shadow faded environment. The figure demonstrates that, even with the aid of a two element adaptive antenna array and its limited degrees of freedom, a substantial call dropping probability reduction was achieved. The performance benefit of increasing the array's degrees of freedom, achieved by increasing the number of antenna elements, becomes explicit from the figure, resulting in a further call dropping probability reduction. Simulations were conducted in conjunction with log-normal shadow fading having a standard deviation of 3 dB, and maximum shadowing frequencies of 0.5 Hz and 1.0 Hz. As expected, the call dropping probability was generally higher at the faster fading frequency, as demonstrated by Figure 5.51. The network was found to support 223 users, corresponding to a traffic load of 1.27 Erlang/km^2/MHz, when subjected to 0.5 Hz frequency shadow fading. The capacity of the network was reduced to 218 users, or 1.24 Erlang/km^2/MHz, upon increasing the maximum shadow fading frequency to 1.0 Hz. On employing two element adaptive antenna arrays, the network capacity increased by 64% to 366 users, or to an equivalent traffic load of 2.11 Erlang/km^2/MHz when subjected to 0.5 Hz frequency shadow fading. When the maximum shadow fading frequency was raised to 1.0 Hz, the number of users supported by the network was 341 users, or 1.98 Erlang/km^2/MHz, representing an increase of 56% in comparison to the network without adaptive antenna arrays. Increasing the number of antenna elements to four, whilst imposing shadow fading with a maximum frequency of 0.5 Hz, resulted in a network capacity of 2.68 Erlang/km^2/MHz or 476 users, corresponding to a gain of an extra 30% with respect to the network employing two element arrays, and of 113% in comparison to the network employing no adaptive antenna arrays. In conjunction with a maximum shadow fading frequency of 1.0 Hz the network capacity was 460 users or 2.59 Erlang/km^2/MHz, which

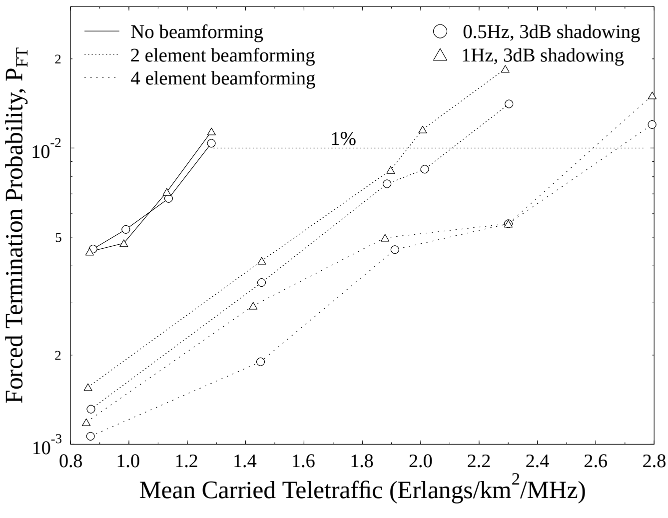


Figure 5.51: Call dropping probability versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds both **with and without beamforming in conjunction with AQAM as well as with shadowing having a standard deviation of 3 dB** for SF=16. See Figure 5.46 for corresponding results without adaptive modulation.

represented an increase of 35% with respect to the network invoking two element antenna arrays, or 111% relative to the identical network without adaptive antenna arrays.

The probability of low quality outage, presented in Figure 5.52, did not benefit from the application of adaptive antenna arrays, or from the employment of adaptive modulation. Figure 5.47 depicts the probability of low quality outage without adaptive modulation, and upon comparing these results to those obtained in conjunction with adaptive modulation shown in Figure 5.52, the performance degradation due to adaptive modulation can be explicitly seen. However, the increase in the probability of low quality access can be attributed to the employment of less robust, but higher throughput, higher-order modulation modes invoked by the adaptive modulation scheme. Hence, under given propagation conditions and using the fixed 4-QAM modulation mode a low quality outage may not occur, yet when using adaptive modulation and a higher order modulation mode, the same propagation conditions may inflict a low quality outage. This phenomenon is further exacerbated by the adaptive antenna arrays, as described in Section 5.4.5, where the addition of a new source of interference, constituted by a user initiating a new call, results in an abrupt change in the gain of the antenna in the direction of the desired user. This in turn leads to low quality outages, which are more likely to occur for prolonged periods of time when using a higher order modulation mode. Again, increasing the number of antenna elements from two to four results in an increased probability of a low quality outage due to the sharper antenna directivity. This results in a higher sensitivity to changes in the interference incident upon it.

The mean transmission power versus teletraffic performance is depicted in Figure 5.53,

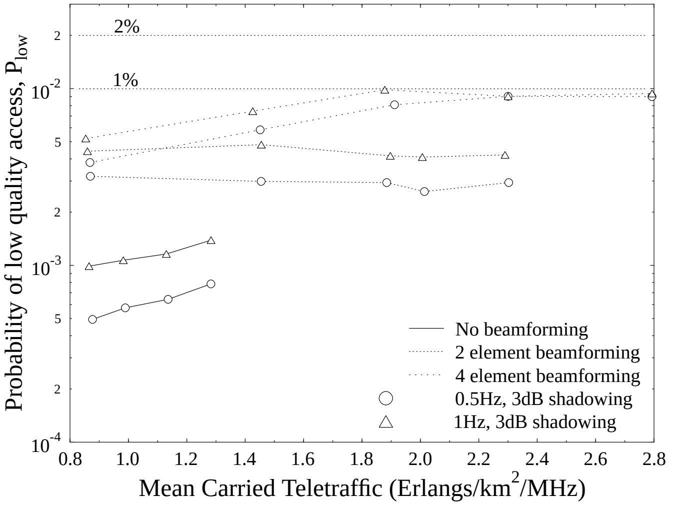


Figure 5.52: Probability of low quality access versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds both **with and without beamforming in conjunction with AQAM as well as with shadowing having a standard deviation of 3 dB** for SF=16. See Figure 5.47 for corresponding results without adaptive modulation.

suggesting that the mean uplink transmission power was always significantly below the mean downlink transmission power, which can be attributed to the pilot power interference encountered by the mobiles in the downlink. This explanation can be confirmed by examining Figure 5.54, which demonstrates that the mean modem throughput in the downlink, without adaptive antenna arrays, was lower than that in the uplink even in conjunction with increased downlink transmission power. Invoking adaptive antenna arrays at the base stations reduced the mean uplink transmission power required in order to meet the service quality targets of the network. The attainable downlink power reduction increased as the number of antenna array elements increased, as a result of the superior interference rejection achieved with the aid of a higher number of array elements. A further advantage of employing a larger number of antenna array elements was the associated increase in the mean uplink modem throughput, which became more significant at higher traffic loads. In the downlink scenario, however, increasing the number of adaptive antenna array elements led to an increased mean downlink transmission power, albeit with a substantially improved mean downlink modem throughput. This suggests that there was some interaction between the adaptive antenna arrays, the adaptive modulation mode switching algorithm and the maximal ratio combining performed at the mobiles. In contrast, simple switched diversity was performed by the base stations on the uplink, thus avoiding such a situation. However, the increase in the mean downlink transmission power resulted in a much more substantial increase in the mean downlink modem throughput, especially with the advent of the four element antenna arrays, which exhibited an approximately 0.5 BPS throughput gain over the two element arrays for identical high traffic

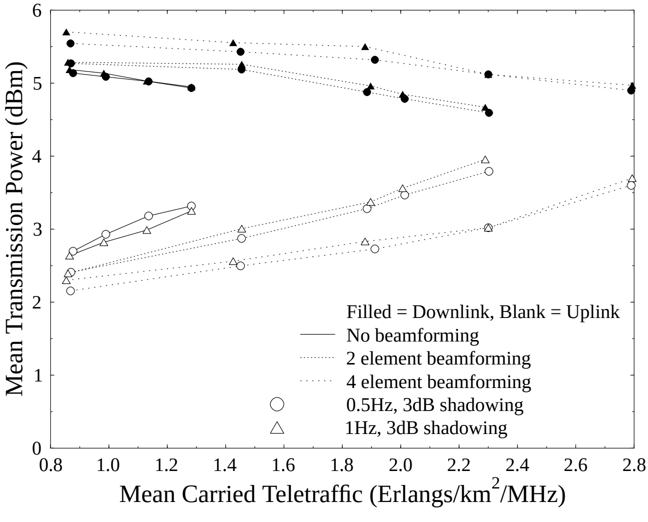


Figure 5.53: Mean transmission power versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds both **with and without beamforming in conjunction with AQAM as well as with shadowing having a standard deviation of 3 dB** for SF=16. See Figure 5.48 for corresponding results without adaptive modulation.

loads which can be seen in Figure 5.54.

A summary of the maximum user capacities of the networks considered in this section in conjunction with log-normal shadowing having a standard deviation of 3 dB, with and without employing beamforming using two and four element arrays is given in Table 5.7. The teletraffic carried the mean mobile and base station transmission powers required, and the mean up- and down-link modem data throughputs achieved are also shown in Table 5.7. Similarly, the lower bounds of the maximum network capacities obtained under identical scenarios in conjunction with a spreading factor of 256, leading to a bit rate of 15 kbps, suitable for speech-rate users are presented in Table 5.8. The network capacity calculations were performed by scaling the number of users supported, as presented in Table 5.7, by the ratio of their spreading factors, i.e. by 256/16=16.

5.5 Summary and Conclusions

We commenced this chapter with a brief overview of the background behind the 3G UTRA standard. This was followed in Sections 5.2 and 5.3 by an introduction to CDMA and the techniques invoked in the UTRA standard.

Network capacity studies were then conducted in Section 5.4, which evaluated the performance of four different soft handover algorithms in the context of both non-shadowed and log-normal shadow faded propagation environments. The algorithm using relative received

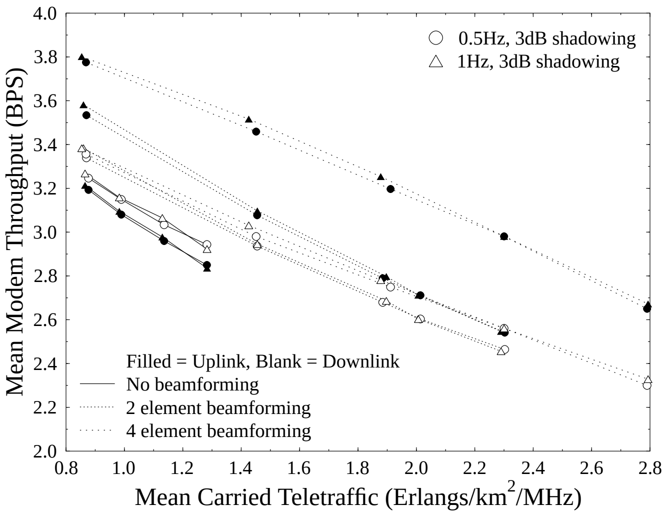


Figure 5.54: Mean modem throughput versus mean carried traffic of a CDMA based cellular network using **relative received** E_c/I_o based soft handover thresholds both **with and without beamforming in conjunction with AQAM as well as with shadowing having a standard deviation of 3 dB** for SF=16.

		Conservative scenario					
			Traffic (Erlangs	Power (dBm)		Throughput (BPS)	
Shadowing	Beamforming	Users	/km^2/MHz)	MS	BS	Uplink	Downlink
0.5 Hz, 3 dB	No	223	1.27	3.25	4.95	2.86	2.95
0.5 Hz, 3 dB	2 elements	366	2.11	3.55	4.7	2.56	2.66
0.5 Hz, 3 dB	4 elements	476	2.68	3.4	5.0	2.35	2.72
1.0 Hz, 3 dB	No	218	1.24	3.3	4.95	2.87	2.96
1.0 Hz, 3 dB	2 elements	341	1.98	3.5	4.9	2.62	2.73
1.0 Hz, 3 dB	4 elements	460	2.59	3.5	4.95	2.4	2.8

Table 5.7: Maximum mean carried traffic and maximum number of mobile users that can be supported by the network, whilst meeting the conservative quality constraints. The carried traffic is expressed in terms of normalised Erlangs (Erlang/km^2/MHz), for the network described in Table 5.2 both **with and without beamforming (using independent up/down-link beamforming), in conjunction with shadow fading having a standard deviation of 3 dB, whilst employing adaptive modulation techniques** for SF=16.

Shadowing	Beamforming	Conservative scenario Users	Traffic (Erlangs /km^2/MHz)
0.5 Hz, 3 dB	No	3568	20.3
0.5 Hz, 3 dB	2 elements	5856	33.8
0.5 Hz, 3 dB	4 elements	7616	42.9
1.0 Hz, 3 dB	No	3488	19.8
1.0 Hz, 3 dB	2 elements	5456	31.7
1.0 Hz, 3 dB	4 elements	7360	41.4

Table 5.8: A lower bound estimate of the maximum mean carried traffic and maximum number of mobile **speech-rate** users that can be supported by the network, whilst meeting the conservative quality constraints. The carried traffic is expressed in terms of normalised Erlangs (Erlang/km^2/MHz), for the network described in Table 5.2 both **with and without beamforming (using independent up/down-link beamforming), in conjunction with shadow fading having a standard deviation of 3 dB, whilst employing adaptive modulation techniques** for SF=256. The number of users supported in conjunction with a spreading factor of 256 was calculated by multiplying the capacities obtained in Table 5.7 by 256/16=16.

pilot-to-interference ratio measurements at the mobile, in order to determine the most suitable base stations for soft handover, was found to offer the highest network capacity when subjected to shadow fading propagation conditions. Hence, this algorithm and its associated parameters were selected for use in our further investigations. The impact of adaptive antenna arrays upon the network capacity was then considered in Section 5.4.5 in both non-shadowed and log-normal shadow faded propagation environments. Considerable network capacity gains were achieved, employing both two and four element adaptive antenna arrays. This work was then extended in Section 5.4.6 by the application of adaptive modulation techniques in conjunction with the previously studied adaptive antenna arrays in a log-normal shadow faded propagation environment, which elicited further significant network capacity gains.

Chapter 7

HSDPA-Style TDD/CDMA Network Performance

7.1 Introduction

In January 1998, the European standardization body created for the definition of the third generation (3G) mobile radio system, namely the European Telecommunications Institute's - Special Mobile Group (ETS ISMG), ratified a radio access scheme referred to as the Universal Mobile Telecommunications System (UMTS) [402]. The UMTS terrestrial Radio Access known as UTRA supports two duplexing modes, namely the Frequency Division Duplexing (FDD) mode, where the uplink and downlink are transmitted on different frequencies, and the Time Division Duplexing (TDD) mode, where the uplink and the downlink are transmitted on the same carrier frequency, but multiplexed in time [402]. UMTS networks will introduce into wide area using a completely new high bit rate radio technology - wideband CDMA (WCDMA).

In UTRA, the different services are expected to be supported in a spectrally efficient manner, either by FDD or TDD. The FDD mode is intended for applications in both macro- and micro-cellular environments, supporting data rates of up to 384 Kbps both at relatively high velocity. The TDD mode, on the other hand, is more suited to micro and pico-cellular environments, as well as for licensed and unlicensed cordless and wireless local loop applications. It makes efficient use of the unpaired spectrum - for example in wireless Internet applications, where much of the teletraffic is expected to be on the downlink - and supports data rates of up to 2 Mbps. Therefore, the TDD mode is particularly well suited for environments generating a high traffic density e.g. in city centres, business areas, airports etc. and for indoor coverage, where the applications require high data rates and tend to have highly asymmetric traffic, again, as in wireless Internet access.

7.2 UMTS FDD Versus TDD Terrestrial Radio Access

A bandwidth of 215 MHz in the region of 2.0 GHz has been allocated for UMTS services in Europe. The paired bands of 1920-1980 MHz (uplink) and 2110-2170 MHz (downlink) have been set aside for FDD W-CDMA systems, and the unpaired frequency bands of 1900-1920 MHz and 2010-2025 MHz for TDD CDMA systems.

A UTRA Network (UTRAN) consists of one or several Radio Network Sub-systems (RNSs), which in turn consist of base stations (referred to as Node BS) and Radio Network Controllers (RNCs). A Node B may serve a single or multiple cells. Mobile stations are known as User Equipment (UE), which are expected to support multi-mode operation in order to enable handovers between the FDD and TDD modes and, prior to complete UTRAN coverage, also to GSM. The two modes differ in a number of ways in the physical layer, but for compatibility and implementation reasons they are harmonized as far as possible, especially in higher layers. More details on the differences and distinctions can be found in [437]. The key parameters of UTRA have been defined in Table 5.1. The harmonization enables the same services to be offered over both modes, while the differences lead to one mode being best utilized in certain system scenarios while the other mode may perform better in other scenarios.

7.2.1 FDD Versus TDD Spectrum Allocation of UTRA

The FDD versus TDD spectrum allocation of UTRA is shown in Figure 7.1. As can be seen, UTRA is unable to utilize the full frequency spectrum allocated for the 3G mobile radio systems during the WARC'92 conference [422], since those frequency bands have also been partially allocated to the Digital Enhanced Cordless Telecommunications (DECT) system [438]. The frequency spectrum was originally allocated based on the assumption that speech and low data rate transmission would become the dominant services offered by IMT-2000 [402, 439]. However, in recent years a paradigm has been experienced towards services that require high-speed data transmission, such as wireless Internet access and multimedia services. A study conducted by the UMTS Forum [440] forecast that the current frequency bands allocated for IMT-2000 are only sufficient for the initial deployment until the year 2005. According to the current demand estimates, it was foreseen that an additional frequency spectrum of 187 MHz might be required for IMT-2000 in high-traffic areas by the year 2010. Among of numerous candidate extension bands, the band 2520-2670 MHz has been deemed to be the most likely. Unlike other bands, which have already been allocated for use in other applications, this band was allocated to mobile services in all regions. Furthermore, the 150 MHz bandwidth available is sufficiently wide for satisfying most of the forecast spectrum requirements.

Again, the UMTS radio access supports both FDD and TDD operations [402]. The operating principles of these two schemes are augmented here in the context of Figure 7.2.

Specifically, the Uplink (UL) and Downlink (DL) signals are transmitted using different carrier frequencies, namely f_{UL} and f_{DL}, respectively, separated by a frequency guard band in the FDD mode. On the other hand, the UL and DL messages in the TDD mode are transmitted using the same carrier frequency f_{TDD}, but in different time-slots, separated by a guard period. As seen from the spectrum allocation of Figure 7.1, the paired bands of 1920-1980 MHz and 2110-2170 MHz are allocated for FDD operation in the UL and DL,

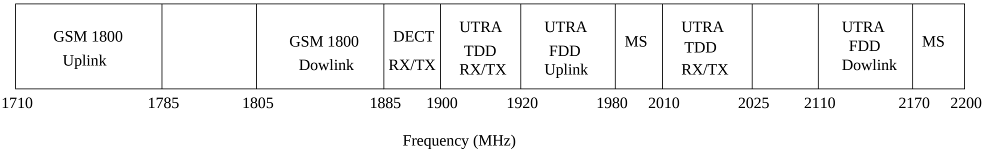


Figure 7.1: The proposed spectrum allocation in UTRA

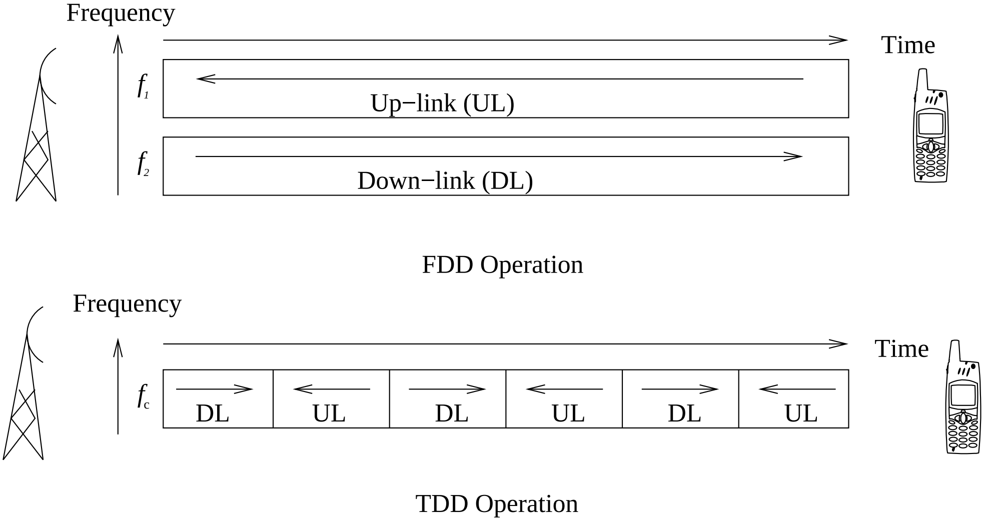


Figure 7.2: Principle of FDD and TDD operation.

respectively, whereas the TDD mode is operated in the remaining unpaired bands. The parameters designed for FDD and TDD operations are mutually compatible so as to ease the implementation of a dual-mode terminal capable of accessing the services offered by both FDD and TDD operators.

7.2.2 Physical Channels

The transport channels are transmitted using the UTRA physical channels [402, 441, 442]. The physical channels are typically organized in terms of radio frames and time-slots, as shown in Figure 7.3. While in GSM [443] each TDMA user had an exclusive slot allocation, in W-CDMA the number of simultaneous users supported is dependent on the users' required bit rate and their associated spreading factors. The MSs can transmit continuously in all slots or discontinuously, for example, when invoking a Voice Activity Detector (VAD) [443].

As seen in Figure 7.3, there are 15 timeslots within each radio frame. The duration of each timeslot is 2/3 ms, which yields a total duration of 10 ms for the radio frame. As we shall see later in this section, the configuration of the information in the time-slots of the

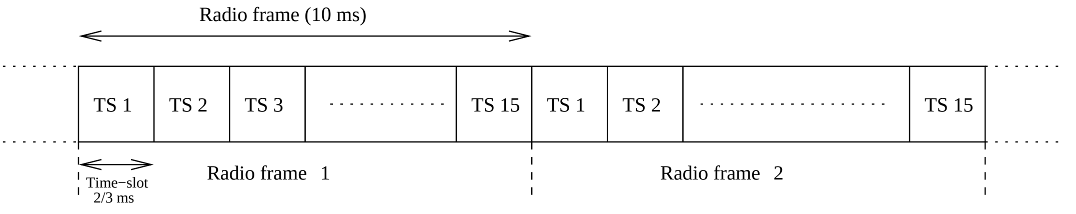


Figure 7.3: UTRA physical channel structure

physical channels differs from one another in the UL and DL, as well as in the FDD and TDD modes. In the FDD mode, a DL physical channel is defined by its spreading code and frequency. Furthermore, in the UL, the modem's orthogonal in-phase(I) and quadrature-phase (Q) branches are used for delivering the data and control information simultaneously in parallel [402]. On the other hand, in the TDD mode, a physical channel is defined by its spreading code, frequency and time-slot.

7.3 UTRA TDD/CDMA System

The UTRA TDD mode is partly a result of the original UMTS spectrum allocation, which consists of one paired and two unpaired bands. This led to an ETSI decision in 1998 that not just one but two of the proposed access technologies should be adopted for the UMTS standard. Hence, the FDD mode should be used in paired band and the TDD mode in the unpaired band. The TDD UTRA scheme will be deployed in the unpaired IMT-2000 frequency bands. The so-called band A is the 3G unpaired frequency allocation in Europe: 1900-1920 MHz and 2010-2025 MHz. In the United States so-called band B, namely the PCS spectrum allocation encompasses the range of 1850-1910 MHz and 1930-1990 MHz. Furthermore, the United States also allocated band C, an unlicensed band from 1910 MHz to 1930 MHz. The nominal channel spacing in UTRA is 5 MHz, with a channel raster of 200kHz, which means that the carrier frequency is a multiple of 200 kHz.

There are a few characteristics that are typical of TDD systems and different from the characteristics of FDD systems. These characteristics are listed below.

- $Utilization\ of\ unpaired\ bands$: the TDD system can be invoked in unpaired bands, while the FDD system always requires a pair of bands. It is more likely that in the future unpaired spectrum resources will be made available for UMTS.

- $Possible\ interference\ between\ uplink\ and\ downlink$: since both the uplink and downlink share the same carrier frequency in TDD, any timeslot can be used in any direction and hence the signals of the two transmission directions may interfere with each other.

- $Flexible\ capacity\ allocation\ between\ the\ uplink\ and\ downlink$: in the TDD mode, the uplink and downlink are divided in the time domain. It is possible to control the switching point [444] between the uplink and downlink, as seen in Figure 7.2, and move capacity form the uplink to downlink, or vice versa, if the capacity requirement is asymmetric between the uplink and downlink.

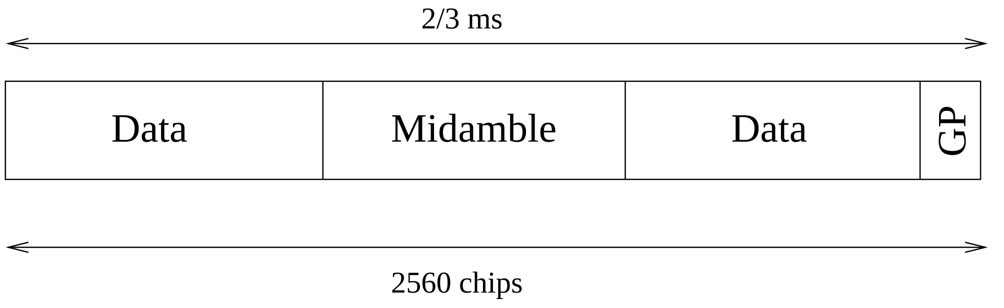
- $Discontinuous\ transmission$: the mobile and the base station transmissions are discontinuous in TDD. Discontinuous transmissions impose specific requirements on the implementation. Switching between the transmission directions requires a reflecting time, since the effects of switching effects of transients must be avoided. Hence, for the aim of avoiding the overlapping of the uplink and downlink transmissions, a guard period is used at the end of each slot.

- $Uplink/Downlink\ channel\ properties$: in case of frequency selective fading the channel's function depends on the frequency and, therefore in the FDD mode the fast fading is typically uncorrelated between the uplink and downlink. Since the same frequency is used both for the uplink and downlink in the TDD mode, the fast fading properties are more similar in the uplink and downlink. The similarity of the fast fading between the uplink and downlink can be exploited in both power control and adaptive antenna arrays used in TDD.

It is unlikely that any of the service providers would operate standalone wide-area TDD networks, but rather they would invoke the FDD UTRA mode and possibly GSM to provide continuous wide-area coverage, while TDD to serve as a separate capacity-enhancing layer in the network [445]. Furthermore, as a benefit of being able to arbitrarily adjust the UL/DL asymmetry, the TDD mode is also capable of supporting high bit rates, ranging from 144 kbps to 2 Mbps in wireless Internet type applications.

7.3.1 The TDD Physical Layer

The UTRA TDD mode has a similar frame structure to that of the UTRA FDD mode. As seen in Figure 7.3, there are 15 slots in a frame, which has a period of 10 ms. Each slot has 2560 chips and lasts for 0.667 ms. A superframe consists of 72 frames and lasts for 720 ms. A physical channel consists of bursts that are transmitted in the same slot of each frame. For specifying a physical channel explicitly, we also have to define its so-called repetition period, repetition length and superframe offset, which will be exemplified below. The number of frames between slots belonging to the same physical channel is the repetition period of a given physical channel, which must be sub-multiple of 72, i.e. 1,2,3,4,6,8,9,12,18,24,36 and 72. An example is given by the physical channel occupying slot 0 in every 12th frame. The superframe offset defines the repetition period offset within a superframe, with respect to the beginning of the frame. Returning to our example, if the superframe offset is 3, the physical channel will occupy slot 0 in frames 3,15,27,39,..., since it was offset by 3 frames, where the corresponding slots are 12 frames apart. The repetition length defines the number of slots associated with each repetition, and may have values of 1,2,3,4. For the example where the physical channel occupies slot 0, the repetition period is 12, the superframe offset is 3, and say, the repetition length is 4, the physical channel will occupy slot 0 in frames (3,4,5,6,), (15,16,17,18), (27,28,29,30), etc.



Burst type	Data	Midamble	Guard Period
Burst Type 1	976	512	96
Burst Type 2	1104	256	96

Figure 7.4: Time slot of the physical channels.

7.3.2 Common Physical Channels of the TDD Mode

The UTRA TDD mode employs time division duplexing for creating bidirectional transmission links. Each slot in a frame can be used for carrying either uplink or downlink information. The switching point or points between uplink and downlink slots may be variable, as is the number of slots allocated to each link. At least one slot must be allocated in each direction.

In TDD operation, the burst structure of Figure 7.4 is used for all the physical channels, where each time-slot's transmitted information can be arbitrarily allocated to the uplink or downlink, as shown in the four possible TDD allocations of Figure 7.5. A symmetric UL/DL allocation refers to a scenario in which an approximately equal number of DL and UL bursts is allocated within a TDD frame, while in case of asymmetric UL/DL allocation there is an unequal number of UL and DL bursts, such as services, etc., for example, in "near-simplex" file download from the wireless Internet or in case of video-on-demand.

In UTRA, two different TDD burst structures, known as $Burst\ Type$ 1 and $Burst\ Type$ 2, are defined, which are shown in Figure 7.4. The Type 1 burst has a longer midamble of 512 chips than the Type 2 burst of length 256 chips. However, both types of bursts have an identical $Guard\ Period$ (GP) of 96 chips. The midamble sequences that are allocated to the different TDD bursts in each time-slot belong to a so-called $midamble\ code\ set$. The codes in each midamble code set are derived from a unique $Basic\ Midamble\ Code$. Adjacent cells are allocated different midamble code sets. This can be exploited to assist in cell identification.

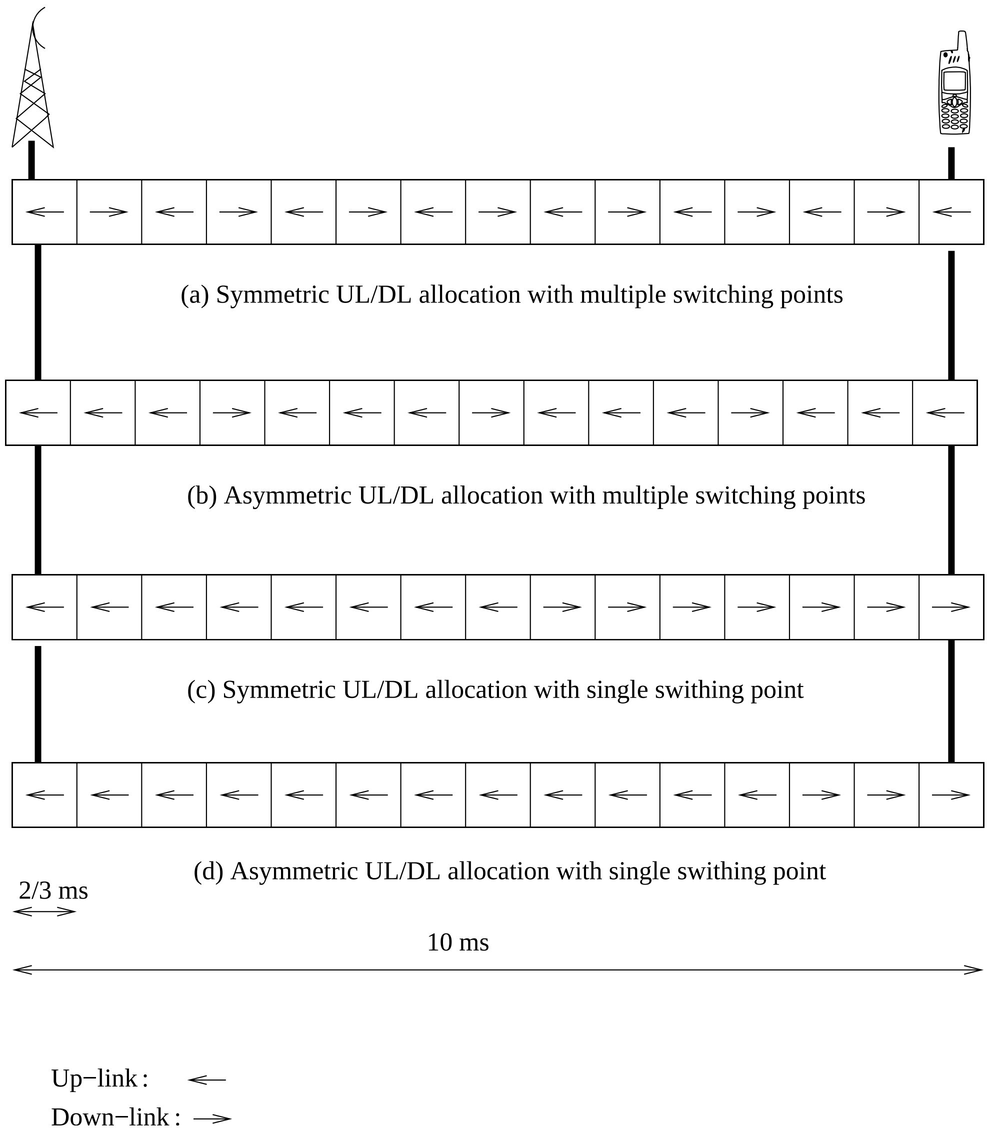


Figure 7.5: Multiple switching points per frame for different slot per frame allocations.

7.3.3 Power Control

Power control of the UTRA TDD mode is performed on a framely basis, for example using a power control update per 10 ms, which is carried out differently for the uplink and downlink.

Specifically, the uplink power control uses an open loop technique, which exploits the similarity of the uplink and downlink channel in a TDD system, in particular as regards to the pathloss. In each cell there is at least one beacon, i.e. a physical channel having a known transmit power. Furthermore, during unallocated uplink timeslots the base station is capable of estimating the uplink interference by exploiting the knowledge of the required target SIR, the MS can set its transmission power in order to fulfill the transmission integrity requirements at the BS. A first-order predictor corresponding to a weighting factor can be used for taking into account the expected delay between the downlink pathloss estimate and the actual uplink pathloss. At the BS, an outer power control loop is used for estimating the SIR of the received signal, which is compared it to the target SIR requirements. Then the necessary MS transmit power is calculated, which is signalled to the MS. This requirement allows the SIR-based outer loop to compensate for the long-term fluctuation of the associated pathlosses.

7.3.4 Time Advance

Timing advance is the mechanism used in UTRA for controlling the transmit time instant of signals from different MSs for mitigating leakage between time slots. During the initial access, the base station estimates the instant of reception for the MSs and advances their instant of transmission by the estimated propagation delay, so that all signals arrive approximately within the expected time window at the BS. The UTRA TDD system can be used in wide area cells, where the employment of this timing advance mechanism is necessary for preventing the up-link burst collisions at the BS receiver. The timing advance operates to a resolution of four chips or 1.04 μs, since the chip-rate is 3.84 Mchip/s. The BS estimates the time offset associated with the PRACH transmissions [402] and calculates the required initial timing advance. The timing advance parameter is transmitted as an 8-bit number, catering for a maximum timing advance of 256×1.04 μs corresponding to the up-link transmissions from the MS. This maximum propagation delay of approximately 256 μs potentially allows for a cell-size of 80 km.

There are proposals to have an enhanced timing advance mechanism with a resolution of one-eighth of a chip period. This potentially holds the promise of quasi-synchronous up-link transmission, which would dramatically decrease the multiple access interference, since all the transmitted codes of the MSs would remain quasi-orthogonal.

When performing a handover to another TDD cell, which is generally synchronized to reference cell, the MS is capable of autonomously applying the right timing advance in the new cell. In any case, the MS has to signal the timing advance it applies to the BS in the new cell.

7.4 Interference Scenario In TDD CDMA

One of the major attractions for the UTRA TDD mode system is that it allows the uplink and downlink capacities to be allocated asymmetrically. The uplink and downlink are transmitted on the same carrier frequency, which creates additional interference scenarios compared to UTRA FDD, and as seen in Figure 7.6, the UL/DL transmission directions of adjacent co-channel BSs may severely interfere with each other. This kind of interference may become particularly detrimental, if the base stations are not synchronized, or if a different ratio of uplink and downlink timeslots is used in adjacent cells, even if the base stations are frame synchronized. Frame synchronization requires an accuracy of a few symbols, rather than an accuracy of a few chips.

The interference between uplink and downlink can also occur between adjacent frequencies. Therefore, the interference between uplink and downlink can take place within one operator's band, and also between two operators.

The interference between uplink and downlink can occur between two mobile stations and between two base stations. In FDD operation the duplex separation prevents the interference between uplink and downlink. In a TDD system there are four types of inter-cell/inter-operator interference. These are:

- MS $\rightarrow$ MS
- BS $\rightarrow$ BS
- MS $\rightarrow$ BS
- BS $\rightarrow$ MS

The interference between a mobile station and a base station is the same both in TDD and in FDD operation. The extent of these interference is dependent on many parameters such as the cell locations and user distributions, however there are two parameters that can greatly affect the system performance and can potentially be managed by the network. There are synchronization between cells, and the asymmetry across the network.

7.4.1 Mobile to Mobile Interference

Mobile to mobile interference occurs in Figure 7.6, at the timeslot 7 the mobile MS_2 is transmitting and the mobile MS_1 is receiving in the same frequency in adjacent cells. Mobile to mobile interference is statistical because the locations of the mobiles cannot be controlled. Therefore, mobile to mobile interference cannot be avoided completely by the network planning.

7.4.2 Base Station to Base Station Interference

Base station to base station interference occurs in Figure 7.6, at the timeslot 7 the base station BS_1 is transmitting and the base station BS_2 is receiving in the same frequency in adjacent cells. Base station to base station interference depends heavily on the path loss between the two base stations, and therefore, the network planning greatly affects this interference scenario [446].

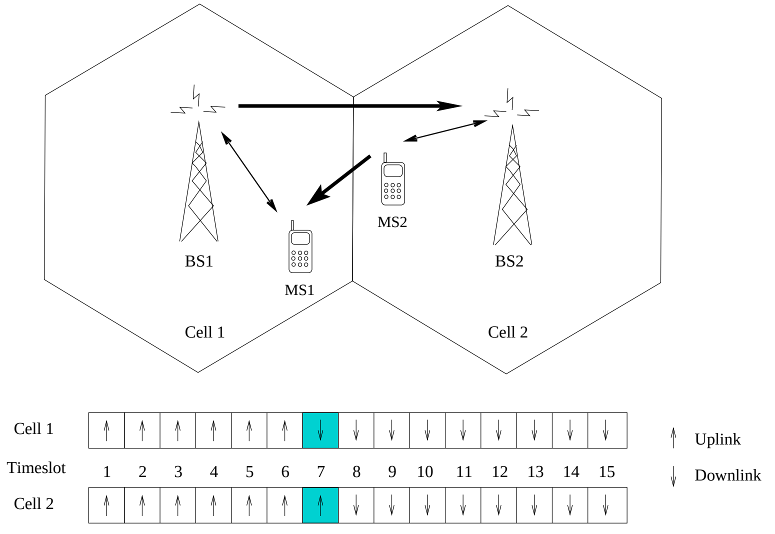


Figure 7.6: MS-to-MS BS-to-BS inter-cell interference

7.5 Simulation Results

A number of studies have been conducted, in order to characterise the network capacity of WCDMA-assisted 3G networks [395–397]. *The Timeslot (TS) opposing technique* proposed by Haas, McLaughlin and Povey [32, 447] enables asynchronous cells to overlap without a significant capacity degradation in comparison to the more idealistic scenario, when the base stations of all cells transmit and receive slot-synchronously in the UTRA-TDD system. Furthermore, the Dynamic Channel Allocation (DCA) [448] aided TS-opposing algorithm [32] enables neighbouring cells to adopt different grades of uplink/downlink (UL/DL) asymmetry without inflicting a significant capacity loss. The co-existence of the UTRA-TDD and FDD modes was studied in [449–451], since they are expected to co-exist in the same geographical area. Owing to the presence of increased levels of interference, capacity degradations are expected. It is crucial to estimate this potential capacity degradation and to identify appropriate countermeasures. Power control is a standard technique of improving the performance of wireless systems. Different power control techniques and their application within the UMTS were presented in [452–455]. More specifically, in [452], received signal level-based and interference level-based power control algorithms were introduced and the achievable system performance was compared by means of simulations. In [453], the UTRA TDD mode was studied in conjunction with an open loop power control algorithm combined with outer loop power control functions, which resulted in an improved rate of successful call establishment in the network. An Optimum Power Control (OPC) method was proposed in [454], which achieved the same performance as Wu's [456] at the cost of a lower complexity. Kurjenniemi [455] studied uplink power control in the context of the UTRA TDD system by the means of system level simulations, demonstrating that the UTRA TDD uplink power control substantially benefited from exploiting accurate interference measurements and hence achieved a high capacity, even in the presence of implementation errors. A pre-Rake smart antenna system designed for TDD CDMA was studied in [457]. The study demonstrated that incorporating an antenna array at the base station significantly improves the achievable capacity by reducing the interference between the uplink and downlink of adjacent cells, which is a consequence of potentially using all timeslots in an arbitrary uncoordinated fashion both in the UL and DL. Conventional single-user detectors, such as the Rake receiver are expected to result in a low network capacity owing to the excessive TDD-induced Multiple Access Interference . By contrast, Multi-User Detectors (MUD) have the potential of increasing the network capacity at the cost of a higher complexity [93, 405, 458].

This section presents our simulation results obtained for a TDD mode UTRA-like CDMA cellular network, investigating the achievable user capacity of the TDD mode in both non-shadowed and shadowed propagation environments. This is in Section 7.5.2 followed by our performance investigations using adaptive antenna arrays, when subjected to both non-shadowed as well as shadowed propagation conditions. Finally, the performance of adaptive modulation techniques used in conjunction with adaptive antenna arrays in shadow faded environments is then characterised in Section 7.5.3.

7.5.1 Simulation Parameters [402]

In this section simulations were conducted for various scenarios and algorithms in the context of a TDD mode UTRA-like CDMA based cellular network in order to study the interactions of the processes involved in such a network. As in the UTRA standard, the frame length was set to 10 ms, containing 15 power control timeslots. The power control target SINR was chosen to give a Bit Error Ratio (BER) of 1×10^{-3}, with a low quality outage occurring at a BER of 5×10^{-3} and an outage taking place at a BER of 1×10^{-2}. The received SINRs at both the mobile and the base stations were required for each of the power control timeslots, and hence the outage and low quality outage statistics were gathered. If the received SINR was found to be below the outage SINR for 75 consecutive power control timeslots, corresponding to 5 consecutive transmission frames or 50 ms, the call was dropped. The post-despreading SINRs necessary for obtaining the target BERs were determined with the aid of physical-layer simulations using a 4-QAM modulation scheme, in conjunction with $1/2$ rate turbo coding and joint detection over a COST 207 seven-path Bad Urban channel [394]. For a spreading factor of 16, the post-de-spreading SINR required for maintaining BER of 1×10^{-3} was 8.0 dB, while for a BER of 5×10^{-3} it was 7.0 dB, and for a BER of 1×10^{-2} was about 6.6 dB. These values can be seen along with the other system parameters specified earlier in Table 5.2. The pre-de-spreading SINR is related to E_b/N_o and to the spreading factor by

$$SINR = (E_b/N_o)/SF, \tag{7.1}$$

where the spreading factor is given by $SF = W/R$, with W being the chip rate and R the data rate. A receiver noise figure of 7 dB was assumed for both the mobile and the base stations [59]. Thus, in conjunction with a thermal noise density of -174 dBm/Hz and a noise bandwidth of 5 MHz, this resulted in a receiver noise power of -100 dBm. The power control algorithm used was relatively simple, and unrelated to the previously introduced schemes of Section 7.3.3. Furthermore, since it allowed a full transmission power change of 15 dB within a 15-slot UTRA data frame, the power control scheme advocated is unlikely to limit the network's capacity.

Specifically, for each of the 15 timeslots per transmitted frame, both the mobile and base station transmit powers were adjusted such that the received SINR was higher than the target SINR, but less than the target SINR plus a 1 dB hysteresis. When in handover, a mobile's transmission power was only increased, if all of the base stations in the Active Base station Set (ABS) requested a power increase, but was it decreased if any of the base stations in the ABS had an excessive received SINR. In the downlink, if the received SINR at the mobile was insufficiently high, then all of the active base stations were commanded to increase their transmission powers. Similarly, if the received SINR was unnecessarily high, then the active base stations would reduce their transmit powers. The downlink intra-cell interference orthogonality factor α, was set to 0.5 [395–397]. Due to using a frequency reuse factor of one, with its associated low frequency reuse distance, it was necessary for both the mobiles and the base stations to increase their transmitted power gradually when initiating a new call or entering handover. This was required for preventing sudden increases in the level of interference, particularly on links using the same base station. Hence, by gradually increasing the transmit power to the desired level, the other users of the network were capable of compensating for the increased interference by increasing their transmit powers, without encountering undesirable outages. In an FDMA/TDMA network this effect is less noticeable due to the significantly higher frequency reuse distance.

Since a dropped call is less desirable from a user's viewpoint than a blocked call, two resource allocation queues were invoked, one for new calls and the other - higher priority - queue, for handovers. By forming a queue of the handover requests, which have a higher priority during contention for network resources than new calls, it is possible to reduce the number of dropped calls at the expense of an increased blocked call probability. A further advantage of the Handover Queueing System (HQS) is that during the time a handover is in the queue, previously allocated resources may become available, hence increasing the probability of a successful handover. However, in a CDMA based network the capacity is not hard-limited by the number of frequency/timeslot combinations available, like in a FDMA/TDMA based network such as GSM. The main limiting factors are the number of available spreading or OVSF codes, or the interference levels in conjunction with the restricted maximum transmit power, resulting in excessive forced termination rates. New call allocation requests were queued for up to 5 seconds, if they could not be immediately satisfied, and were blocked if the request had not been completed successfully within the 5 second.

There are several performance metrics that can be used for quantifying the quality of service provided by a cellular network. The following performance metrics have been widely used in the literature and were also advocated by Chuang $et\ al.$ [383]:

- New Call Blocking probability, P_B,
- Call Dropping or Forced Termination probability, P_{FT},
- Probability of low quality connection, P_{low},
- Probability of Outage, P_{out},
- Grade Of Service, GOS.

The new call blocking probability, P_B, is defined as the probability that a new call is denied access to the network. In an FDMA/TDMA based network, such as GSM, this may occur because there are no available physical channels at the desired base station or the available channels are subject to excessive interference. However, in a CDMA based network this does not occur, and hence the new call blocking performance is typically very high.

The forced termination probability, P_{FT}, is the probability that a call is forced to terminate prematurely. In a GSM type network, an insufficiently high SINR, which inevitably leads to dropped calls, may be remedied by an intra- or inter-cell handover. However, in CDMA either the transmit power must be increased, or a soft handover must be performed in order to exploit the available diversity gain.

Again, the probability of a low quality connection is defined as :

$$\begin{aligned} P_{low} &= P\{SINR_{uplink} < SINR_{req} \text{ or } SINR_{downlink} < SINR_{req}\} \\ &= P\{min(SINR_{uplink}, SINR_{downlink}) < SINR_{req}\}. \end{aligned} \tag{7.2}$$

The GOS was defined in [383] as :

$$\begin{aligned} GOS &= P\{\text{unsuccessful or low-quality call access}\} \\ &= P\{\text{call is blocked}\} + P\{\text{call is admitted}\} \times \\ & \quad P\{\text{low signal quality and call is admitted}\} \\ &= P_B + (1 - P_B)P_{low}, \end{aligned} \tag{7.3}$$

and is interpreted as the probability of unsuccessful network access (blocking), or low quality access, when a call is admitted to the system. However, since the new call blocking probability of CDMA based networks is negligible, this metric has been omitted.

In our forthcoming investigations, in order to compare the network capacities of different networks, it was decided to use two scenarios defined as :

- A *conservative scenario*, where the maximum acceptable value for the new call blocking probability, P_B, is 3%, the maximum forced termination probability, P_{FT}, is 1%, and P_{low} is 1%.
- A *lenient scenario*, where the maximum acceptable value for the new call blocking probability, P_B, is 5%, the maximum forced termination probability, P_{FT}, is 1%, and P_{low} is 2%.

In the next section we characterise the capacity of an adaptive modulation [13] assisted, beam-steering aided TDD/CDMA system. In TDD/CDMA the mobiles suffer from interference inflicted by the other mobile stations (MSs) both in the reference cell the MS is roaming in (intracell interference) as well as due to those in the neighbouring cells (intercell interference). Furthermore, in contrast to FDD/CDMA, where the Base Stations (BSs) transmit in an orthogonal frequency band, in TDD/CDMA there is additional interference imposed by other BSs of the adjacent cells, since all times-slots can be used in both the uplink and downlink. In return for this disadvantage TDD/CDMA guarantees the flexible utilization of all the available bandwidth, which meets the demand for the support of asymmetric uplink and downlink services, such as high data rate file download in mobile Internet services, etc. In wireless systems the link quality fluctuates due to either fading- and dispersion-induced channel impairments or as a consequence of the time-variant co-channel interference imposed by the teletraffic fluctuations due to the varying number of users supported. Owing to these impairments conventional wireless systems often drop the call. By contrast, a particular advantage of employing adaptive modulation is that the transceiver is capable of automatically reconfiguring itself in a more error-resilient transmission mode, instead of dropping the call. Here we study the achievable network performance by simulation and compare it to that of the FDD/UTRA system.

7.5.2 Performance of Adaptive Antenna Array Aided TDD CDMA Systems

In this section we study the impact of adaptive antenna arrays on the network's performance. The investigations were conducted using a spreading factor of 16. Given that the chip rate of UTRA is 3.84 Mchips/sec, this spreading factor corresponds to a channel data rate of $3.84 \times 10^6/16 = 240$ kbps. Applying 1/2 rate error correction coding would result in an effective data throughput of 120 kbps, whereas utilizing a 2/3 rate error correction code would provide a useful throughput of 160 kbps. A cell radius of 150 m was assumed, and a pedestrian walking velocity of 3 mph was used.

The advanced UTRA FDD system level simulator [402] employing adaptive antenna arrays at the basestation as well as adaptive modulation [13] was extended to the UTRA TDD mode for evaluating the system's achievable performance. We observed quite significant performance gains as a direct result of the interference rejection capabilities of the adaptive antenna arrays and adaptive modulation invoked. Network performance results were obtained using two and four element adaptive antenna arrays, both in the absence of shadow fading, and in the presence of 0.5 Hz and 1.0 Hz frequency shadow fading exhibiting a standard deviation of 3 dB. The adaptive beamforming algorithm used was the Sample Matrix Inversion (SMI) algorithm [402]. The specific adaptive beamforming implementation used in our TDD/CDMA based network was identical to that used in the network simulations of [402]. Briefly [402], one of the eight possible 8-bit BPSK reference signals was used for uniquely and unambiguously identifying the desired user, while the remaining interfering users-up to seven of-them were assigned the other seven 8-bit reference signals. The received signal's autocorrelation matrix was then calculated, and from the knowledge of the desired user's reference signal the receiver's optimal antenna array weights were determined with the aid of the SMI algorithm. This implementation of the algorithm only calculated the receiver's antenna array weights, namely the antenna array weights used by the base station for receiving the mobiles' uplink transmissions. However, it was demonstrated in [402] that further performance gains are attainable, if the BS's UL and DL array patterns, namely the transmit and receive beamforms are optimised individually. The antenna array weights were re-calculated for every power control step, i.e. 15 times per UTRA data frame, owing to the potential significant changes in terms of the desired signal and interference powers that may occur during one UTRA frame as a result of the maximum possible 15 dB change in the power transmitted by each user.

Figure 7.7 shows the forced termination probability associated with a variety of traffic loads without shadowing, measured in terms of the mean normalised carried traffic expressed in Erlangs/km^2/MHz. The figure suggests that the TDD network's performance was poor in comparison to the FDD mode both with and without employing antenna arrays at the base stations. As expected, the "No beamforming" scenario suffered from the highest forced termination probability of the three beamforming scenarios at a given traffic load, which was valid

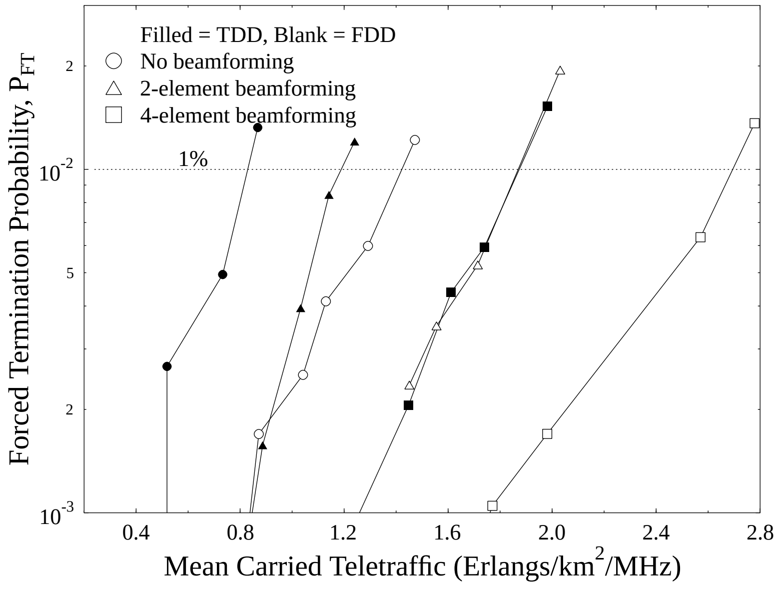


Figure 7.7: Forced termination probability versus mean carried traffic of the UTRA-like FDD and TDD/CDMA based cellular network of Table 5.2 both **with as well as without beamforming and without shadowing** for SF=16.

for both the TDD and FDD modes. Our discussions are focused here on the TDD mode, using FDD as the benchmark. When using "2-element beamforming", the adaptive antenna arrays have considerably reduced the levels of interference, leading to a reduced forced termination probability. Without employing antenna arrays at the base stations the network capacity was limited to 142 users, or to a teletraffic load of approximately 0.81 Erlangs/km^2/MHz. However, with the advent of employing 2-element adaptive antenna arrays at the base stations the number of users supported by the network increased by 45% to 206 users, or almost to 1.18 Erlangs/km^2/MHz. Replacing the 2-element adaptive antenna arrays with 4-element arrays led to a further capacity increase of 56%, or 127% with respect to the capacity of the network using no antenna arrays. This is associated with a network capacity of 322 users, or 1.85 Erlangs/km^2/MHz. We can also see in Figure 7.7 that the capacity of the UTRA-like TDD/CDMA cellular system is significantly poorer than that of the UTRA-like FDD/CDMA system under the same propagation conditions. The "TDD 4-element beamforming" scenario has a similar performance to the "FDD 2-element beamforming" scenario. This is because the TDD system suffers from the effects of the extra inter-cell interference, which we alluded to in Section 7.4.

Figure 7.8 portrays the probability of low quality access versus various traffic loads. It can be seen from the figure that higher traffic loads were carried with the aid of the 4-element array at a sufficiently low probability of a low quality, than that achieved using a 2-element array. Again, the user-capacity of the TDD mode is often a factor two lower than that of the FDD mode close to the 1% P_{low} limit and TDD system is more prone to rapid performance degradation. However, at lower traffic loads the FDD mode performance with four-element was worse than that using two-element. It is because in a network using adaptive antenna

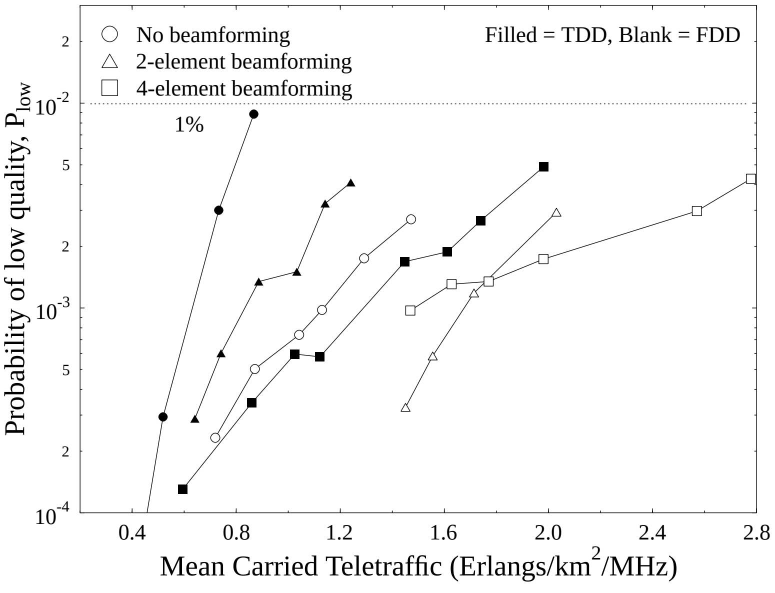


Figure 7.8: Probability of low quality access versus mean carried traffic of the UTRA-like FDD and TDD/ CDMA based cellular network both **with as well as without beamforming and without shadowing** for SF=16.

arrays, when new calls started, the adaptive antenna arrays are used to null the sources of interference, and the array may reduce the antenna gain in the direction of the desired user, in order to maximise the SINR. This phenomenon was more marked, when using four-element arrays since the directivity, and thus sensitivity to interfering signals is greater.

Figure 7.9 shows the achievable Grade-Of-Service for a range of teletraffic loads. Similar trends were observed regarding the probability of call blocking to those shown in Figure 7.7. The grade of service is better (i.e. lower) when the traffic load is low, and vice versa for high traffic loads. This is mainly attributable to the higher call blocking probability of the "No beamforming" scenario, particularly in the region of the highest traffic loads. As before, the TDD mode is more prone to rapid interference-level fluctuations as well as to avalanche-like teletraffic overload and its teletraffic capacity is up to a factor two lower than that of the FDD mode. Our expectation is that this performance trend may be partially mitigated with the aid of the adaptive modulation techniques of Section 7.5.3 [13], because when the instantaneous SINR is low, we activate a robust, but low-throughput modulation mode, and vice versa.

The impact of adaptive antenna arrays recorded in a propagation environment subjected to shadow fading was then investigated. The associated forced termination performance is shown in Figure 7.10. This figure illustrates the substantial network capacity gains achieved with the aid of both 2- and 4-elements adaptive antenna arrays under shadow fading propagation conditions. Simulations were conducted in conjunction with log-normal shadow fading having a standard deviation of 3 dB, experiencing maximum shadowing frequencies of both 0.5 Hz and 1.0 Hz. As expected, the network capacity was reduced at the higher shadow fading frequency in both the FDD and TDD modes. Without employing adaptive antenna arrays, the TDD network supported just over 71 users and 62 users, when subjected to 0.5 Hz and

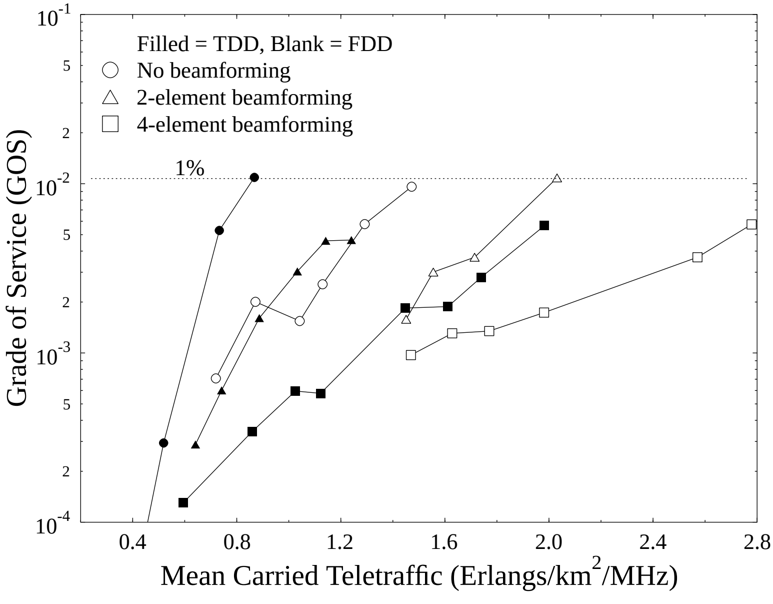


Figure 7.9: Grade-Of-Service (GOS) versus mean carried traffic of the UTRA-like FDD and TDD/CDMA based cellular network both **with as well as without beamforming and without shadowing** for SF=16.

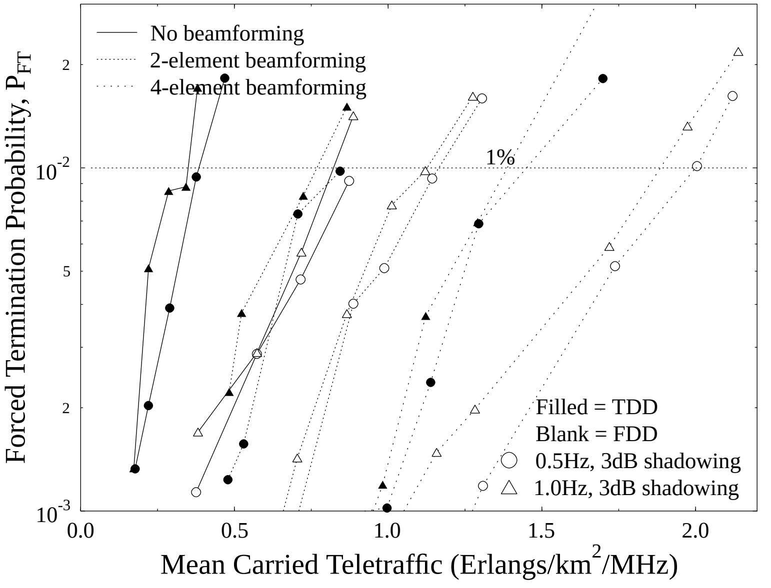


Figure 7.10: Forced termination probability versus mean carried traffic of the UTRA-like FDD and TDD/CDMA based cellular network both **with as well as without beamforming and with shadowing** for SF=16.

1.0 Hz frequency shadow fading, respectively. With the application of 2-element adaptive antenna arrays, these capacities increased by 111% and 113%, to 151 users and 131 users, respectively. The employment of 4-element adaptive antenna arrays led to a TDD network capacity of 245 users at a 0.5 Hz shadowing frequency, and 234 users at a 1.0 Hz shadowing frequency. This corresponded to relative gains of 62% and 78% over the capacity provided in the TDD mode with the aid of two-element adaptive antenna arrays. In comparison to the FDD benchmark we have recorded again up to a factor two lower teletraffic capacity.

The probability of low quality access performance is depicted in Figure 7.11. As expected, a given P_{low} value was associated with a higher traffic load, as the number of antenna elements increased. When the maximum shadow fading frequency was increased from 0.5 Hz to 1.0 Hz, P_{low} also increased. The probability of low quality seen in Figure 7.11 is similar in the scenarios employing adaptive antenna arrays in the UTRA TDD and FDD CDMA systems. It should be noted, however that the probability of low quality access always remained below the 1% constraint of the conservative scenario under the scenarios studied, and the forced termination probability was considerably reduced by the adaptive antenna arrays, as it will demonstrated during our later discussion in the context of Figure 7.13. When using beamforming, the inferiority of the TDD mode was less pronounced than in the context of the previously studied performance metrics.

Figure 7.12 presents the Grade-Of-Service (GOS) for a range of teletraffice loads with and without beamforming as well as in conjunction with shadowing. A summary of the maximum network capacities of the various scenarios considered in this section both with and without shadowing having a standard deviation of 3dB, as well as with and without employing beamforming using two and four element arrays is given in Table 7.1. Throughout this section we have observed that the capacity of the TDD mode was consistently lower than that of the FDD mode owing to the fact that any timeslot may be used both in the uplink and in the downlink. In the next section we will invoke adaptive modulation as a further countermeasure for mitigating this deficiency.

7.5.3 Performance of Adaptive Antenna Array and Adaptive Modulation Aided TDD HSDPA-Style Systems

In this section we build upon the results presented in the previous section by applying Adaptive Quadrature Amplitude Modulation (AQAM) techniques [13]. The various scenarios and channel conditions to be investigated here were identical to those of the previous section, except for the application of AQAM. Since in the previous section an increased network capacity was achieved due to using independent up- and down-link beamforming, this procedure was invoked in these simulations. AQAM involves the selection of the appropriate modulation mode in order to maximise the achievable data throughput over a given channel, whilst maintaining a given target the Bit Error Ratio. More explicitly, the philosophy behind adaptive modulation is the most appropriate selection of a modulation mode according to the instantaneous radio channel quality experienced [13]. Therefore, if the SINR of the channel is high, then a high-throughput high-order modulation mode may be employed for exploiting the high instantaneous quality of the radio channel. Similarly, if the channel is instantaneously of low quality, exhibiting a low SINR, a high-order modulation mode would result in an unacceptably high BER or FER, and hence a more robust, but lower throughput modulation mode would be employed. Therefore, adaptive modulation combats the effects of

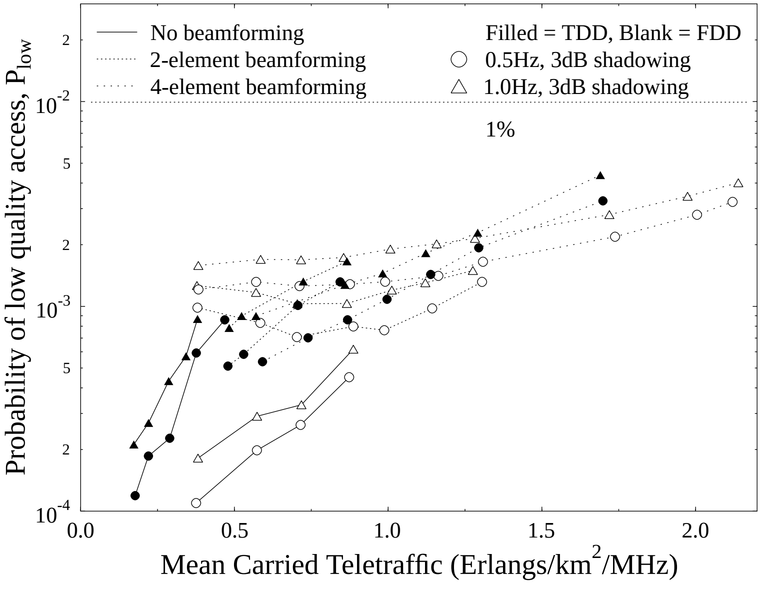


Figure 7.11: Probability of low quality access versus mean carried traffic of the UTRA-like FDD and TDD/CDMA based cellular network both **with as well as without beamforming and with shadowing** for SF=16.

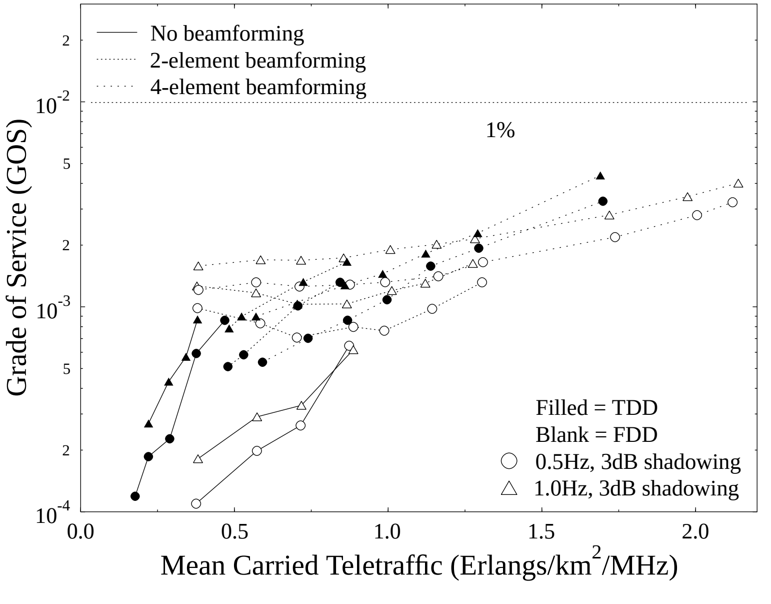


Figure 7.12: Grade-Of-Service (GOS) versus mean carried traffic of the UTRA-like FDD and TDD/CDMA based cellular network both **with as well as without beamforming and without shadowing** for SF=16.

		Conservative scenario			
		Number of Users		Traffic (Erlangs/km^2/MHz	
Shadowing	Beamforming	FDD	TDD	FDD	TDD
No	No	256	142	1.42	0.81
No	2 elements	325	206	1.87	1.18
No	4 elements	480	322	2.75	1.85
0.5 Hz, 3 dB	No	150	72	0.87	0.41
0.5 Hz, 3 dB	2 elements	203	151	1.16	0.87
0.5 Hz, 3 dB	4 elements	349	245	2.0	1.39
1.0 Hz, 3 dB	No	144	62	0.82	0.35
1.0 Hz, 3 dB	2 elements	201	131	1.12	0.75
1.0 Hz, 3 dB	4 elements	333	234	1.88	1.33

Table 7.1: Maximum mean carried traffic and maximum number of mobile users that can be supported by the FDD/TDD network, whilst meeting the conservative quality constraints. The carried traffic is expressed in terms of normalised Erlangs (Erlang/km^2/MHz), for the network described in Table 5.2 both **with and without beamforming, and also with and without shadow fading having a standard deviation of 3 dB** for SF=16. The FDD benchmark results were adopted from [402].

time-variant channel quality, while also attempting to maximise the achieved data throughput, and maintaining a given BER or FER. In the investigations conducted, the modulation modes of the up and downlink were determined independently, thus taking advantage of the lower levels of co-channel interference on the uplink, or of the potentially higher transmit power of the base stations.The particular implementation of AQAM used in these investigations is illustrated in [402].

Comparison Figure 7.13 to Figure 7.10 shows the significant reduction in the probability of a dropped TDD call, achieved by employing adaptive antenna arrays in conjunction with adaptive modulation [402, 405] in a log-normal shadow faded environment. The figure demonstrates that even with the aid of a two-element adaptive antenna array, a substantial forced termination probability reduction was achieved. The single-antenna based TDD network was found to support 153 users, corresponding to a traffic load of 0.875 Erlang/km^2/MHz, when subjected to 0.5 Hz frequency shadow fading. The capacity of the single-antenna aided TDD network was slightly reduced to 152 users, corresponding to 0.874 Erlang/km^2/MHz, when increasing the maximum shadow fading frequency to 1.0 Hz. Upon employing two-element adaptive antenna arrays, the TDD network capacity increased by 109% to 320 users, or to an equivalent traffic load of 1.834 Erlang/km^2/MHz, when subjected to 0.5 Hz frequency shadow fading. When the maximum shadow fading frequency was increased to 1.0 Hz, the number of users supported by the TDD network was 307, or 1.82 Erlang/km^2/MHz, representing an increase of 102% in comparison to the network refraining from using adaptive antenna arrays. It is seen in Figure 7.13 that the forced termination probability of the UTRA-like TDD/CDMA scenarios is close to that of the FDD/CDMA scenarios, when employing adaptive antenna arrays in conjunction with adaptive modulation.

The probability of low quality outage, presented in Figure 7.14, did not benefit from

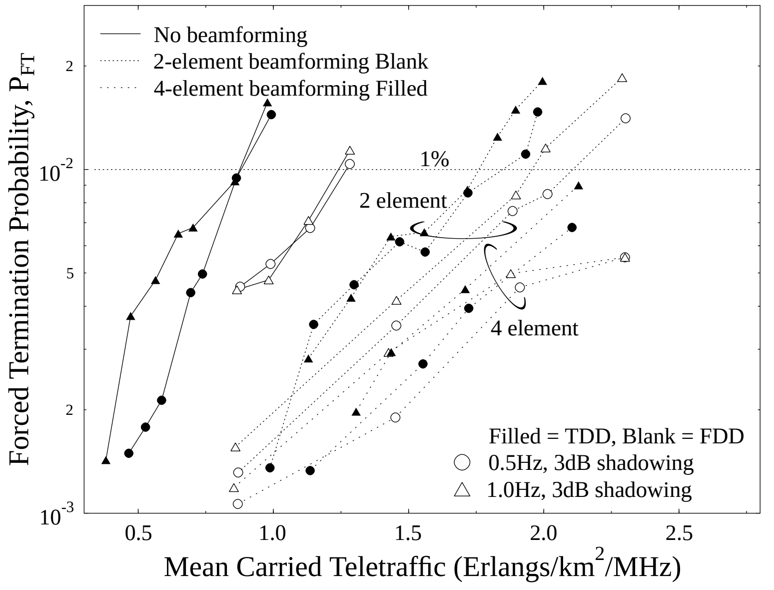


Figure 7.13: Forced termination probability versus mean carried traffic of the UTRA-like FDD and TDD/CDMA based cellular network both **with and without beamforming in conjunction with AQAM as well as with shadowing having a standard deviation of 3 dB** for SF=16.

the application of adaptive antenna arrays, in fact on the contrary. Furthermore, recall that Figure 7.11 depicted the probability of low quality outage without adaptive modulation, i.e. using fixed modulation, and upon comparing these results to those obtained in conjunction with adaptive modulation shown in Figure 7.14, the performance degradation owing to the employment of adaptive modulation can be explicitly seen. This is because the increase in the probability of low quality access can be attributed to the employment of less robust, but higher throughput, higher-order modulation modes invoked by the adaptive modulation scheme. Hence, under given propagation conditions and using the interference-resilient fixed 4-QAM modulation mode, as in Figure 7.11, a low quality outage may not occur. By contrast, when using adaptive modulation invoking a less resilient, but higher-throughput and higher-order modulation mode, the same propagation conditions may inflict a low quality outage.

A summary of the maximum user capacities of the FDD and TDD networks considered in this section both with and without shadowing having a standard deviation of 3dB as well as with and without employing beamforming using two and four element arrays, whilst employing adaptive modulation is given in Table 7.2.

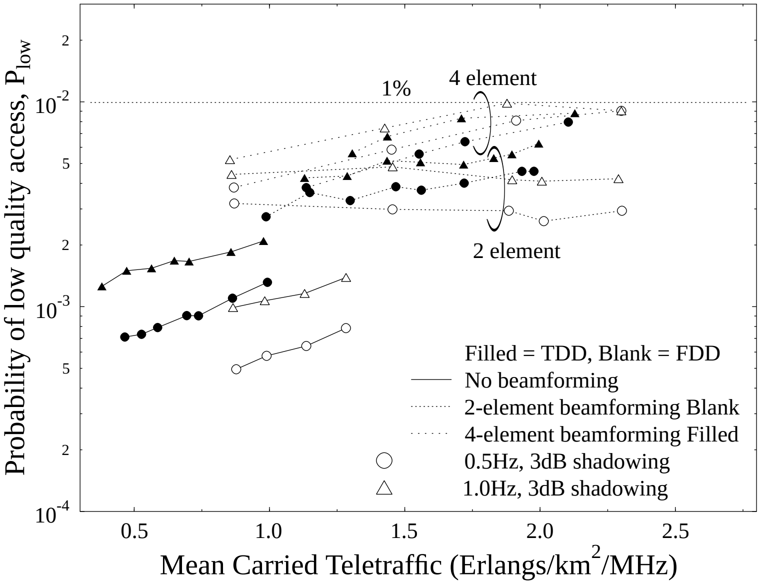


Figure 7.14: Probability of low quality access versus mean carried traffic of the UTRA-like FDD and TDD/CDMA based cellular network both **with and without beamforming in conjunction with AQAM as well as with shadowing having a standard deviation of 3dB** for SF=16.

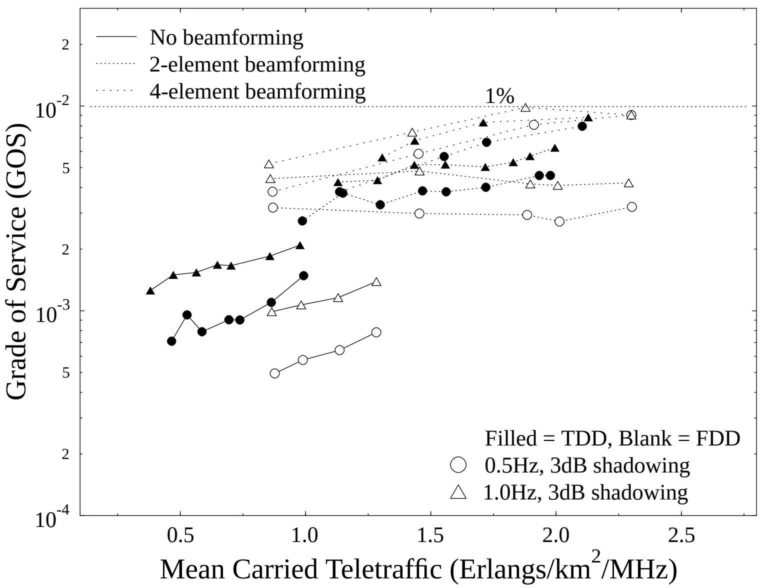


Figure 7.15: Grade-Of-Service (GOS) versus mean carried traffic of the UTRA-like FDD and TDD/CDMA based cellular network both **with and without beamforming in conjunction with AQAM as well as with shadowing having a standard deviation of 3dB** for SF=16.

		Conservative scenario			
		Number of Users		Traffic (Erlangs/km^2/MHz	
Shadowing	Beamforming	FDD	TDD	FDD	TDD
0.5 Hz, 3 dB	No	223	153	1.27	0.875
0.5 Hz, 3 dB	2 elements	366	320	2.11	1.834
0.5 Hz, 3 dB	4 elements	476	420	2.68	2.41
1.0 Hz, 3 dB	No	218	152	1.24	0.874
1.0 Hz, 3 dB	2 elements	341	307	1.98	1.758
1.0 Hz, 3 dB	4 elements	460	393	2.59	2.234

Table 7.2: Maximum mean carried traffic and maximum number of mobile users that can be supported by the FDD and TDD network, whilst meeting the conservative quality constraints. The carried traffic is expressed in terms of normalised Erlangs (Erlang/km^2/MHz), for the network described in Table 5.2 both **with and without beamforming, in conjunction with shadow fading having a standard deviation of 3 dB, whilst employing adaptive modulation techniques** for SF=16. The FDD benchmark results were adopted from [402].

7.6 Loosely Synchronized Spreading Code Aided Network Performance of UTRA-like TDD/CDMA Systems

7.6.1 Introduction

In this section we investigate the achievable capacity of a UTRA-like TDD/CDMA system employing Loosely Synchronized (LS) spreading codes. The family of operational CDMA systems is interference limited, suffering from Inter-Symbol-Interference, since the orthogonality of the spreading sequences is destroyed by the frequency selective channel. They also suffer from Multiple-Access-Interference owing to the non-zero cross-correlations of the spreading codes. By contrast, the family of LS codes exhibits a so-called Interference Free Window (IFW), where both the auto-correlation and cross-correlation values of the codes become zero. Therefore LS codes have the promise of mitigating the effects of both ISI and MAI in time dispersive channels. Hence, LS codes have the potential of increasing the capacity of CDMA networks. This section studies the achievable network performance in comparison to that of a UTRA-like TDD/CDMA system using Orthogonal Variable Spreading Factor (OVSF) codes.

The air interface of UMTS supports both FDD and TDD mode [402], in order to facilitate an efficient exploitation of the paired and unpaired band of the allocated spectrum. The FDD mode is intended for applications in both macro- and micro-cellular environments, when supporting both medium data rates and high mobility. In contrast to the FDD mode, the TDD mode was contrived for environments associated with a high traffic density and asymmetric uplink as well as downlink indoor coverage. Although the UTRA/TDD mode was contrived for the sake of improving the achievable network performance by assigning all the timeslots on a demand basis to the uplink and downlink [422], this measure may result in an excessive $BS \rightarrow BS$ interference and hence in a potentially reduced number of system users [459, 460]. As seen in Figure 7.6, if BS_1 is transmitting and BS_2 is receiving at the same time in a given timeslot, $BS \rightarrow BS$ interference takes place, provided that these base stations are in adjacent cells. In [459] we demonstrated that the employment of adaptive arrays in conjunction with AQAM limited the detrimental effects of co-channel interference on the UTRA-like TDD/CDMA system and resulted in performance improvements both in terms of the achievable call quality and the number of users supported. However, in comparison to a UTRA-like FDD/CDMA system, the capacity of the UTRA-like TDD/CDMA cellular system was shown to remain somewhat poorer than that of the UTRA-like FDD/CDMA system under the same propagation conditions.

The network performance of the UTRA-like FDD/CDMA systems was quantified in our previous research [413], when supported by adaptive beam-steering [405] and LS [407] spreading codes. It was demonstrated that the network performance of a UTRA-like FDD/CDMA system employing LS spreading codes was substantially better than that of the system using OVSF codes [406]. We consider the employment of this specific family of LS spreading codes in the UTRA-like TDD/CDMA system. The LS spreading codes exhibit a so-called Interference Free Window (IFW), where the off-peak aperiodic autocorrelation values as well as the aperiodic cross-correlation values become zero. With the advent of the IFW we may encounter both zero ISI and zero MAI, provided that all the delayed asynchronous transmissions arrive within the IFW. More specifically, interference-free CDMA communications become possible, when the total time offset expressed in terms of the number of chip intervals, which is the sum of the time-offset of the mobiles plus the maximum channel-induced delay spread is within the code's IFW [408]. By employing this specific family of codes, we are capable of reducing the ISI and MAI, since users in the same cell do not interference with each other, as a benefit of the IFW provided by the LS codes used.

7.6.2 LS Codes in UTRA TDD/CDMA

There exists a specific family of LS codes [407], which exhibits an IFW, where both the autocorrelation and cross-correlation values of the codes become zero. Specifically, LS codes exploit the properties of the so-called orthogonal complementary sets [407, 417]. An example of the design of LS spreading codes can be found in [413]. In the UTRA TDD mode, the uplink and downlink timeslots are transmitted on the same carrier frequency, which creates additional undesirable and grave interference infested scenarios compared to UTRA FDD. More explicitly, as argued in the context of Figure 7.6, both transmission directions may interfere with each other, resulting in MS $\rightarrow$ MS and BS $\rightarrow$ BS interference, respectively. The interference experienced at the mobile may be divided into two categories. Firstly, interference is imposed by the signals transmitted to other mobiles from the same base station, which is known as intra-cell interference. Secondly, interference is encountered owing to the signals transmitted to other mobiles from other basestations, as well as to other basestations from other mobiles, which is termed inter-cell interference.

The instantaneous SINR is obtained upon dividing the received signal powers by the total interference plus thermal noise power, and then by multiplying this ratio by the spreading factor, SF, yielding [402]

$$SINR_{DL} = \frac{SF \cdot P_{BS}}{(1-\alpha)I_{Intra} + I_{Inter} + N_0}, \tag{7.4}$$

where $\alpha = 1$ corresponds to the ideal case of perfectly orthogonal intra-cell interference and $\alpha = 0$ to completely asynchronous intra-cell interference. Furthermore, P_{BS} is the signal

Parameter	**Value**	**Parameter**	**Value**
Noisefloor	-100dBm	Pilot power	-9dBm
Frame length	10ms	Cell radius	78m
Multiple access	TDD/CDMA	Number of basestations	49
Modulation scheme	4QAM/QPSK	Spreading factor	16
Min BS transmit power	-48dBm	Min MS transmit power	-48dBm
Max BS transmit power	17dBm	Max MS transmit power	17dBm
Low quality access SINR	5.2dB	Outage (1% BER) SINR	4.8dB
Pathloss exponent	-2.0	Target SINR	6.2dB
Average inter-call-time	300s	Max. new-call queue-time	5s
Average call length	60s	Pedestrian speed	3mph
Max consecutive outages	5	Signal bandwidth	5MHz

Table 7.3: Simulation parameters [413].

power received by the mobile user from the base station, N_0 is the thermal noise, I_{Intra} is the intra-cell interference and I_{Inter} is the inter-cell interference. Again, the interference plus noise power is scaled by the spreading factor, SF, since during the despreading process the associated low-pass filtering reduces the noise bandwidth by a factor of SF. The inter-cell interference is not only due to the MSs, but also due to the BSs illuminating the adjacent cells by co-channel signals. Owing to invoking LS spreading codes in our UTRA-like TDD/CDMA system, the intra-cell interference may be completely eliminated, hence we have $\alpha = 1$. Our current research is building on our previous findings recorded in the context of a UTRA-like TDD system [459], where we found that invoking adaptive modulation as well as beam-steering proved to be a powerful means of enhancing the capacity of TDD/CDMA. In the investigations of [459], OVSF codes were used as spreading codes. However, the intra-cell interference is only eliminated by employing orthogonal OVSF codes, if the system is perfectly synchronous and provided that the mobile channel does not destroy the OVSF codes' orthogonality. In an effort to prevent intra-cell interference, again, in this section we employ LS codes, which exhibit ideal auto-correlation and cross-correlation functions within the IFW. Thereby, the "near far effect" may be significantly reduced and hence the user capacity of the system can be substantially enhanced. As a benefit of the LS codes' interference resilience, it was shown in [413] that the achievable BER performance of LS codes is better than that of OVSF codes. For a spreading factor of 16, the post-despreading SINR required for maintaining a BER of 1×10^{-3} was 6.2 dB in case of LS codes, which is almost 2 dB lower than that necessitated by the OVSF codes.

7.6.3 System Parameters

The cell-radius was 78 m, which was the maximum affordable cell radius for the IFW duration of ± 1 chip intervals at a chip rate of 3.84 Mchip/s. The mobiles were capable of moving freely, at a speed of 3mph, in random directions, selected at the start of the simulation from a uniform distribution, within the infinite simulation area of 49 wrapped-around traffic cells [402]. Furthermore, the post-despreading SINRs required for obtaining the target

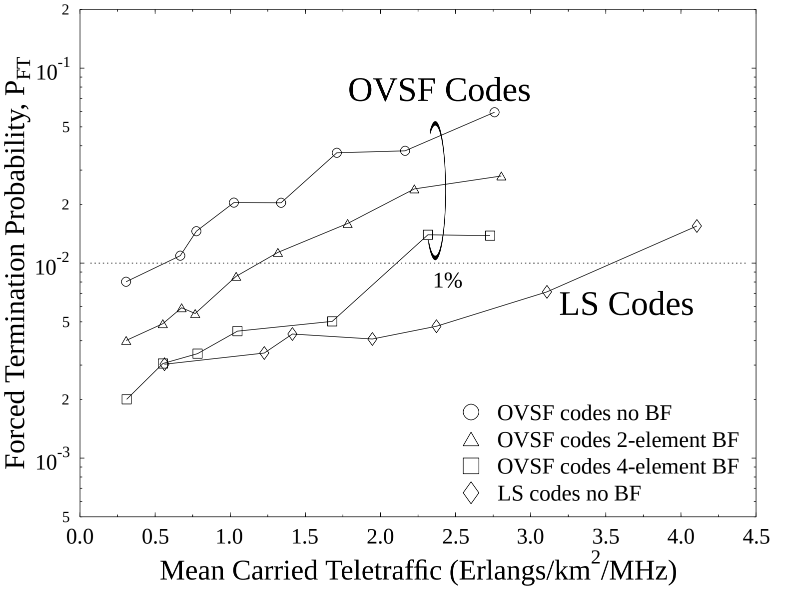


Figure 7.16: Forced termination probability versus mean carried traffic of the UTRA-like TDD cellular network using **LS codes and OVSF codes** both with as well as without beamforming in conjunction with shadowing having a frequency of 0.5 Hz and a standard deviation of 3dB for a spreading factor of SF=16.

BERs were determined with the aid of physical-layer simulations using a 4QAM modulation scheme, in conjunction with 1/2-rate turbo coding for transmission over a COST 207 seven-path Bad Urban channel [420]. Using this turbo-coded transceiver and LS codes having a spreading factor (SF) of 16, the post-despreading SINR required for maintaining the target BER of 1×10^{-3} was 6.2 dB. The BER, which was deemed to correspond to low-quality access, was stipulated at 5×10^{-3}. This BER was exceeded for SINRs falling below 5.2 dB. Furthermore, a low-quality outage was declared, when the BER of 1×10^{-2} was exceeded, which was encountered for SINRs below 4.8 dB. These values can be seen along with the other system parameters in Table 7.3. All other experimental conditions were identical to those in [402].

7.6.4 Simulation Results

Figure 7.16 shows the forced termination probability associated with a variety of traffic loads quantified in terms of the mean normalized carried traffic expressed in Erlangs/km^2/MHz, when subjected to 0.5 Hz frequency shadowing having a standard deviation of 3 dB. As observed in the figure, nearly an order of magnitude reduction of the forced termination probability has been achieved by employing LS spreading codes compared to those of using OVSF spreading codes. In conjunction with OVSF codes, the “No beamforming” scenario suffered from the highest forced termination probability of the four traffic scenarios characterized in

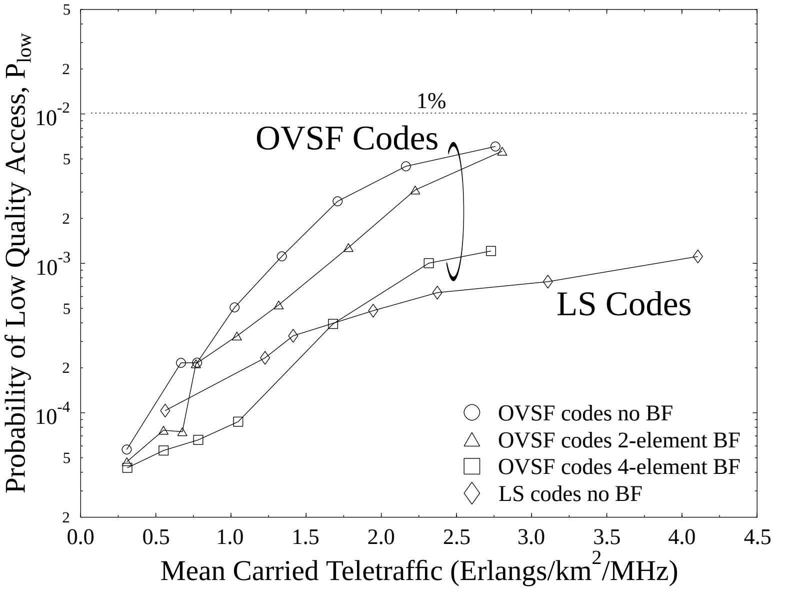


Figure 7.17: Probability of low quality access versus number of users of the UTRA-like TDD cellular network using **LS codes and OVSF codes** both with as well as without beamforming in conjunction with shadowing having a frequency of 0.5 and a standard deviation of 3dB for a spreading factor of SF=16.

the figure at a given load. Specifically, the network capacity was limited to 50 users, or to a teletraffic density of approximately 0.55 Erlangs/km^2/MHz. With the advent of employing 4-element adaptive antenna arrays at the base stations the number of users supported by the TDD system increased to 178 users, or a teletraffic density of 2.03 Erlangs/km^2/MHz. However, in conjunction with LS codes, and even without employing antenna arrays at the base stations, the TDD system was capable of supporting 306 users, or an equivalent traffic density of 3.45 Erlangs/km^2/MHz.

Figure 7.17 portrays the probability of low quality access versus various traffic loads. In conjunction with OVSF codes, it can be seen from the figure that without beamforming the system suffered from encountering more multiuser interference, as the traffic loads increased. Hence the probability of low quality access became higher. When invoking beamforming, both the intra- and inter-cell interference was reduced and hence the probability of low quality access was reduced as well. As a benefit of employing LS codes, the intra-cell interference was efficiently reduced and therefore the probability of low quality access was found to be lower even without beamforming, than that of the system using OVSF codes and employing 2-element beamforming. We also observed that at lower traffic loads the probability of low quality access for the “LS codes no BF” scheme is higher than that of “OVSF codes 4-element BF” scheme. This is a consequence of the associated high probability of forced termination for the “LS codes no BF” scheme, as shown in Figure 7.16, because the higher the probability of forced termination, the lower the number of users supported by the TDD

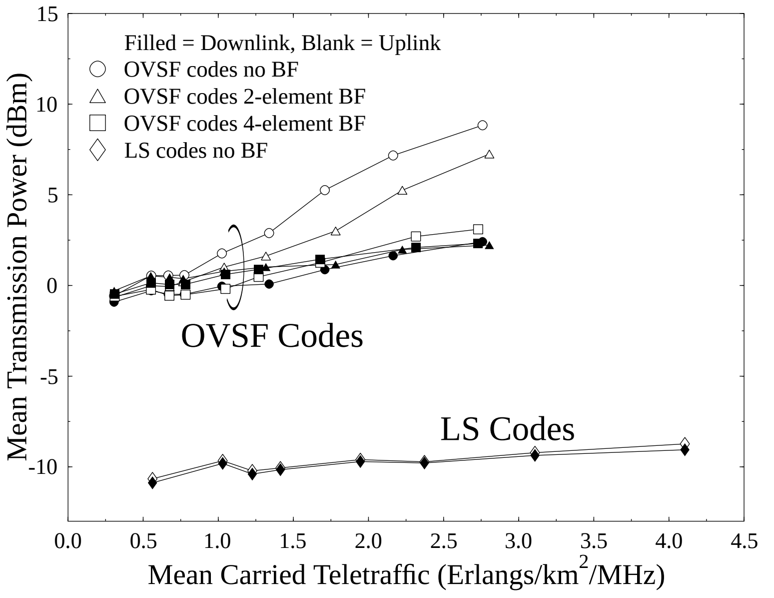


Figure 7.18: Mean transmission power versus number of users of the UTRA-like TDD cellular network using **LS codes and OVSF codes** both with as well as without beamforming in conjunction with shadowing having a frequency of 0.5 Hz and a standard deviation of 3dB for a spreading factor of SF=16.

system and hence the effects of co-channel interference imposed by the existing connections remain more benign when a new call starts.

Spreading Code	Beamforming	Users	Traffic (Erlangs /km^2/MHz)	Power (dBm) MS	Power (dBm) BS
OVSF codes	No	50	0.55	0.54	-0.28
OVSF codes	2-elements	113	1.18	1.33	0.90
OVSF codes	4-elements	178	2.03	2.07	1.81
LS codes	No	306	3.45	-9.11	-9.21

Table 7.4: Maximum mean carried traffic and maximum number of mobile users that can be supported by the network, whilst meeting the network quality constraints of Section 7.6.3, namely $P_B \leq 3\%$, $P_{FT} \leq 1\%$, $P_{low} \leq 1\%$ and GOS $\leq 4\%$. The carried traffic is expressed in terms of normalized Erlangs (Erlang/km^2/MHz) using **OVSF codes and LS codes** in conjunction with shadow fading having a standard deviation of 3 dB and a frequency of 0.5 Hz for a spreading factor of SF=16.

For the sake of characterizing the achievable system performance also from a different perspective, the mean transmission power versus teletraffic performance is depicted in Figure 7.18. Again, as a benefit of employing LS codes, both the required mean uplink and downlink transmission power are lower than that necessitated by OVSF codes. The TDD system using OVSF codes required an average 10 dBm to 20 dBm more signal power compared to the TDD system using LS codes. In [460] it was shown that the major source of interference is constituted by the BS-to-BS interference as a consequence of the BS's high signal power and the near-LOS propagation conditions prevailing between BSs. Even though the employment of LS codes can only reduce the intra-cell interference, it results in a substantial reduction of the BSs' power consumption, as shown in Figure 7.18. Hence the source of $BS \rightarrow BS$ inter-cell interference was also reduced. In other words, the employment of LS codes indirectly reduced the severe $BS \rightarrow BS$ inter-cell interference by keeping the BSs' transmission power at a low level.

Figure 7.19 shows the achievable Grade-Of-Service for a range of teletraffic loads. We observe similar trends regarding the probability of low quality access, as shown in Figure 7.17. In Equation 4.15, the GOS performance is jointly determined by P_B and P_{low}, which is interpreted as the probability of unsuccessful network access (blocking), or the probability of encountering a low quality, provided that a call is admitted to the system. The employment of the LS codes may cause the shortage of spreading codes and hence may lead to the blocking of a new call, since there are only 8 LS codes that can be used, when the IFW duration is ± 1 chip-length. The call duration and inter-call periods were Poisson distributed having the mean values shown in Table 7.3. When encountering this call arrival distribution, we observe that the new call blocking probability is negligible, as shown in Figures 7.17 and 7.19.

A summary of the maximum user capacities of the UTRA-like TDD/CDMA system using OVSF codes and LS codes in conjunction with log-normal shadowing having a standard deviation of 3dB and a shadowing frequency of 0.5 Hz as well as both with and without beamforming is given in Table 7.4. The teletraffic carried and the mean mobile and base station transmission powers required are also shown in Table 7.4.

7.6.5 Summary and Conclusions

In this section we studied the network performance of a UTRA-like TDD/CDMA system employing LS spreading codes. The computer simulation results provided showed that the TDD system invoking LS codes had a better performance compared to the system using OVSF codes. We designed a 49-cell "wrapped around" simulation area, constituted by sufficiently small 78 m radius cells, which guaranteed that the delayed asynchronous transmissions arrive within the IFW, where the auto-correlation and cross-correlation values of the LS codes became zero and hence eliminated the effects of intra-cell interference. The SINR required by the LS codes for the sake of maintaining a BER of 1×10^{-3} was almost 2 dB lower than that necessitated by the OVSF codes. Furthermore, a low mobile and base station transmission power has been maintained. Hence the average intra- and inter-cell interference level has become low, the severe $BS \rightarrow BS$ interference has been reduced and this resulted in TDD system performance improvements both in terms of the achievable call quality and the number of users supported. Our future research is focussed on further improving the performance of TDD systems using genetic algorithm based timeslot scheduling.

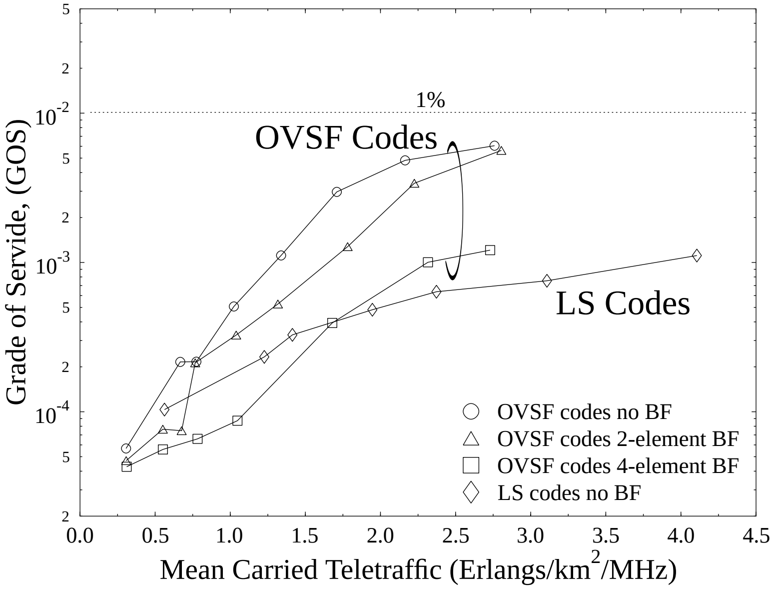


Figure 7.19: Grade-Of-Service (GOS) versus number of users of the UTRA-like TDD cellular network using **LS codes and OVSF codes** both with as well as without beamforming in conjunction with shadowing having a frequency of 0.5 Hz and a standard deviation of 3dB for a spreading factor of SF=16.

Glossary

AWGN	Additive White Gaussian Noise
BS	A common abbreviation for Base Station
CDMA	Code Division Multiple Access
CMA	Constant Modulus Algorithm
DCS1800	A digital mobile radio system standard, based on GSM, but operates at 1.8GHz at a lower power.
DOA	Direction Of Arrival
FDD	Frequency Division Duplex
GSM	A Pan-European digital mobile radio standard, operating at 900MHz.
HIPERLAN	High Performance Radio Local Area Network
IF	Intermediate Frequency
LMS	Least Mean Square, a stochastic gradient algorithm used in adapting coefficients of a system
MS	A common abbreviation for Mobile Station
MSE	Mean Square Error, a criterion used to optimised the coefficients of a system such that the noise contained in the received signal is minimised.
PDF	Probability Density Function
RF	Radio Frequency
RLS	Recursive Least Square
SDMA	Spatial Division Multiple Access
SINR	Signal to Interference plus Noise ratio, same as signal to noise ratio (SNR) when there is no interference.
SIR	Signal to Interference ratio
SNR	Signal to Noise Ratio, noise energy compared to the signal energy
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunication System

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