Research into the Impact of Dead Zones on the Performance of 3G Cellular Networks

Final Report

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Executive Summary

Research into the Impact of Dead Zones on the Performance of 3G Cellular Networks

Final Report

The UK Radiocommunications Agency (RA) commissioned Multiple Access Communications (MAC) Ltd to investigate the impact of dead zones on the performance of the frequency division duplex (FDD) mode of universal mobile telecommunications system (UMTS) terrestrial radio access (UTRA) cellular networks. These dead zones are characterised by poor signal quality and hence an increase in the probability of call blocking and call dropping. For downlink transmissions the mobiles that are in the vicinity of another network’s base stations (BSs) may experience sufficient adjacent channel interference from these BS transmissions that the mobiles are prevented from communicating to their serving BSs. The situation is more complex for uplink transmissions. In this case mobiles in one 3G network may generate sufficient adjacent channel interference at the BS receivers in another 3G network that the noise floor of these BS receivers may increase resulting in the mobiles in the boundary areas of their cells suffering an increase in the call blocking and dropping probabilities. Unlike GSM networks, where an operator has many RF carriers and can, to a large extent, overcome adjacent network interference by judicial spatial assignment of BS carriers, UTRA FDD network operators have only two or three carriers at their disposal. This means that dead zones are inevitable, and the strategy is how to minimise them. The RA is particularly interested in quantifying the dead zone problem and identifying what measures should be introduced to lessen their impact. Consequently, the objectives of this study are to

- ‘investigate and quantify the impact of the dead zone problem on the performance of 3G cellular networks’; and
- ‘suggest remedies to the problem and quantify the cost, application and benefit of these remedies’.

This report presents our findings from this study. Before summarising the results and conclusions of the study, let us describe the dead zone problem in more detail. As we outlined above, dead zones are caused by adjacent channel interference (ACI) between uncoordinated
UTRA FDD networks operating on adjacent RF carriers. ACI occurs because of adjacent channel leakage in the mobile, known as user equipment (UE) in 3G terminology, and BS transmitters. This leakage generates signals in the adjacent band. Also ACI occurs because of imperfect rejection of adjacent channel power by the UE and BS receivers, which results in power in the adjacent band appearing as noise to the wanted signal. A dead zone occurs when a victim UE moves to a location where the downlink signal from its serving BS is weak compared to the adjacent channel signal power received from a nearby BS of another 3G network. In a dead zone a UE will experience a reduced energy per traffic channel bit to interference power spectral density ratio ($E_b/I_0$) and may therefore suffer call blocking or dropping. The size and severity of these dead zones will depend upon the data rate and type of service being used, as these will affect the signal-to-interference ratio (SIR) requirements. On the uplink, the presence of another UE communicating with its serving cell on an adjacent channel will cause a noise rise for the receiver of the victim BS. This may not cause a dead zone as such, but may result in a reduction in the size and capacity of the victim cell.

Our initial analysis was based on link budgets that allowed us to examine the mechanisms involved in the creation of dead zones. Four individual links were considered, namely the uplink and downlink for a victim network, and the uplink and downlink for an adjacent channel (or interfering) network. A critical parameter for the adjacent channel interference analysis is the adjacent channel protection (ACP) of each link, which is derived from the adjacent channel leakage ratio (ACLR) of the transmitter and the adjacent channel selectivity (ACS) of the receiver. Minimum required values of ACLR and ACS are defined in the UTRA FDD specifications, and result in an ACP of 33 dB for both the uplink and downlink.

Initially we used an ACP value of 33 dB for the link budgets. However, to quantify the number and size of dead zones occurring in operational 3G networks we also needed to use an ACP value that is more typical of the UTRA FDD BS and UE transceivers that are currently being manufactured, or are likely to be deployed in the years ahead. This ACP value will be higher than the specified minimum of 33 dB. In order to estimate this ACP value, we researched the typical ACLR and ACS performance of 3G equipment by contacting 3G equipment manufacturers and network operators, by conducting a literature search and by making measurements of our own. It was concluded that a reasonable typical value for ACP is 43 dB for both the uplink and downlink.
The link budgets were adjusted to model some specific scenarios that are likely to give rise to dead zones. The three scenarios considered are listed below.

1. A motorway or fast train scenario, for which we used a linear model having adjacent channel sites interleaved with those of the victim network. The sizes of dead zones for fast- and slow-moving users were examined.

2. A rural scenario, for which we used the COST231 quasi-open-rural pathloss model, with a typical cell radius of 5.6 km.

3. An urban scenario, for which we modelled high user densities by increasing the uplink interference margin from 3 dB to 6 dB. This increased the cell loading from approximately 50% to 75%. The lower site-to-site separations in urban locations were modelled by reducing the typical cell size to just 300 metres. As clutter-based pathloss prediction models are not valid over small distances, the free space propagation model was used for the urban link budget analysis. We acknowledged that using such a model was likely to cause inaccuracies in the link budget results.

For the motorway or fast train scenario, we showed that under worst-case ACI conditions for a UE using a speech service, dead zones with radii of 0.39 km and 0.09 km occurred on the downlink, for macrocells and microcells, respectively. These results were based on an ACP value of 33 dB. The worst-case time spent in a dead zone was 59 seconds based on the downlink results. This time was reduced to 33 seconds if we assumed an ACP value of 43 dB. For the uplink, as the victim and the interfering UEs were moving, the dead zones fluctuated in size depending on the relative positions of the UE. This means that the impact of ACI on the uplink is insignificant compared to the downlink.

For the rural scenario, we showed that the worst-case size of a dead zone on the downlink was 650 m for an ACP value of 33 dB. The size of this dead zone reduced to a radius of 330 m if the ACP value was increased by 10 dB. Compared to the cell radius, this dead zone size is relatively small. In line with the motorway scenario, we concluded for the rural scenario that the uplink should present less of a problem in terms of ACI compared to the downlink. The urban link budget results indicated that dead zones were not likely to occur. However, these results were masked by the inaccuracy of using the free space propagation model in urban areas for the link budget analysis.
For the rural and urban scenarios, simulations were performed to establish the likelihood and severity of dead zones that may occur in practice. The simulations were run using MAC Ltd’s MACcdma Monte Carlo CDMA network simulator. MACcdma places UEs in the network, one by one, at random locations until the user-specified offered traffic density level is reached. A snapshot of the network is taken and the process is repeated many times. The performance of the network is evaluated by averaging over many simulation snapshots. A mix of services consisting of 80% speech and 20% data was simulated.

For the rural scenario, the victim network consisted of a hexagonal tessellation of three-sectored sites. Three adjacent channel interfering networks were created. The first of these adjacent channel networks was appropriately named ‘co-sited’, and had all of its sites collocated with the victim network sites. The other two adjacent networks were shifted replicas of the victim network. The first of the two shifted adjacent channel networks were positioned in the worst-case locations from an interfering potential standpoint, ie, at locations equidistant from the nearest three victim sites. This network was named ‘offset 2’. The other shifted network had sites positioned halfway between the collocated positions and the worst-case positions. This network was called ‘offset 1’.

The COST231 quasi-open-rural propagation model was used to predict the coverage from the victim and adjacent network sites. These predictions were imported into MACcdma. MACcdma generated a number of interesting results for the rural scenario. The most important results are shown in Figure A.

The y-axis is the number of effective speech calls served by the network. This metric provides us with an indication of the overall capacity of the network. The thick brown bar represents the capacity of the victim network without ACI. Note that the middle of the brown bar is the mean of 10 simulations and the thickness is equal to twice the standard deviation. This is done to illustrate the statistical variability of the results. The pink, blue and dark blue curves provide the results for the network with ACI generated by the co-sited, offset 1 and offset 2 adjacent channel networks, respectively. Each data point that makes up these curves is the result of one simulation, rather than the mean of several simulations. We would expect the variability of these results to be similar to the ‘no ACI’ case, although, it is not possible to put error bars on the pink, blue or dark blue curve because each data point is a sample of a distribution rather than a mean. As one would expect, the co-sited adjacent channel network has no impact on the capacity of the victim network, ie, the pink curve is similar to the brown
bar. The offset 2 adjacent channel network has the most impact in terms of generating ACI to decrease the capacity of the victim network. Recall that these sites are located in the worst-case positions. It would be extremely unlikely for all sites of an adjacent channel network to be positioned in the worst places. If we examine the offset 1 curve in Figure A, then for an ACP value of 33 dB, the capacity of the victim network is 99.4% of the capacity with no ACI. This capacity degradation is negligible.

![Overall network performance for the offset 1, offset 2 and co-sited rural network configurations.](image)

Note that the relative positions of two real 3G networks (with adjacent channels) are likely to be random, apart from some that will be collocated. Out of the random relative positions, only a small proportion are likely to be in positions to cause dead zones.

For the urban scenario, we simulated more realistic victim and adjacent channel networks with sites essentially randomly located, provided that certain minimum site separation rules were not broken. Note that 14% of macrocell sites were collocated with adjacent channel network sites. The site densities were also chosen carefully along with a number of important MAC\textit{cdma} input parameters. Accurate urban predictions were generated using MAC Ltd’s proprietary urban network planning tool, the NP WorkPlace. The overall network capacity results are presented in Figure B.
The capacity of the network without ACI is denoted by the brown rectangular bar. The middle of the line is equal to the mean of 12 simulations and the thickness is equal to twice the standard deviation of the number of served calls. These results are represented in this way to highlight the variability of the results. Recall that a similar brown bar or region was created for the rural simulation results. The dark blue curve provides the results for the network with ACI included for various ACP values. It is not possible to put error bars on the dark blue curve because each data point is the result of one simulation rather than a mean of several simulations. Bearing the statistical significance of the results in mind, the main conclusion is that the overall capacity of the urban network in the presence of ACI was similar to the capacity without ACI for the UTRA FDD specification value of ACP (33dB). This is an important result, particularly as the urban network we simulated closely matches the expected characteristics of a real 3G network. Also the urban propagation models employed were accurate and the complex dynamics of a CDMA system were characterised by a suitable statistical model. As a consequence, we can have a high level of confidence in the conclusions made from the results produced by this approach.

**Figure B** Total effective number of speech calls served by the urban network with and without ACI.
Although we have shown that ACI should not significantly affect the overall performance of a 3G network, dead zones still occur in certain locations of the network. We demonstrated this by only evaluating network performance statistics for the victim network within 50 m of the adjacent channel network sites. Indeed, our simulation results highlighted that interfering microcells were worse contributors to ACI than macrocells. This is mainly due to the low minimum coupling losses\(^1\) normally associated with microcells. However, the overall network performance is hardly affected in reality because only a small proportion of these adjacent channel sites are likely to be near the edge of cells in the victim network. A problem arises when a dead zone occurs in a location that is of particular importance to a network operator. A solution to the problem is to use a mitigation technique to reduce the effects of ACI. On this note, the results of MAC\textit{cdma} simulations showed that increasing the minimum coupling loss dramatically decreased the effects of ACI produced within the vicinity of adjacent channel microcell sites. If a minimum coupling loss of 70 dB can be achieved, then the effects of ACI produced by microcells, in particular, can be decreased significantly. A few methods of increasing the minimum coupling loss were suggested. For instance, a low vertical beamwidth panel antenna could be used instead of the patch antennas normally installed for microcells. This is not the most feasible of ACI mitigation techniques, given the impracticalities of using large macrocell antennas at microcell sites. However, we certainly demonstrated the technical effectiveness of increasing the minimum coupling loss for microcells.

An entire section of the report was devoted to investigating mitigation techniques. The techniques examined were grouped by category, as follows, where each category is highlighted in bold.

**Category 1: Reduce ACI**

- Improved Hardware Design
- Operator Cooperation
- BS Desensitisation
- Increased Minimum Coupling Loss
- Repeating Adjacent Channel Signals

\(^1\) The minimum coupling loss is the minimum path loss between a BS antenna and nearby UEs.
Category 2: Increase signal-to-interference ratio of wanted signal

- Interference Cancellation
- Smart Antennas (BS and UE)
- Increased Site Density
- Placing Sites in Traffic Hotspots

Category 3: Avoid situations where high ACI is experienced

- Call Admission Control
- Bit Rate Relegation
- Hard Handover
- Inter-Operator Roaming

It is worth noting that the techniques that fall under Category 2 are not specific to mitigation of ACI. These techniques can be viewed as ways of improving network capacity in general rather than being methods specific to overcoming ACI. It is unlikely that an operator is going to implement a capacity-enhancing solution to apply it to mitigating ACI. Instead an operator is more likely to apply such a technique to improve the capacity of its own network.

All of the techniques listed above were investigated. Each of the mitigation techniques was scored in terms of feasibility, effectiveness, degree of operator cooperation, and also classified as an ‘own network benefit’ or an ‘other network benefit’. As mentioned above, the ‘increased minimum coupling loss’ technique is an effective solution, although it may not be the most feasible of solutions. It is interesting to note that the other techniques that scored well in terms of effectiveness also require operator cooperation. These techniques include the use of repeaters, inter-operator roaming and the collocation of sites.

Given that one of the main conclusions of this report was that ACI has a negligible effect on overall network performance, less is required of mitigation techniques. In other words, instead of using mitigation techniques to provide widespread network improvements, they will be used to improve certain areas where dead zones are of particular concern.

In conclusion, we showed that the impact of the dead zone problem on the overall performance of 3G cellular networks is negligible. We also demonstrated that dead zones could occur under certain conditions, eg, near an adjacent channel microcell BS located at the
edge of a serving network cell. We also summarised remedies to the problem in these areas, mostly by using ACI mitigation techniques that will require a high level of operator cooperation.

Prepared by Multiple Access Communications Ltd
January 2004
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List of Abbreviations

2G  Second Generation
3G  Third Generation
3GPP Third Generation Partnership Project
ACI  Adjacent Channel Interference
ACIR  Adjacent Channel Interference Ratio
ACLR  Adjacent Channel Leakage Ratio
ACP  Adjacent Channel Protection
ACPL  Adjacent Channel Power Leakage
ACS  Adjacent Channel Selectivity
AWGN  Additive White Gaussian Noise
BER  Bit Error Rate
BS  Base Station
CAC  Call Admission Control
CDF  Cumulative Distribution Function
CDMA  Code Division Multiple Access
CPICH  Common Pilot Channel
DPCCH  Dedicated Physical Control Channel
$E_b/I_0$  Energy per Traffic Channel Bit to Interference Power Spectral Density Ratio
EGPRS  Enhanced General Packet Radio Service
EIRP  Effective Isotropic Radiated Power
ETSI  European Telecommunications Standards Institute
FBI  Feedback Indication
FDD  Frequency Division Duplex
GPRS  General Packet Radio Service
GPS  Global Positioning System
GSM  Global System for Mobile Communications
IF    Intermediate Frequency
IP3   Third Order Intercept Point
IRC   Interference Rejection Combining
ITT   Invitation to Tender
LNA   Low Noise Amplifier
LOS   Line-of-sight
MAC Ltd  Multiple Access Communications Limited
MCL   Minimum Coupling Loss
MIMO  Multiple Input Multiple Output
MISO  Multiple Input Single Output
MMSE  Minimum Mean Square Error
MRC   Maximal Ratio Combining
PDF   Probability Distribution Function
PSD   Power Spectral Density
QoS   Quality of Service
RA    Radiocommunications Agency
RF    Radio Frequency
RRC   Root Raised Cosine
RSSI  Received Signal Strength Indicator
RTCG  Radio Technology and Compatibility Group
SHO   Soft Handover
SIMO  Single Input Multiple Output
SINR  Signal-to-Interference-plus-Noise-Ratio
SIR   Signal-to-Interference-Ratio
SMG2  Special Mobile Group 2
SNR   Signal-to-Noise -Ratio
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>STTD</td>
<td>Space-Time Block Coding-Assisted Transmit Diversity</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TSUNAMI</td>
<td>Technology in Smart antennas for UNiversal Advanced Mobile Infrastructure</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
</tr>
<tr>
<td>UTRA</td>
<td>UMTS Terrestrial Radio Access</td>
</tr>
<tr>
<td>WCDMA</td>
<td>Wideband Code Division Multiple Access</td>
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1 Introduction

Since the UK Government auctioned five licences for Third Generation (3G) mobile telecommunications spectrum in April 2000 the five successful operators, O2, Vodafone, Orange, T-Mobile and Hutchison 3G, have begun the process of building out their networks. One of these operators, Hutchison 3G, has already launched its network and the other four operators intend to start marketing service on their 3G networks soon. Recently some of the operators have approached the Radiocommunications Agency (RA) with concerns about building and operating 3G networks. One particular concern is the potentially high level of adjacent channel interference (ACI) that can arise when adjacent radio frequency (RF) carriers are used by competing operators in the same location. The RA has commissioned Multiple Access Communications (MAC) Ltd to investigate whether ACI is a significant problem, and whether there are any techniques that can be used to lessen its effect.

All five operators intend to use the code division multiple access (CDMA)-based technology known as the universal mobile telecommunications system (UMTS). Each of the five operators received paired 3G spectrum allocations and most also have some unpaired spectrum allocated to them. Initially they will deploy systems based on the UMTS terrestrial radio access (UTRA) frequency division duplex (FDD) radio interface in their paired spectrum allocations. Some of the operators may also choose to deploy systems based on the time division duplex (TDD) version of the UTRA standard in their unpaired spectrum allocations at some time in the future.

Adjacent channel power leakage (ACPL) and spurious emissions generated by base stations (BSs) and user equipment (UE) operating on one channel will cause interference to receiver equipment operating on an adjacent channel. Interference will also be experienced due to the adjacent channel selectivity (ACS) of the BSs and the UE. ACS defines a receiver’s ability to reject power in an adjacent channel. This interference can lead to degraded performance for systems operating on adjacent channels [1]. For example, when a 3G UE is far from its serving BS, the downlink signal received by the UE is weak. Strong adjacent channel emissions from a nearby BS may cause the signal-to-interference ratio (SIR) at the 3G UE to be too low, meaning that the UE can no longer communicate with its serving BS. Likewise, when the UE is far from its serving BS its uplink transmit power needs to be high. If the UE is close to a BS of another network that is using an adjacent channel, that BS may experience
excessive interference from the UE, reducing the BS’s capacity. This phenomenon is an example of the near-far problem and the resulting areas of poor coverage are often called dead zones.

UTRA FDD requires approximately 5 MHz for each channel and there is only sufficient spectrum for each operator to use two or three channels, depending on whether they have a licence for 2×10 MHz or 2×15 MHz of spectrum, respectively. In GSM networks the near-far problem is overcome by employing 200 kHz (ie, one GSM carrier) guard bands at either end of an operator’s spectrum. Guard bands of this size will be much less effective in UTRA FDD systems because of the much wider channel bandwidth. It is not feasible to use wider guard bands of, say, 5 MHz since this will require operators to sacrifice one channel out of the two or three that they have been allocated. The effect of ACI is to raise the background noise floor. This reduces the capacity and coverage of a UTRA FDD cell site resulting in increased expense to the operators who would need to deploy more sites to offset the diminished coverage and capacity. Depending on the size of the dead zones and the resulting drop in service quality, alternative techniques may need to be used to reduce the size of the dead zones and the amount of ACI.

UTRA FDD networks will also experience intra-network ACI, ie, interference from adjacent channels used within the same network, but this is not expected to be a problem because, in general, the UE can hand over to a new site before the level of ACI becomes too high. It is expected that soft handovers would be used most of the time. When these fail to overcome the ACI, the UE can make a hard handover to the new carrier. In this report we will assume that intra-operator ACI is negligible and can be overcome easily; thus we will not consider this phenomenon.

Following MAC Ltd’s formal response [2] to the RA’s Invitation to Tender (ITT), Reference Number AY4571, MAC Ltd was commissioned to

- ‘investigate and quantify the impact of the dead zone problem on the performance of 3G cellular networks’; and
- ‘suggest remedies to the problem and quantify the cost, application and benefit of these remedies’.
In this report we present the work performed by MAC Ltd in fulfilling these tasks. We begin in Section 2 with a description of the dead zone problem and mechanisms involved in its occurrence, before going on to describe our endeavours to quantify the adjacent channel protection (ACP) of real 3G UEs and BSs. To help identify scenarios in which dead zones may occur, we have created link budgets that model the effect of ACI. These link budgets are used to investigate three different scenarios, which are described in Section 3. Two of these scenarios have been simulated using MAC Ltd’s 3G simulation tool, called MAC\textit{cdma}. The simulation results are described in Section 4. One of the main aims of this work is to identify and assess some techniques that could potentially reduce the effect of ACI and reduce the size of dead zones. This is the subject of Section 5. Finally, the conclusions of this project are presented in Section 6.

2 The Dead Zone Problem

For the purposes of this report a dead zone is defined as an area where a UE experiences an unacceptably low energy per traffic channel bit to interference spectral density ratio ($E_b/I_0$) on the downlink due to the presence of a BS of another, uncoordinated, network that is transmitting on an adjacent RF channel. Figure 1 illustrates how a dead zone may occur. A UE is simultaneously near to the cell boundary of its serving cell and close to a BS of another network that is using an adjacent channel. The signal received by the UE on its assigned channel will be weak because it is near to the boundary of its own cell. However, the signal from the neighbouring network will be received at relatively high power, even though it is on an adjacent channel. This will cause a reduction in the $E_b/I_0$ on the downlink. Hence, a UE close to another operator’s BS will experience higher rates of call blocking and call dropping. If the degradation in $E_b/I_0$ is large enough, the UE can no longer communicate with its serving BS and it is said to be in a dead zone.
The presence of the UE will also have an adverse effect on the BS in the neighbouring network, causing a noise rise on its uplink. Rather than creating a dead zone in the coverage of the other operator’s BS, the uplink noise rise will reduce the capacity and size of the neighbouring cell. It can be seen that the UE of the victim network will experience a relatively well-defined area of poor service, which will be static but will perhaps grow or shrink depending on the loading and power allocation in the victim cell. However, base stations in the neighbouring network will experience interference levels that change as the adjacent channel UE moves around.

Dead zones can occur in macrocellular, microcellular and combined macro/microcellular environments, although we might expect variations in terrain and urban morphology to influence their size and location. Our simulations will aim to uncover scenarios that are more likely to give rise to dead zones.

The size and severity of the dead zones will depend upon the network configuration and upon the service being used. For example, a high rate data service will most likely require a higher signal-to-interference ratio than a voice service to maintain a usable link, so the dead zone will appear smaller for the voice service. The type of call admission control (CAC) algorithm employed will also influence the size of the dead zone, as link quality thresholds can be used in different ways to decide when new calls can be accepted.
2.1 Adjacent Channel Interference

The ACI that causes dead zones to occur arises from imperfections in the BS and UE radio transceivers. These imperfections cause out-of-band emissions from the transmitters and imperfect rejection in the receivers. The imperfections arise mainly through non-linearities in the analogue components, in particular in the transmitter’s power amplifier and the receiver’s front-end low noise amplifier (LNA) and mixer. The finite adjacent channel attenuation of the transmit and receive filters also contributes to this effect.

To illustrate the mechanisms by which ACI occurs, Figure 2 shows the power spectrum of a wanted signal in the presence of an adjacent channel signal at a higher received power. The most significant mechanism is adjacent channel leakage in the transmitter, arising from third-order intermodulation products generated by non-linearities in the power amplifier (see point a. in Figure 2).

The non-constant envelope of the wideband code division multiple access (WCDMA) modulation scheme makes amplifier linearity particularly critical. Indeed, the performance of some amplifiers is now specified in terms of adjacent channel leakage using a WCDMA signal (see Reference [3], for example), rather than the more conventional third-order intercept point (IP3). The level of ACI generated may be reduced somewhat by decreasing (or ‘backing off’) the transmit power, although this has power efficiency implications for UE transmitters in particular. It has been shown that a 1 dB reduction in transmit power can result in a 3-4 dB reduction in ACI [4].
The non-linearity of the receiver front end will also add interference, as third-order products resulting from the adjacent channel will arise within the frequency band of the wanted signal (see point b. in Figure 2). No attenuation of the adjacent channel signal before it arrives at the receiver LNA and downconverter can be expected, as it is likely that the passband of the front-end filter will encompass the entire UMTS band, rather than being tuned to the band of a particular operator. Rejection of the adjacent channel itself will be performed by the receiver intermediate frequency (IF) filter, which will attenuate the unwanted signal by a finite amount. Some adjacent channel power will be admitted, which, although it will not be in the wanted signal band, will still cause interference in the de-spreading process of the wanted channel (see point c. in Figure 2).

It should be further noted that the power spectral density (PSD) of the transmitted signal will vary with the type of traffic signal, choice of channelisation codes and number of physical channels included in the transmitted multiplex, as these will all vary the peak-to-average power ratio.

2.2 Adjacent Channel Protection

In order to mitigate against the effects of ACI, the UTRA FDD specifications [5, 6] define the minimum required adjacent channel performance for BS and UE transceivers, in terms of the adjacent channel leakage ratio (ACLR) for the transmitter and the adjacent channel selectivity (ACS) for the receiver. ACLR and ACS are defined as follows.

- The ACLR of a transmitter is the ratio of the average transmitted power in the assigned channel to that in an adjacent channel, in both cases as measured through a root raised cosine (RRC) filter with a bandwidth of 3.84 MHz and a roll-off of $\alpha = 0.22$.

- The ACS of a receiver is the ratio of the receiver attenuation in the assigned channel to that in the adjacent channel\(^2\).

\(^2\) This definition of ACS was taken from the UTRA FDD specifications. Note that this definition produces negative values. The correct definition should have the assigned and adjacent channels swapped over.
The specified minimum performance values are set out in Table 1 for the first and second adjacent channels, ie, at frequency offsets of ±5 MHz and ±10 MHz, respectively.

<table>
<thead>
<tr>
<th>First Adjacent Channel</th>
<th>Second Adjacent Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS</td>
<td>UE</td>
</tr>
<tr>
<td>ACLR</td>
<td>45 dB</td>
</tr>
<tr>
<td>ACS</td>
<td>45 dB</td>
</tr>
</tbody>
</table>

Table 1  UTRA FDD specified minimum values for ACLR and ACS.

The ACS for the BS receiver is not explicitly stated in Reference [6], but may be derived from the test conditions defined. For a 12.2 kbps speech service, the bit error rate (BER) should not exceed 0.001 with a wanted signal level of −115 dBm in the presence of an adjacent channel interferer at a frequency offset of 5 MHz and a signal level of −52 dBm. Additionally, the BS reference sensitivity requirement states that a wanted signal of -121 dBm shall be received with a BER not exceeding 0.001 with no interferer present. Therefore, the adjacent channel interferer can introduce a noise rise of up to −115 dBm - (-121 dBm) = 6 dB. The total noise and interference power, assuming a receiver noise figure of 5 dB, is

\[ -174 \text{ dBm/Hz} + 10 \log(3.84 \times 10^6) \text{ dB} + 5 \text{ dB} + 6 \text{ dB} = -97 \text{ dBm}, \]

giving an adjacent channel selectivity of −52 dBm − (−97 dBm) = 45 dB.

The ACLR and ACS for a transmitter and receiver pair can be combined in linear terms to provide a measure of total adjacent channel protection for the link, using the following equation,

\[ ACP = \frac{1}{1 + \frac{1}{ACLR} + \frac{1}{ACS}}. \]  \hspace{1cm} (1)

Using Equation 1 and the values from Table 1, we can derive a first adjacent channel ACP value of approximately 33 dB for the downlink and the uplink. The receiver ACS is not specified for the second adjacent channel, so we are unable to define an ACP value in this case. For the purposes of this study, we will generally not consider the interference from channels at frequency offsets of more than ±5 MHz, as their effects will not be significant
compared to that of the first adjacent channel. It can be seen that the ACP value of the downlink and the uplink is dominated by the performance of the UE transceiver. We would expect the performance of the BS transceiver to be better than the performance of a miniaturised UE transceiver, and the specifications reflect this. Real BS and UE transceivers would be expected to outperform these specified minimum values by a margin that may be considerable, although over time, manufacturers may allow the ACLR and ACS performance of their products to deteriorate to reduce manufacturing costs.

2.2.1 Adjacent Channel Protection of Real 3G Equipment

As part of this analysis we sought to establish the ACLR and ACS performance of typical 3G BS and UE transceivers, as these values will be key to how we interpret the results of our simulations. We have used several different approaches to establish these values, namely, contacting 3G network operators and equipment manufacturers, conducting a literature search, and making handset measurements. Our aim was to acquire as much information as possible from different sources to identify suitably realistic ACP values.

2.2.1.1 Equipment Manufacturers and Network Operators

A survey of the major 3G equipment manufacturers and network operators was conducted to determine whether they were willing to share information about the equipment that they manufacture or use in their networks. Of the equipment manufacturers, we contacted Nokia, Siemens, Motorola, Nortel Networks and Alcatel. Of the network operators, we contacted Hutchison 3G, Vodafone, O2, Orange and Telefonica.

The majority of the organisations that responded to our request for information confirmed that their 3G equipment (both UEs and BSs) outperforms the UTRA ACLR and ACS specifications by a reasonable margin [7, 8, 9]. However, all were unable, or unwilling for commercial reasons³, to expand upon the actual ACLR and ACS performance beyond what was already available in the public domain. A number of the respondents, in particular Motorola [8], had performed their own simulations of ACI and had concluded that the current

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³ Note that at the time of writing, discussions were on-going with Vodafone.
minimum ACLR and ACS values are sufficiently high to prevent ACI being a significant limitation to system performance.

2.2.1.2 Literature Search

The literature search was aimed not only at establishing the performance of typical 3G equipment, but also to search for additional information about ACI, dead zones, minimum coupling loss⁴ and potential ACI mitigation techniques.

Before the UTRA FDD standards were finalised, Hämäläinen et al [4] conducted some simulations to establish the minimum ACP requirements for acceptable performance. They concluded that a minimum ACP value of 30 dB would be sufficient for use in a hierarchical cellular network. Furthermore, they suggested that the uplink could tolerate a lower ACP value than the downlink. A great deal of research and simulation work was undertaken before the UTRA FDD standard was finalised. The work of the ETSI Special Mobile Group 2 (SMG2) and latterly the 3GPP Technical Specification Group, Radio Access Networks Working Group 4 (TSG-RAN4) is particularly relevant to this study. Contributions to these groups came from a wide range of industry researchers. Motorola [10], Ericsson [11, 12], Nokia [13] and Telia AB [14] all contributed simulation results to the SMG2 committee. The general conclusion drawn from these contributions was that a minimum ACP value of around 30 dB would be sufficient to minimise the system capacity reduction due to ACI (limited to 5% or less). Furthermore, it was shown that ACI affected the downlink capacity to a lesser extent than the uplink capacity, but since the current feeling is that 3G systems are likely to be downlink capacity limited, it could be argued that a greater loss due to ACI on the uplink is acceptable, so the minimum ACP should be set based on the downlink performance.

These results were submitted before the IMT-2000 harmonisation exercise had been completed in 1999, so the simulations all assumed a chip rate of 4.096 Mcps. A later study [15] examined the effect of the change to 3.84 Mcps and concluded that this would have a minimal effect on ACP requirements. It was shown that the requirements could be relaxed slightly if the nominal channel spacing was retained at 5 MHz. Following this, Faure and Johnson [1] provided a summary of a series of ACI simulations performed by Motorola

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⁴ The minimum coupling loss is the minimum pathloss between a BS and a UE.
that were submitted to the 3GPP TSG-RAN4. The effect of ACP is quantified in these studies by a reduction in system capacity. It was found that the system capacity decreased exponentially with decreasing ACP. With an ACP value of 35 dB the capacity reduction was 1-2% for voice users.

The extent and impact of dead zones in UTRA FDD systems has been simulated in a combined macrocellular and microcellular network by Thompson [16], in indoor picocells by Povey et al. [17] and in a macrocellular network by Wacher and Laiho [18]. For all three simulations the worst-case ACP value of 33 dB was assumed. Their results are largely consistent with each other, finding that dead zones are generally not a significant problem in macrocell-only networks, but can occur around microcell and picocell BSs of adjacent channel networks. It was suggested that the coupling loss between a UE and an adjacent channel interfering microcell or picocell BS can be significantly less than the coupling loss between a UE and an adjacent channel interfering macrocell BS.

A small number of prototype UTRA handsets have been described in the literature. Wong et al. [19] described an example transceiver design based on commercially available components, and evaluated its predicted performance by simulation. ACLRs of 40.8 dB and 41.5 dB were predicted for frequency offsets of +5 MHz and –5 MHz, respectively. An ACS of 53.7 dB was predicted for the first adjacent channel. Furukawa et al. [20] and Lee et al. [21] described prototype transceivers that have been built and tested. They reported ACLRs more than 10 dB greater than the 3GPP specification (ie, > 43 dB), and 43.77 dB, respectively. ACS values were not reported specifically, although in Reference [21] the receiver is shown to pass the 3GPP ACS test. A power amplifier for use in UTRA mobile applications described by Vintola et al. [22] was reported to perform with an ACLR of 41.6 dB at an output power of 24 dBm. This is the maximum output power for a Class 3 UE, so if this amplifier were to be used in a Class 4 UE (21 dBm maximum transmit power), the ACLR is likely to be better.

2.2.1.3 Measurements

With the assistance of the RA’s Radio Technology and Compatibility Group (RTCG), some measurements on a test UE were performed using an Agilent 8960 Series 10 test set. At the time of writing, only a limited number of 3G UEs were commercially available; the RTCG had acquired a Motorola Model A830, which was used for the measurements.
The mean ACLR of our small number of measurements was 43 dB in the first adjacent channel (ie, at ±5 MHz frequency offsets) and 59 dB in the second adjacent channel (±10 MHz frequency offsets). This is significantly greater than the specified minimum, and also greater than that suggested by the specification of the power amplifier described in Reference [3] (40 dB and 50 dB in the first and second adjacent channels, respectively), but it is consistent with the prototype UTRA handset measurements described in Section 2.2.1.2.

The ACS performance was also measured with a loop back BER test, using the ACS test conditions specified in Reference [5], with an appropriate adjacent channel interferer signal generated by a Rohde and Schwarz SMIQ03B signal generator. It was found that the interferer could be increased to –31 dBm (worst case) at the UE antenna input before the BER exceeded the specified acceptable value. This is 21.7 dB greater than the 3GPP test conditions, and therefore implies an ACS performance of 54.7 dB. This is reasonably consistent with the value of 53.7 dB reported in Reference [19].

Some similar measurements were performed for two different UEs by researchers at Orange UK [23]. ACLRs of 44 dB and 47 dB were measured in the first adjacent channel (5 MHz offset), and ACLRs of 58 dB and 61 dB were measured in the second adjacent channel (10 MHz offset). These measurements correspond well with our own measurements. The ACS of one of the test UEs was also evaluated, by measurement of the $E_c/I_0$ degradation with different wanted-to-interfering signal power ratios. The resulting curve was compared to a set of curves obtained analytically for different ACS values. It was found that the results most closely matched the curves for an ACS of 33 dB, ie, the specified minimum value, which is significantly worse than our own measurement. This difference can perhaps be attributed to the different UE that was used for the measurements, as well as considerable difference in the test methodology. Without more information about the test procedures used by Orange, it is difficult to further evaluate the discrepancy between the different ACS measurements.

2.2.1.4 Typical ACP Value

It was decided that two ACP values would be used to analyse the simulation results. A worst-case analysis would be based on the specified minimum ACP value, whilst typical performance would be analysed using ACP values that actual UEs and BSs would be expected to provide. We have seen that the uplink and downlink ACP value will be dominated by the performance of the UE, so we can assert that the uplink ACP value will be
approximately equal to the ACLR of the UE transmitter, and the downlink ACP value will be approximately equal to the ACS of the UE receiver.

From our own measurements and the results reported in the literature, we can conclude that the typical UE ACLR will be approximately 10 dB better than the specified minimum. We have therefore selected a typical uplink ACP value of 43 dB.

The results for the UE ACS are less consistent. Our own measurements and other data from a number of sources indicate that the UE ACS performance is likely to be approximately 20 dB better than the specified minimum value. However, other studies have indicated that the UE ACS performance is likely to be close to the specified minimum value. As we already plan to use the specified minimum UE ACS value for analysis of the worst-case scenario, for consistency with our chosen typical UE ACLR, we will also assume a typical UE ACS of 43 dB (ie, 10 dB better than the specified minimum). Hence, we assume a typical downlink ACP value of 43 dB. However, we recommend that further work be undertaken to reconcile the differences in the ACS values that have been reported for 3G handsets.

2.3 Realistic Interference Models

In order to analyse the impact of dead zones on 3G network performance we will use interference models to investigate different network scenarios. In this section we present the link budgets that will be used to model the dead zones when we analyse the different network scenarios described in Section 3. Using these link budgets we will be able to change the site separations for the victim network and the adjacent channel network. We can also investigate the effect of a microcell BS compared with a macrocell BS on the size of dead zones, in addition to examining the effect of changing other parameters, such as the site configuration (eg, the height above the terrain), the antenna type and the service being used. Using different pathloss prediction models we can also identify the effect of ACI in different propagation environments, eg, rural or urban environments.

Despite the various changes that can be made to the link budget to model different scenarios, caution is required in interpreting the results. This is because the link budgets can only model one specific scenario at a time, whereas in a real network many different scenarios will exist simultaneously.
2.3.1 Downlink Link Budget

Table 2 shows an example link budget for the downlink. The downlink interference margin is 10.1 dB [24] and this margin models intra-cell and inter-cell interference from other sites in the network. Slow fading will cause the pathloss to rise and fall as the UE moves into and out of signal fades caused by the environment. Including a fading margin of 7.3 dB allows us to be 95% confident that the signal strength is sufficient across the entire coverage area of a cell [25]. Fast fading, or Rayleigh fading, is a result of the UE moving through deep fades caused by constructive and deconstructive interference between different paths from a transmitter. In our simple link budget we assume that the UE moves at 3 kph. This means a 4 dB fast fading margin is required for the closed loop fast power control to compensate for fast fading at the cell edge [25]. We also assume a processing gain of 315, which is equivalent to a data rate of 12.2 kbps when the chip rate is 3.84 Mcps. We assume a constant soft handover (SHO) gain of 2 dB [25]. This is a reasonable assumption to make because we are analysing the performance at the cell edge, where the SHO gain is greatest. One can see that the cell radius varies considerably depending on the environment and associated propagation model. Note that this is a macrocell link budget for a traffic channel power of 32 dBm, an antenna gain of 16 dBi and an antenna height of 30 metres above the ground.

How do we incorporate the effect of ACI into this link budget? The receiver noise power is an absolute quantity and the system interference (inter-cell and intra-cell interference) is modelled as a margin (or a multiplier in linear terms). The ACI is calculated as an absolute quantity. If all three factors were absolute quantities, then the total interference plus noise power would be the simple addition of the absolute powers. However, the interference margin is not an absolute factor. Given that this is the case, there are two possible methods of computing the total interference plus noise power.

One method of modelling the effect of ACI on the downlink is to assume that the ACI will add to the receiver noise power given in Table 2, ie, ACI on the downlink increases the noise floor of each UE receiver. Subsequently, we can assume that interference from the serving network, ie, the inter-cell and intra-cell interference represented by the 10.1 dB interference margin, increases the revised noise floor by 10.1 dB causing the total noise plus interference floor of each UE to be raised.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Formulae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max traffic channel power</td>
<td>32</td>
<td>dBm</td>
<td>a</td>
</tr>
<tr>
<td>BS antenna gain</td>
<td>16</td>
<td>dBi</td>
<td>b</td>
</tr>
<tr>
<td>Downlink line loss</td>
<td>4</td>
<td>dB</td>
<td>c</td>
</tr>
<tr>
<td>Effective isotropic radiated power</td>
<td>44</td>
<td>dBm</td>
<td>d=a+b−c</td>
</tr>
<tr>
<td>Thermal noise density</td>
<td>-174</td>
<td>dBm/Hz</td>
<td>e</td>
</tr>
<tr>
<td>Downlink noise figure</td>
<td>9</td>
<td>dB</td>
<td>f</td>
</tr>
<tr>
<td>Receiver noise density</td>
<td>-165</td>
<td>dBm/Hz</td>
<td>g=e+f</td>
</tr>
<tr>
<td>Chip rate</td>
<td>3.84×10⁶</td>
<td>cps</td>
<td>h</td>
</tr>
<tr>
<td>Receiver noise power</td>
<td>-99.1</td>
<td>dBm</td>
<td>i=g+10log(h)</td>
</tr>
<tr>
<td>RAKE efficiency factor</td>
<td>0.5</td>
<td>-</td>
<td>j</td>
</tr>
<tr>
<td>Downlink processing gain</td>
<td>315</td>
<td>-</td>
<td>k</td>
</tr>
<tr>
<td>Downlink required $E_b/I_0$</td>
<td>5</td>
<td>dB</td>
<td>l</td>
</tr>
<tr>
<td>Downlink interference margin</td>
<td>10.1</td>
<td>dB</td>
<td>m</td>
</tr>
<tr>
<td>Receiver sensitivity</td>
<td>-106</td>
<td>dBm</td>
<td>n=i−10log(j)−10log(k)+l+m</td>
</tr>
<tr>
<td>UE antenna gain</td>
<td>0</td>
<td>dBi</td>
<td>o</td>
</tr>
<tr>
<td>Body loss</td>
<td>3</td>
<td>dB</td>
<td>p</td>
</tr>
<tr>
<td>Max pathloss</td>
<td>147</td>
<td>dB</td>
<td>q=d−n+o−p</td>
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<td>Lognormal fading margin</td>
<td>7.3</td>
<td>dB</td>
<td>r</td>
</tr>
<tr>
<td>Fast fading margin</td>
<td>4</td>
<td>dB</td>
<td>s</td>
</tr>
<tr>
<td>SHO gain</td>
<td>2</td>
<td>dB</td>
<td>t</td>
</tr>
<tr>
<td>Allowed propagation loss</td>
<td>137.7</td>
<td>dB</td>
<td>u=q−r−s+t</td>
</tr>
<tr>
<td>UE height</td>
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<td>m</td>
<td></td>
</tr>
<tr>
<td>BS height</td>
<td>30</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>2.14</td>
<td>GHz</td>
<td></td>
</tr>
<tr>
<td>Cell radius (COST231 dense-urban)</td>
<td>0.8</td>
<td>km</td>
<td></td>
</tr>
<tr>
<td>Cell radius (COST231 suburban)</td>
<td>0.9</td>
<td>km</td>
<td></td>
</tr>
<tr>
<td>Cell radius (COST231 quasi-open-rural)</td>
<td>5.8</td>
<td>km</td>
<td></td>
</tr>
</tbody>
</table>

Table 2  Downlink traffic channel link budget for a 12.2 kbps speech user.

There is one fundamental shortfall with the approach adopted above. By assuming that the ACI adds to the UE receiver noise floor and the resulting revised noise floor is subsequently increased by the 10.1 dB downlink interference margin, we are essentially assuming that the
power transmitted to all UEs would have to be increased to overcome ACI. On the downlink, other than the UEs close to the adjacent channel BS, most UEs are unaffected by ACI, and therefore the power levels that these UEs require is also unaffected by ACI. The UEs that are not directly affected by ACI experience only a marginal increase in interference as a result of the additional downlink power allocated to the few UEs affected by ACI. Therefore, it is appropriate to revise the methodology of modelling the effect of ACI on the downlink. With the revised method, we assume that the serving network interference level would be 10.1 dB higher than the receiver noise floor and then the ACI is added to this total. In this way, only UEs affected by ACI will have their noise floors raised. Therefore, using the notation of Table 2, receiver sensitivity, $n$, is given by

$$n = 10\log(10^{(i+m)/10} + ACI) - 10\log(j) - 10\log(k) + l$$

(2)

Let us consider examples of the two alternative methods for modelling the effect of ACI on the link budget for the downlink. Firstly, we need to determine what would be a suitable level of interfering power from an adjacent site. Table 3 shows the maximum downlink interference power that could be received by a UE from an interfering macrocell. We have not included the body loss because in the worst-case scenario the user’s body does not intercept the interference signal. Note that this power is dependent on how far the UE is from the interfering site.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Formulae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max total downlink power</td>
<td>43</td>
<td>dBm</td>
<td>a</td>
</tr>
<tr>
<td>BS antenna gain</td>
<td>16</td>
<td>dBi</td>
<td>b</td>
</tr>
<tr>
<td>Downlink line loss</td>
<td>4</td>
<td>dB</td>
<td>c</td>
</tr>
<tr>
<td>Effective isotropic radiated power</td>
<td>55</td>
<td>dBm</td>
<td>d=a+b−c</td>
</tr>
<tr>
<td>Downlink adjacent channel protection</td>
<td>32.75</td>
<td>dB</td>
<td>e</td>
</tr>
<tr>
<td>Pathloss</td>
<td>PL</td>
<td>dB</td>
<td>f</td>
</tr>
<tr>
<td>UE antenna gain</td>
<td>0</td>
<td>dBi</td>
<td>g</td>
</tr>
<tr>
<td>Downlink interference power</td>
<td>22.3−PL</td>
<td>dBm</td>
<td>h=d−e−f+g</td>
</tr>
</tbody>
</table>

Table 3 Downlink adjacent channel interference power.

---

5 The actual value of ACP calculated from the UTRA FDD specifications is 32.7 dB, as indicated here. In the text of this report, we mostly refer to this ACP value as 33 dB.
For example, an interfering macrocell that is 100 metres from a UE (the signals from which are subject to free space pathloss of 79 dB) will cause a downlink interference power of -56.7 dBm. Given the UE receiver noise power of -99 dBm and an ACI power of -56.7 dBm, in our original link budget formulation we would have a modified noise floor of approximately -56.7 dBm. We then would have applied a 10.1 dB interference margin to this modified receiver noise floor and obtained a total interference floor of -46.6 dBm. In our revised formulation for the link budget, we add the interference margin to the receiver noise floor yielding an interference level of -89 dBm. To this we add the ACI power of -56.7 dBm to obtain a total interference floor of approximately -56.7 dBm. Consequently, with the revised computation the total interference (including the ACI power) is approximately 10.1 dB less than the original computation. The precise effect of ACI on the total interference level will be dependent on how close the interfering UE is to its serving site, and how heavily loaded the serving site is. Note that we have assumed that the UEs adhere to the UTRA FDD specification for ACP [5,6].

### 2.3.2 Uplink Link Budget

As well as its effect on the downlink we can also consider the effect of the ACI on the uplink. On the uplink we can adopt an approach similar to the original formulation used for the downlink link budget above. We can assume that the uplink ACI generated by a UE affects the single BS receiver that is close to the UE. In this way we can add the ACI power directly to the receiver noise floor because it affects all users in the cell. Table 4 shows an example uplink budget.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Formulae</th>
</tr>
</thead>
<tbody>
<tr>
<td>UE max transmit power</td>
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<td>dBm</td>
<td>a</td>
</tr>
<tr>
<td>UE omni antenna gain</td>
<td>0</td>
<td>dBi</td>
<td>b</td>
</tr>
<tr>
<td>Body loss</td>
<td>3</td>
<td>dB</td>
<td>c</td>
</tr>
<tr>
<td>Effective isotropic radiated power</td>
<td>18</td>
<td>dBm</td>
<td>d=a+b−c</td>
</tr>
<tr>
<td>Thermal noise density</td>
<td>-174</td>
<td>dBm/Hz</td>
<td>e</td>
</tr>
<tr>
<td>Uplink noise figure</td>
<td>5</td>
<td>dB</td>
<td>f</td>
</tr>
<tr>
<td>Receiver noise density</td>
<td>-169</td>
<td>dBm/Hz</td>
<td>g=e+f</td>
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<tr>
<td>Chip rate</td>
<td>3.84×10^6</td>
<td>cps</td>
<td>h</td>
</tr>
<tr>
<td>Receiver noise power</td>
<td>-103.1</td>
<td>dBm</td>
<td>i=g+10log(h)</td>
</tr>
<tr>
<td>RAKE efficiency factor</td>
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<td>-</td>
<td>j</td>
</tr>
<tr>
<td>Uplink processing gain</td>
<td>315</td>
<td>-</td>
<td>k</td>
</tr>
<tr>
<td>Uplink required $E_b/I_0$</td>
<td>5</td>
<td>dB</td>
<td>l</td>
</tr>
<tr>
<td>Uplink interference margin</td>
<td>3</td>
<td>dB</td>
<td>m</td>
</tr>
<tr>
<td>Receiver sensitivity</td>
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<td>dBm</td>
<td>n=i−10log(j)−10log(k)+l+m</td>
</tr>
<tr>
<td>BS antenna gain</td>
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<td>dBi</td>
<td>o</td>
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<tr>
<td>Uplink line loss</td>
<td>3</td>
<td>dB</td>
<td>p</td>
</tr>
<tr>
<td>Max pathloss</td>
<td>148.1</td>
<td>dB</td>
<td>q=d−n+o−p</td>
</tr>
<tr>
<td>Lognormal fading margin</td>
<td>7.3</td>
<td>dB</td>
<td>r</td>
</tr>
<tr>
<td>Fast fading margin</td>
<td>4</td>
<td>dB</td>
<td>s</td>
</tr>
<tr>
<td>SHO gain</td>
<td>2</td>
<td>dB</td>
<td>t</td>
</tr>
<tr>
<td>Allowed propagation loss</td>
<td>138.8</td>
<td>dB</td>
<td>u=q−r−s+t</td>
</tr>
<tr>
<td>UE height</td>
<td>1.5</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>BS height</td>
<td>30</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>1.95</td>
<td>GHz</td>
<td></td>
</tr>
<tr>
<td>Cell radius (COST231 dense-urban)</td>
<td>0.9</td>
<td>km</td>
<td></td>
</tr>
<tr>
<td>Cell radius (COST231 suburban)</td>
<td>1.1</td>
<td>km</td>
<td></td>
</tr>
<tr>
<td>Cell radius (COST231 quasi-open-rural)</td>
<td>6.6</td>
<td>km</td>
<td></td>
</tr>
</tbody>
</table>

| Table 4  | Uplink traffic channel link budget for a 12.2 kbps speech user. |

In this case we have used an interference margin of 3 dB [24] to model 50% cell loading. The cell radius for the uplink is 6.6 km when the COST231 quasi-open-rural pathloss model is used. One can see that the downlink is the limiting link from our two example link budgets because the allowed propagation loss, and hence cell radius in all three environments, is less.
Calculation of the uplink interference from UEs transmitting in an adjacent channel network is more difficult than the downlink calculation. Unlike the downlink case in which the single interfering BS has a maximum transmit power and a fixed position, there may be many interfering UEs each of which is likely to be in a different position and transmitting at a different power level. For simplicity we will assume that there is only a single significant interfering UE, and that this UE transmits at full power. Table 5 shows the potential interference power of this UE. Note that in the worst-case scenario there is no body loss on the uplink for the adjacent channel UE (ie, for the interfering UE). If we assume the interfering UE is one kilometre away from the victim site, the noise floor at that site barely changes. However, as the UE comes closer to the victim site the noise floor rises. For example, if the interfering UE is 100 metres from the victim site (ie, 79 dB pathloss) then the uplink ACI power is −74.7 dBm (4.3 dBm − 79 dB). If we add this ACI power to the receiver noise floor of −103.1 dBm, then the total interference power is approximately −74.7 dBm. This interference power is smaller than that found on the downlink, which is what we expect because the UE has a smaller effective isotropic radiated power (EIRP) and generates less interference to an adjacent network than a BS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Formulae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max total uplink power</td>
<td>21</td>
<td>dBm</td>
<td>a</td>
</tr>
<tr>
<td>UE antenna gain</td>
<td>0</td>
<td>dBi</td>
<td>b</td>
</tr>
<tr>
<td>Effective isotropic radiated power</td>
<td>21</td>
<td>dBm</td>
<td>c=a+b</td>
</tr>
<tr>
<td>Uplink adjacent channel protection</td>
<td>32.7</td>
<td>dB</td>
<td>d</td>
</tr>
<tr>
<td>Pathloss</td>
<td>PL</td>
<td>dB</td>
<td>e</td>
</tr>
<tr>
<td>BS antenna gain</td>
<td>16</td>
<td>dBi</td>
<td>f</td>
</tr>
<tr>
<td>Uplink interference power</td>
<td>4.3–PL</td>
<td>dBm</td>
<td>g=c−d−e+f</td>
</tr>
</tbody>
</table>

**Table 5** Uplink adjacent channel interference power.

In the next section the link budgets for both the uplink and the downlink will be used to perform an initial analysis to establish which operational scenarios are likely to give rise to dead zones.
3 Network Scenarios Most Susceptible to Dead Zones

In the previous section we introduced two link budgets that can be used to determine the signal powers for the uplink and the downlink of victim and interfering UTRA FDD networks. These link budgets, along with other considerations, can be used to provide a preliminary analysis of different scenarios to establish what conditions give rise to dead zones. Note that in this section we identify specific scenarios in which dead zones may occur, although as these are hypothetical scenarios we note that in practice these specific scenarios may rarely occur or may be of little consequence to the overall network quality of service (QoS). For this reason, network operators may perceive more value in analyses that establish the network-wide implications of ACI. Simulations can be devised to determine which ACI mitigation techniques provide the most benefit in terms of the overall QoS for realistic operational scenarios, rather than simply analysing worst-case scenarios. Furthermore, although dead zones are the most noticeable manifestation of ACI, there may also be an overall reduction in the capacity and coverage of the network that will not be clearly quantifiable through a simple link budget-based analysis. Again, simulations will help to quantify this effect. In the following discussions of the different scenarios we will determine those scenarios that require simulation for more thorough analysis.

3.1 Urban Scenario

The first scenario to consider is an urban environment in which the number of subscribers is high. In this environment there is a high offered traffic level and hence we assume a high cell site density to support this traffic. The high traffic load can be factored into our uplink budgets in Table 4 by changing the interference margin from 3 dB to 6 dB [25]. This is equivalent to assuming an increase in the loading of cells from 50% to 75%. We will keep the downlink interference margin the same because the interference from other sites is assumed to be the same. In previous work for the RA [26] we stated that the number of sites in a 25 square kilometre area will be approximately 105, based on the site density of a typical 2G GSM network. This gives an average site density of 4.2 sites per square kilometre. From this site density, and by assuming the cells are hexagonal, we can estimate the average cell radius, \( R \). The area of a hexagonal cell, \( A \), is given by,

\[
A = \frac{3 \cdot \sqrt{3}}{2} \cdot R^2. \tag{3}
\]
This gives an average cell radius of 303 metres.

Clutter-based pathloss prediction models are not valid over small distances. The COST231 models can be used for frequencies up to 2 GHz and are valid for cell radii between one kilometre and 20 km. Since the cell radius is considerably less than one kilometre we will use the free space pathloss model instead of the COST231 pathloss model in this urban analysis. Note that in practice the pathloss will be greater than the free space loss when the receiver is not in line-of-sight with the transmitter. Another error will be the antenna gain since a UE close to a macrocellular site is likely to be underneath the main lobe of the antenna, and the actual received signal strength will be less than that predicted if a constant antenna gain is assumed.

It is worth pointing out that throughout this section (urban scenario) and subsequent sections that deal with the rural and motorway scenarios, we have modified the definition of a dead zone. The link budget given in Table 2 includes a lognormal fading margin of 7.3 dB. This margin ensures that the cell area coverage reliability is 95%. The presence of one or two dead zones at the cell perimeter will not have much effect on this coverage reliability. This means that the cell size is not altered significantly due to the presence of a dead zone at the cell boundary. Therefore, it is still appropriate to use the 7.3 dB lognormal fading margin when evaluating the cell radius. However, it does not necessarily make sense to apply this fading margin when determining the size of a dead zone. We will, therefore, define a dead zone as the area in which there is less than 50% probability of coverage. If we assume that dead zones are located at the cell edge, the slow fading margin used to calculate the serving signal level at a UE (and the related calculation for the dead zone radius) will be set to 0 dB rather than the 7.3 dB presented in Table 2. By doing this the 50% probability of coverage in the dead zone area is taken into account.

The ideal scenario for combating ACI is to collocate sites of one network with the sites of the adjacent channel network. In this case the adjacent channel signal strength will only be high when the wanted channel signal strength is also high; consequently, ACI would not present a problem. For example, using our downlink link budget described in Section 2.3.1 and Equation 2, the ACI from an adjacent channel macrocellular site would reduce the UE sensitivity from -106.0 dBm to -83.3 dBm for a 300 m BS-to-UE separation. However, the
power received at the UE from its serving cell, also 300 metres away, will be -49.6 dBm.\textsuperscript{6} This represents a margin of 33.7 dB. Clearly, this exceeds the minimum margin of 0 dB required for the link to be maintained and no dead zones are created.

The worst-case scenario is when there is an adjacent channel macrocellular or microcellular site at the furthest distance from the serving cell site, ie, 300 metres from each serving site. When the UE is directly underneath this adjacent site, the ACI will dominate. Using the downlink link budget from Section 2.3.1, utilising Equation 2 to calculate the receiver sensitivity and assuming a free space pathloss model, the results in Table 6 are obtained. One can see that the margin for the macrocell interferer has decreased from 33.7 dB, when the sites are collocated, to 16.2 dB when the sites are separated. This margin, being positive, shows that the UE at the cell edge is not in a dead zone. In practice the victim UE will be below the main lobe of the interfering site’s antenna, resulting in a better margin. However, if the UE is not in line-of-sight with its serving site, the pathloss will be higher and the margin will decrease.

In the case of an adjacent channel microcellular site, although the microcell’s antenna is at street level and is only 3.5 metres from the UE (taking into account a UE height of 1.5 metres), the microcell actually presents only 2.2 dB more interference to the UE than the macrocell. In addition to the UE being below the main lobe of the interfering site’s antenna (mentioned above), this is because we assume a lower transmit power (37 dBm [24]) for the microcell compared to the macrocell (43 dBm). Also, the microcell antenna is assumed to be a low gain panel antenna (6 dBi), which has considerably less gain than a typical macrocell BS antenna at 16 dBi. The result is that the margin for the microcell is only 2.2 dB poorer than the macrocell. This means that in this example a dead zone would not be expected. However, as for the macrocell, if the UE is not in line-of-sight with its serving site, the pathloss will be greater, perhaps 30 dB greater. This increased pathloss may cause the margin to fall below zero and the UE may find itself in a dead zone.

\textsuperscript{6} Note that, as mentioned earlier, the received signal power does not include a 7.3 dB lognormal fading margin for this example.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Macrocell</th>
<th>Microcell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum total downlink power (dBm)</td>
<td>43</td>
<td>37</td>
</tr>
<tr>
<td>BS antenna gain (dBi)</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>Downlink line loss (dB)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>EIRP of interferer (dBm)</td>
<td>55</td>
<td>28.1</td>
</tr>
<tr>
<td>Distance to server (metres)</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Distance to interferer (metres)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Height of interferer (metres)</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>Effective distance to interferer (metres)</td>
<td>28.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Pathloss to interferer (dB)</td>
<td>68.1</td>
<td>49.9</td>
</tr>
<tr>
<td>Receiver sensitivity of UE (dBm, due to ACI)</td>
<td>-65.9</td>
<td>-63.6</td>
</tr>
<tr>
<td>Margin in victim UE’s link budget (dB)</td>
<td>16.2</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 6: The margin available in the victim UE’s downlink budget whilst in the presence of ACI from an adjacent channel macrocell or microcell site.

From the results given in Table 6 one could conclude that downlink dead zones will not occur when a UE is close to an interfering macrocell or near an interfering microcell. We note that, with such high receive levels, other effects, such as intermodulation effects in the UE receiver, may cause loss of reception in the receiver. This has not been modelled in this analysis. There are several other reasons why the situation is not as simple as that implied by the link budget results. Firstly, the sites will not be distributed evenly in a typical network. This means that there will be some sites that have a larger cell radius than other sites. An adjacent channel site at the edge of these larger cells will result in a smaller margin. As we have already discussed, the second issue is that the free space pathloss model is less than ideal. In reality there will be buildings that significantly attenuate the serving signal. Even a small degradation in signal strength is expected to cause dead zones to become larger. The third factor that will affect the extent of dead zones is the actual service being used by the UE. In our link budgets we have assumed a data rate of 12.2 kbps, which gives a processing gain of 315. If the UE was to use a data rate of, say, 64 kbps the processing gain would decrease to 60. Assuming the same $E_b/I_0$ for both services, the decrease in processing gain results in a 7.2 dB degradation in the UE’s receive sensitivity, which will increase the size of the dead zones even further. In Section 4.3 simulations of a typical dense urban network are presented. The results illustrate issues similar to those described above.
Up to now we have only considered the downlink in our urban scenario. We will now consider the uplink. Let us assume that the cell radius is 300 metres and there is a UE trying to make a call to a serving macrocell site from the cell edge. Using our uplink budget (with 75% loading) and assuming the UE transmits at full power, ie, 21 dBm, the power received from the UE at the serving site is -66.1 dBm. This value takes into account both the slow and the fast fading margins. It is worth noting that contrary to the method employed for the downlink, we include the slow fading margin in the uplink serving cell calculations. This is because an interfering UE on the uplink can have a detrimental effect on the performance of the serving cell, ie, a noise rise could occur at the serving BS that affects all serving UEs. To assess the impact on the serving cell coverage, it is appropriate to use the 95% cell area coverage criterion. On the downlink, an adjacent site can cause serving UEs to be dropped by the network, but this should not affect the performance of other UEs in the serving cell area. In this case, by defining the size of a dead zone as the area in which there is less than 50% probability of coverage (ie, no slow fading margin), this has negligible impact on the serving cell’s coverage area reliability.

Returning to the uplink calculations, the receiver sensitivity of the serving site in the absence of ACI is -114.1 dBm, and therefore there is ample power available for the UE to reach the serving site. If we now place an interfering UE directly underneath the serving site, and assume that it transmits at full power, the receiver sensitivity of the serving BS degrades from -114.1 to -77.0 dBm. However, as this is still below the received power of –66.1 dBm, the UE at the edge of the cell still has enough power to reach its serving site. We note that the margin is only 10.9 dB, which is significantly worse than the equivalent downlink margin of 16.2 dB. Dead zones would be formed in the uplink\textsuperscript{7} if the data rate was increased sufficiently (eg, to 75 kbps).

### 3.2 Rural Scenario

We have discussed the effect of ACI in an urban network and showed that dead zones are likely to be experienced in the downlink when an interfering BS is at the edge of the serving cell.

\textsuperscript{7} A dead zone on the uplink would most likely manifest itself as an effective decrease in serving cell size due to the degradation of BS receiver sensitivity.
BS. It is also useful to investigate the existence of dead zones in a rural environment, which we consider in more detail in this section.

The cell radii will be larger in a rural environment than an urban environment so we can use the COST231 quasi-open-rural pathloss model. As the COST231 models are not valid for distances below one kilometre, we will use the free space propagation model at small distances, and the COST231 model for distances between 1 km and 20 km. However, there will be a gap in the coverage where the free space model becomes invalid (the free space model is valid for small distances where the transmitter is in line-of-sight with the receiver) and before the COST231 model becomes valid. Therefore, we will take the largest pathloss from the two models to give a smooth transition for distances below one kilometre. Although this pathloss model is reasonable for open rural areas with flat terrain, it tends to over-predict signal strengths in an urban environment, where in practice, due to building attenuation, the total signal attenuation will be more than that predicted by the free space pathloss model.

From the link budgets given in Table 2 and Table 4 (for a cell loading of 50%), the maximum downlink radius is about 5.8 km and the maximum uplink radius is about 6.6 km. Let us assume that the network has been designed for a maximum cell radius of 5.6 km, to allow for a 0.5 dB margin against ACI on the downlink. As for the urban environment, the best situation is when the sites in the adjacent channel network are collocated with the sites in the victim network. On the downlink, the wanted and adjacent channel signals will therefore suffer similar pathloss, and so the ACI will be minimised.

The worst-case scenario is obtained when the interfering sites are positioned at the cell edges of the serving network. Let us first consider the downlink. One can envisage the UE being directly next to the interfering site and 5.6 km from the serving site. Due to the relatively high pathloss to the serving site, the UE received power is low and the UE is found to be completely swamped by the ACI since its receive sensitivity decreases from -106.0 dBm to -65.9 dBm (see Table 6). (We assume that the effect of being directly under a site in a rural environment is the same as the effect of being under a macrocell site in an urban environment). We once again define a dead zone as the area where there is less than 50% probability of coverage. Based on this assumption, the link is only restored when the pathloss falls to about 104 dB, which is when the UE is about 650 m from the interfering site. This dead zone size is based on the assumption that 3G equipment meets the specification value for ACP of 33 dB. It is interesting to note that for an ACP value of 43 dB, that is arguably
expected of real 3G equipment (refer to Section 2.2.1.4), the link is restored when the UE is about 330 m from the interfering site. Thus, a relatively small portion of the total cell area becomes a dead zone due to the adjacent channel site.

Later in Section 4.2, we present simulation results for a rural network with adjacent channel network sites located in the worst positions at the cell boundaries of the serving sites. One result from these simulations is the radii of the dead zones formed for the speech service as a function of ACP value and is shown in Figure 3. It is interesting to observe that our link budget-generated results are similar to the simulation results.

![Figure 3](image)

**Figure 3**  Radius of dead zones in a rural network as a function of ACP value (produced by simulation).

We have considered the best-case scenario in which the adjacent channel network sites are collocated with the victim network sites. We have also considered the worst-case scenario in which the adjacent channel network sites are located at the cell boundaries of the victim network sites. It will be interesting to investigate a network that is in between these two scenarios. A network fitting this description is simulated in Section 4.2.
Let us now consider the uplink. Following a similar argument to the urban uplink analysis, let us assume that there is a UE attempting to make a call to a serving macrocell site from the cell edge (5.6 km from the serving site location). Assuming that the UE transmits at full power, the power received from the UE at the serving site is \(-114.7\) dBm. The receiver sensitivity of the serving site in the absence of ACI is \(-117.1\) dBm (for 50% loading). Therefore, there is sufficient power to reach the serving site. If we assume that an interfering UE transmits at full power directly underneath the serving site, the receiver sensitivity of the serving BS degrades from \(-117.1\) dBm to \(-80\) dBm. This is \(34.7\) dB more than the received power of \(-114.7\) dBm from the served UE at the cell edge, which has insufficient power to reach its serving site. The link is only restored again if the interfering UE moves 900 m away from the serving site, ie, the path loss from the interfering UE to the serving site falls to about 108 dB. As part of this calculation we have assumed an ACP value of 33 dB (specification value). If we assume that the ACP expected of real 3G equipment outperforms the specification value of ACP by 10 dB, then the minimum path loss from the interfering UE to the serving BS to maintain the link from the served UE to the serving BS is 98 dB. This path loss is obtained if the interfering UE is separated from the serving BS by 470 m.

Note that compared to the downlink, ACI appears to have slightly more of an effect on the uplink for the rural scenario. However, we must note that we have considered a worst-case condition that has a low probability of occurring in practice. We have assumed that an interfering UE is transmitting at full power and is located relatively close to a serving BS. Furthermore, we have monitored the effect of ACI on the worst-case link between a UE at the cell edge and the serving BS. In practice, the interfering UEs and victim UEs will be moving and the effects of ACI will vary depending on the relative positions of these UEs. Conversely, on the downlink, if an adjacent channel site is located at the periphery of the coverage area of a serving cell, a definite dead zone is formed. Therefore, we can conclude that the impact of ACI on the uplink is likely to be insignificant compared to the downlink.

3.3 Motorway (or Fast-moving Train) Scenario

The RA is concerned that a UE used in a fast-moving vehicle on a motorway or along a railway track might repeatedly move in and out of dead zones as it travels through its serving cells and the cells of a network using an adjacent channel. We have analysed this problem for a vehicular UE that is moving fast and one that is moving more slowly. We have assumed
that the vehicle is travelling at either 80 mph or 30 mph. This is equivalent to 129 kph and 48 kph, respectively.

For the downlink it is relatively easy to estimate the time that a UE is in a dead zone because the interfering site is stationary and we can model a single vehicle UE. Figure 4 shows the model that we have used. A served vehicular UE (blue) starts from the first macrocellular serving site (blue) on the left of Figure 4. It then moves towards the second macrocellular serving site (blue), moving past an adjacent channel macrocellular or microcellular site (red) as it does so. The distance, $d_3$, in the diagram is equal to twice the cell radius and, in the worst-case scenario, the sum of the distances $d_1$ and $d_2$ is equal to the cell radius since the adjacent channel site is at the edge of two serving cells.

It is more difficult to model the uplink because we also need to consider a fast-moving interfering UE. For every served UE position, we can model the interfering UE (red) moving from left to right in Figure 4. The distance of the interfering UE from the left serving site is given by the distance, $d_4$.

![Figure 4](image)

Before modelling a fast-moving vehicular UE, various changes need to be made to the link budget to model this scenario. Firstly, there will be an extra loss in the link between the server (and any interferers) and the UE due to the penetration of the signal into the vehicle. We will assume that this vehicle loss is 8 dB [25] for both a train and a car. Furthermore, the required $E_s/I_0$ varies with the speed of the vehicle. We will assume that the target $E_s/I_0$ is 6.8 dB at 48 kph and 7.1 dB at 129 kph [25].
If we assume the vehicle is moving directly away from or towards its serving BS, the Doppler shift, $v_d$, (in m/s) is given by [27],

$$v_d = \frac{v_v}{\lambda},$$

(4)

where $v_v$ is the velocity of the vehicle (in m/s) and $\lambda$ is the wavelength of the carrier (in metres). The fast fading margins for Doppler frequencies of 250 Hz and 100 Hz are 0.2 dB and 1.9 dB, respectively [24]. Assuming a carrier frequency of 2 GHz and using Equation 4, these two Doppler frequencies correspond to vehicle speeds of 135 kph and 54 kph, respectively, so we will assume that these two fast fading margins are suitable for our two vehicle speeds. SHO provides a further gain in the link [24] and these gains are shown in Table 7 for the two Doppler frequencies considered and for varying level differences between the two links involved in handover. In the uplink the level difference is the difference in signal strength received by the two BS receivers involved in SHO. In the downlink the level difference is the difference in signal strength of the two BS transmitters as received at the UE. When the vehicle is equidistant between the two serving cells, SHO gains of 2.5 dB and 1.3 dB will be used for Doppler frequencies of 100 Hz and 250 Hz, respectively.

<table>
<thead>
<tr>
<th>Doppler Frequency (Hz)</th>
<th>Level Difference Between SHO Links (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>2.5</td>
</tr>
<tr>
<td>250</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 7 SHO gains given two SHO links.

With the above $E_b/I_0$ values, vehicle loss and fast fading margins, and assuming SHO gains of 2.5 and 1.3 dB for the cell edge, we can calculate the cell radii that will permit maximum vehicle speeds of 48 and 129 kph (in the absence of ACI). The link budget given in Section 2.3 is used. These cell radii are shown in Table 8, along with the parameters that were used to calculate them. These cell radii equate to half the cell separation, $d_3$, shown in Figure 4.
Link Speed (kph) $E_b/I_0$ (dB) Vehicle Loss (dB) Fast Fading Margin (dB) SHO Gain (dB) Cell Radius (km)

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink</td>
<td>48</td>
<td>6.8</td>
<td>8</td>
<td>1.9</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>129</td>
<td>7.1</td>
<td>8</td>
<td>0.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Uplink</td>
<td>48</td>
<td>6.8</td>
<td>8</td>
<td>1.9</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>129</td>
<td>7.1</td>
<td>8</td>
<td>0.2</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 8 The cell radii for the downlink and uplink at the two vehicle speeds.

Using the above changes in vehicle loss, fast fading margin and SHO we have analysed both the uplink and downlink, beginning with the downlink. As adopted for the rural analysis in Section 3.2, we define a dead zone as the area where there is less than 50% probability of coverage. The size of the dead zones for the downlink are shown in Table 9 along with the expected time a vehicle would spend in these zones while travelling at the given speed. One can see that for the example link budget the interfering macrocellular BS creates larger dead zones than a microcellular BS. The worst-case time spent in a dead-zone is 57 s.

<table>
<thead>
<tr>
<th>Interferer</th>
<th>Speed (kph)</th>
<th>Maximum Allowable Distance of Served UE from Server, $d_1$, (km)</th>
<th>Radius of Dead Zone Around Interfering Server, $d_2$, (km)</th>
<th>Time Spent in Dead Zone (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macrocell</td>
<td>48</td>
<td>3.205</td>
<td>0.395</td>
<td>59</td>
</tr>
<tr>
<td>Macrocell</td>
<td>129</td>
<td>3.230</td>
<td>0.370</td>
<td>20.6</td>
</tr>
<tr>
<td>Microcell</td>
<td>48</td>
<td>3.505</td>
<td>0.095</td>
<td>14.2</td>
</tr>
<tr>
<td>Microcell</td>
<td>129</td>
<td>3.506</td>
<td>0.094</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Table 9 Size of dead zones and time spent in dead zones whilst travelling at different speeds. The results for interfering macrocells and microcells are shown.

Again, the results in Table 9 are based on the assumption that the 3G equipment just meets the UTRA FDD specification for ACP, ie, an ACP value of 33 dB. The time spent in a dead zone varies between about 5 and 59 seconds. Examined another way, the proportion of time in a dead zone varies between 2.5% and 11%, if the proportion of time is measured as the time in a dead zone divided by the time it takes to travel between the two serving sites (blue sites in Figure 4). Obviously, not all adjacent channel sites are going to be located midway between serving sites along a stretch of motorway or railway. Therefore, the proportions of
time above are on the pessimistic side. It is worth noting that if the UE outperforms the specification by 10 dB, then the time spent in a dead zone varies between approximately 2 s and 33 s depending on the type of interferer and the speed of the UE.

We will now consider what happens on the uplink. Again we model the served UE moving from the left of Figure 4 to the right. We also assume there is a moving interfering UE. For both the fast and slow UE we will use the downlink cell radii as these are the smaller radii of the two links, ie, 3.6 km for the 48 kph case and 3.7 km for the 129 kph case. Figure 5 shows the margin available in the link budget for the 48 kph scenario, given different served and interfering UE positions.

![Figure 5](image)

**Figure 5** The margin in the link budget for the 48 kph fast-moving UE scenario.

The blue area shows when the margin is negative. It can be seen that when the interfering UE is close to the victim BS, the victim cell size is reduced significantly. The worst-case scenario would be if the interfering UE was directly underneath the victim site. In this case the victim site can only serve a UE that is closer than about 0.5 km.
Figure 6 shows a similar plot for the case where the UE is moving at 129 kph, and like before, if the interfering UE is below the victim site, the UE has to be within about 0.5 km of that site to transmit sufficient power. Note that there is no significant difference in the results for the two vehicle speeds.

We expect dead zones to form in the uplink and disappear again as the interfering UEs move close to and away from the victim sites.

The rural and urban link budget analyses presented in this section require more involved simulations to better characterise the effect of ACI in these environments. This is the subject for the next section.
4 MACcdma Simulations

The previous section provided us with a preliminary assessment of the likelihood of dead zones in urban, rural and motorway environments. In this section, we present simulation results for the urban and rural scenarios to shed further light on the overall impact of ACI in these scenarios. MAC Ltd has developed a WCDMA simulation tool, known as MACcdma, that allows a network planner to investigate the quality of a WCDMA network given radio coverage information, network configuration details and traffic profiles. MACcdma is a Monte Carlo simulator for 3G CDMA network planning. UEs are placed into the network one at a time in a random location until the specified level of offered traffic is reached. Then a snapshot of the network performance is taken. This is repeated many times and the performance of the network is averaged over all the snapshots. Random fluctuations in the network performance are averaged out over successive snapshots.

A rural and an urban scenario were examined by running a number of MACcdma simulations. These scenarios are described in this section and the simulation results are presented. Firstly, let us briefly describe the basic simulation parameters that were used by MACcdma.

4.1 MACcdma Parameters

Before running MACcdma various parameters must be defined for the specific UTRA FDD network to be simulated. These parameters are quite extensive and so we have included them in Appendix A for reference (also a MACcdma Data Sheet is given in Appendix B). We chose parameter values that we believed were appropriate for a typical UTRA FDD network and the majority of these parameters were agreed with the RA [26] in previous work. The service mix given in Table 10 was also agreed with the RA.

<table>
<thead>
<tr>
<th>Service</th>
<th>Proportion of Users (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice (12.2 kbps)</td>
<td>80</td>
</tr>
<tr>
<td>Medium Data Rate (64 kbps)</td>
<td>15</td>
</tr>
<tr>
<td>High Date Rate (144 kbps)</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 10 Proposed service mix to be used in simulations.
4.2 Rural Scenario

In addition to evaluating a number of interesting effects of ACI on the performance of a rural network, another purpose of this part of the project is to approximate the separation distance required between victim network sites and interfering network sites to keep ACI within acceptable levels. In the next three subsections we describe the method employed for simulating the rural network. The remainder of the section is devoted to analysing the simulation results.

4.2.1 Coverage Predictions and Network Configurations

The cells in the rural scenario were relatively large compared to those in the urban scenario. In addition, the propagation environment is very different. It is not appropriate to use MAC Ltd’s prediction algorithms, MiniWorks and MicroWorks, for the rural analysis because these algorithms are only suited to small cells in urban areas where high resolution building data are available. Instead, a clutter-based prediction model was used, namely, the COST231 quasi-open-rural pathloss prediction model. As described for the urban scenario analysis in Section 3.1, the maximum values of the free space pathloss and the COST231 quasi-open-rural pathloss were used for distances smaller than one kilometre. From Section 3.2 we observed that the dead zones could be potentially several hundred metres in radius. It would have been ideal to, say, adopt 20 metre radio coverage prediction bins to ensure sufficient resolution for the analysis. However, due to the run-time constraints of using such high-resolution predictions over a large simulation area, we were forced to use 100 m resolution predictions. There was no evidence from the simulation results indicating that this prediction bin size was too large. These predictions are one of the inputs to MACcdma.

We observed in Section 3.2 that the distance between the sites in a victim network and the sites in an adjacent channel network significantly affects the impact of ACI in the victim network. In order to investigate this phenomenon further we simulated a rural scenario for different site separations. The rural scenario was based on a hexagonal cell deployment. The worst-case scenario was simulated, in which the adjacent channel sites were at the cell edges of the victim network’s sites. In addition, we analysed the best-case scenario, in which all

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8 MiniWorks and MicroWorks are the prediction algorithms used by MAC Ltd’s proprietary radio network planning tool, called the NP WorkPlace.
sites were collocated. Also a network that was in between these two scenarios was analysed. In Section 3.2 we decided on a rural cell radius of 5.6 km for the link budget-based analyses, and this was used in our simulations. By applying basic geometry, a site separation of 9.7 km was calculated based on the cell radius for a hexagonal cell tessellation.

Figure 7 shows the positions of the sites of the victim network and locations of the sites for our two interfering networks. The black arrows in the diagram indicate the victim network sectors and the sector deployment pattern follows a ‘cloverleaf’ hexagonal pattern of cells. Also the orientation of the sectors is indicated by the direction of the arrows. The colour of the cells (hexagons) will be explained later in Section 4.2.2. The yellow circles denote the location of the worst-case adjacent channel site locations, i.e., sites at the cell edge of the victim site and at positions equidistant from the nearest three sites. The network formed by these sites will be referred to as the ‘offset 2’ network from this point forwards.

As mentioned above, another adjacent channel network was simulated in which all sites are collocated with the victim network sites. This network will be called the ‘co-sited’ network. Clearly it is not necessary to represent these sites in Figure 7 because they have the same locations as the victim network sites. An adjacent channel network in between the co-sited network (best-case scenario) and the offset 2 network (worst-case scenario) was also simulated. The sites that form this ‘offset 1’ network are indicated by blue circles in Figure 7. Although, not explicitly shown in Figure 7, the sites for all three adjacent channel networks are three-sectored sites with orientations identical to the orientation of the victim network sectors.
4.2.2 Simulation Area

A few important points must be made about the exact simulation area used by MAC\textit{cdma}. To illustrate these points, the diagram in Figure 7 has been reproduced in Figure 8 with the adjacent sites removed and two circles added. Firstly, note that the coverage areas for the victim network sectors are indicated by black arrows. The site positions for the ‘offset 1’ and ‘offset 2’ adjacent channel networks are indicated by blue and yellow circles, respectively.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7}
\caption{Diagram showing the site layout for the serving and adjacent channel networks used in the rural network simulations. The victim network sectors are indicated by black arrows. The site positions for the ‘offset 1’ and ‘offset 2’ adjacent channel networks are indicated by blue and yellow circles, respectively.}
\end{figure}
are expected to be repeatable over a larger hexagonal network due to the symmetrical nature of such a network. Any results generated by MACcdma were only produced for the pink area.

The brown-coloured part of the network forms two tiers of sites around the pink simulation area. The coverage area formed by both the pink and brown cells was populated with UEs by the simulation, ie, these areas form the traffic area of the network. Note that the brown sites were chosen to ensure that the inter-cell interference produced by two tiers around the pink area were characterised. Also it was important to ensure that the pink area was surrounded by sites with similar network loading. The green area represents the final edge area. This area was not populated with UEs because some of these UEs would be better served by BSs beyond this area. This cannot be represented in the simulation because BSs are not defined.
beyond the green tier of sites. In summary, the brown and green rings of cells provide sufficient traffic and coverage buffers, respectively, to minimise the effect of any edge effects on the simulation results produced in the pink region.

MACcdma allows a user to specify rectangular or circular areas for the traffic map and simulation results areas. The blue circle in Figure 8 was used to define the simulation results area and the red circle specified the traffic area. These circles approximate the area covered by the pink and brown hexagons, respectively.

4.2.3 Determining the Offered Traffic Density Level

A few steps need to be followed in order to evaluate the performance of a network using MACcdma. Before the ACI is introduced, one must first ascertain the offered traffic density level for the victim network that provides an acceptable quality of service (QoS). The next step is to add ACI to the network and evaluate the resulting QoS using the same traffic density level. This enables the QoS to be compared between the network not subjected to ACI and the network that is subjected to ACI.

4.2.3.1 QoS Definition

We need to first determine a suitable measure for the QoS of a 3G network. Due to the shortage of operational 3G networks in the world, a so-called industry accepted figure has not, as yet, emerged for the QoS of a 3G network. Note that 2G networks tend to be dimensioned to provide a 2% blocked call rate. Also in 2G networks, the call blocking experienced by a user within a cell is not dependent on the geographical location of the user. However, in 3G networks, the levels of call blocking can be dependent on the locations of the users. For instance, for a relatively loaded cell, a user located near a BS is not likely to be blocked by the network because its downlink power requirement is low. On the other hand, a user initiating a call at the periphery of the cell’s service area is more likely to be blocked. Therefore, it is important that the QoS measure for a 3G network incorporates geographical area. Given that there is no widely accepted measure for the QoS of a 3G network, with agreement from the RA we decided to define the QoS as the percentage area of the network over which the probability of blocking is less than or equal to 2%. A high QoS means that good service is likely to be obtainable over a large area of the network.
4.2.3.2 Traffic Density Level

The offered traffic density level for the victim network that provided an acceptable QoS for the speech service was determined. Note that at this stage ACI was not added to the victim network. For the rural network an acceptable QoS was assumed to be 97%. This percentage is slightly higher than the 95% value adopted for the urban network considered later (refer to Section 4.3.3). It was not the original intention to have different acceptable QoS levels; originally, the acceptable QoS percentage for the rural network was 95%. We initially determined that an offered traffic density value of 1160 mErlangs/km\(^2\) provided 95% QoS. However, in the simulations we ran initially, insufficient snapshots were specified for the MAC\(cdma\) simulations to determine this traffic density figure. Subsequent simulations were run for the same number of snapshots with ACI added to the network, and the results were found to be inaccurate. The later simulations were repeated with a higher number of snapshots (1000 snapshots). The results of these simulations had sufficient accuracy. However, when we repeated the original simulations that did not include ACI, the QoS results shown in Figure 9 were obtained for the speech service. Figure 9 shows that the 1160 mErlangs per km\(^2\) traffic density figure produces a 97% QoS value rather than a 95% value. Due to time constraints it was not possible to re-run the ‘with ACI’ simulations with a different offered traffic density value to provide 95% QoS. For the purposes of this study it is not important that this QoS figure is different from the value adopted for the urban network. We are mostly interested in examining comparative results of the QoS for a network with and without ACI, and hence, within reason, the exact value of QoS for a network without ACI is not critical.
4.2.3.3 Accuracy of Results

As noted above 1000 snapshots were run to generate each of the data points in Figure 9. There is a trade-off between the accuracy of the results (each data point) and the number of snapshots. Running simulations for more snapshots improves the statistical validity of the results at the expense of increased simulation time. In an ideal world we would have run \( \text{MACcdma} \) for many more snapshots, but this would have required computational resources beyond the scope of this study. Instead, it is important for us to note the accuracy of the results obtained. To provide us with an indication of this accuracy, \( \text{MACcdma} \) was run 10 times for a traffic density level of 1160 mErlangs per square kilometre with 1000 snapshots for each run. The mean and standard deviation (stdev) of the resulting QoS for the speech (12.2 kbps), 64 kbps and 144 kbps services is shown in Table 11.

![Figure 9](image.png)

**Figure 9** Speech service QoS for various offered traffic densities.
Note that the standard deviation of the QoS values increases as the data rate increases. It is beyond the scope of this project to delve into the statistical processes that affect the results of MAC\textit{cdma}. Indeed, many factors affect the accuracy of the results. These factors include the average blocking rate and offered traffic density for each service and also the number of sectors in the simulation area. For the data services (64 kbps and 144 kbps) the traffic density is low (20% of the total offered traffic density) and the average blocked call rate is higher than the speech service. This has the effect of decreasing the accuracy of the results for the 64 kbps and 144 kbps data services. Note that the number of snapshots would have to be increased substantially to improve the accuracy of the results for the data services. There was insufficient time to improve the accuracy of these results within the scope of this project. We were, however, satisfied that conclusions could be drawn with a reasonable level of confidence based on the rural simulation results presented in this report. We also used the results in Table 11 to define the size of error bars on many of the graphs presented in this section. This helps us bear in mind the statistical validity of the results when making conclusions about them.

### 4.2.4 Impact of ACI on the QoS for Speech

As described in Section 4.2.1, we modified the adjacent channel interference from three different rural network configurations, namely, the co-sited, offset 1 and offset 2 networks. The offered traffic density for these interfering networks was assumed to be equal to the offered traffic density for the victim rural network. A number of MAC\textit{cdma} simulations were run for a range of victim network ACP values. The speech service QoS results for the three adjacent channel network configurations are shown in Figure 10 together with the QoS results of the victim network when no ACI is present. All of these results are based on the evaluation of 1000 snapshots for each MAC\textit{cdma} simulation. As explained in Section 4.2.3, there is a degree of variability inherent in the results provided by MAC\textit{cdma} that is

<table>
<thead>
<tr>
<th></th>
<th>Speech</th>
<th>64 kbps</th>
<th>144 kbps</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>97.06%</td>
<td>72.62%</td>
<td>28.62%</td>
</tr>
<tr>
<td><strong>Stddev</strong></td>
<td>0.35%</td>
<td>2.42%</td>
<td>3.15%</td>
</tr>
</tbody>
</table>

Table 11: Accuracy of QoS results generated by MAC\textit{cdma} for the victim network without ACI modelled. The results are based on 10 repeated simulations of MAC\textit{cdma} where each simulation was evaluated for 1000 snapshots.
dependent on the number of snapshots run for each simulation. To reflect this variability, the standard deviation of the QoS for the ‘no ACI’ curve is portrayed in Figure 10 by the thickness of the brown curve. The centre of this line corresponds to the mean QoS (shown in Table 11) and the width of the line is equal to two times the standard deviation (also shown in Table 11), i.e., the extremities of the line are equal to the mean plus or minus one standard deviation. If we assume a Gaussian distribution for the QoS values generated by MACc\textit{cdma} for the ‘no ACI’ scenario, then we would expect approximately two thirds of the QoS values to fall within the brown area in Figure 10.

![Figure 10](image)

**Figure 10** Victim network speech QoS results when subjected to ACI produced by three different adjacent channel rural networks. Refer to Section 4.2.1 for a description of the adjacent channel network configurations.

The co-sited, offset 1 and offset 2 curves displayed in Figure 10 are based on data points that correspond to single MACc\textit{cdma} simulations rather than an average of a number of independent MACc\textit{cdma} simulations. Therefore, it would not be correct to insert error bars on these curves, but instead we should bear in mind that the variability of these results is going to be similar to the variability of the ‘no ACI’ results. Because each of the data points that define the co-sited, offset 1 and offset 2 curves is just one sample of the distribution (rather than an average), there is a small probability that some of these data points are outliers. A
probable example of an outlier is the data point for the co-sited curve for an ACP value of 43 dB.

Keeping in mind the statistical significance of the results shown in Figure 10, let us now examine the trends of the curves. As we would expect the co-sited results are similar to the ‘no ACI’ results because the wanted and adjacent channel signals suffer similar pathloss, and so the ACI is minimised. The trends of the offset 1 and offset 2 curves are similar. For an ACP value of 23 dB (10 dB worse than the UTRA FDD specification value of 33 dB), there is a noticeable difference between these curves and the ‘no ACI’ results. The ACI introduced by the offset 1 and offset 2 networks clearly degrades the speech service QoS of the victim rural network. However, given that an ACP value of 23 dB is 10 dB worse than the specification value, we would not expect to see this performance degradation in reality. We are more interested in the QoS results for ACP values of 33 dB and more. The speech service QoS results for ACP values of 33 dB to 37 dB inclusive are all slightly less than the results without ACI. However, given the statistical significance of the results, it is difficult for us to make this statement with a high degree of conviction. It is possible that these results are equivalent to the ‘no ACI’ results. Certainly for ACP values of more than 37 dB, the QoS for speech is similar to the scenario in which no ACI is presented to the victim network.

It is interesting to note that for ACP values less than or equal to 37 dB, the QoS for the offset 1 scenario seems worse than the QoS for the offset 2 scenario. This was unexpected because the offset 2 scenario was supposed to represent the worst-case interfering scenario and the position of the offset 1 adjacent network sites were in between the locations of the best-case and worst-case positions for adjacent channel network sites. One could argue that the limited accuracy of the results makes it impossible to draw any conclusions given that the data points for these two scenarios are relatively similar. However, there is only a small probability that the offset 1 QoS results for ACP values of 23, 33, 35 and 37 would all be lower than the respective QoS values for the offset 2 network configuration by chance. As a consequence, it is difficult to dismiss this observation as ‘chance’ and hence, further investigation into this matter is warranted.

To shed more light on this issue, consider the plots shown in Figure 11. The key for the plots is shown in Figure 11 (b). The remainder of the plots in the figure show the speech service blocking probability in the simulation results area (within the pink circle in Figure 8) for the ‘no ACI’ case [Figure 11 (a)], the offset 2 [Figure 11 (c)] and offset 1 [Figure 11 (d)]
scenarios. The latter two plots are for an ACP value of 23 dB (10dB worse than the specification). This ACP value was chosen for illustration purposes because this value provides the largest difference in QoS between the offset 1 and offset 2 scenarios.

Figure 11 Victim network speech service blocking probability for the offset 1 and 2 adjacent channel rural network configurations for an ACP value of 23 dB. Also the blocking probability when no ACI is present is shown. Refer to Section 4.2.1 for a description of the adjacent channel network configurations.
In each of these plots small hollow cyan-coloured circles depict the locations of the victim network sites. To avoid cluttering the plots with further symbols, the adjacent channel network sites are not displayed. Please refer to the pink area in Figure 8 for the locations of these sites relative to the victim network site locations.

The main point to note about Figure 11 (a) is that the locations with the most severe blocking are at positions equidistant from the location of the nearest three sites. In Figure 11 (c) the dead zones are clearly shown as light-purple solid circles, if we define a dead zone as an area with between 96% and 100% blocking. As expected, these dead zones are centred at the positions of the adjacent sites that make up the offset 2 adjacent network. These dead zones are centred on half of the poorest locations in the victim network when no adjacent channel interference is modelled [Figure 11 (a)]. Conversely, the blocking probability plot for the offset 1 scenario, which is displayed in Figure 11 (d), indicates that the dead zones (which are not exhibited as well defined circular solid light purple areas in this case) are not centred on locations that had high blocking for the network with no ACI [Figure 11 (a)].

The locations of the dead zones for the offset 1 and offset 2 scenarios helps explain the differences in QoS observed in Figure 10 for the speech service. Recall that the QoS (proportion of the simulation area with more than or equal to 2% blocking) for the offset 1 case is worse than for the offset 2 configuration for low ACP values. Although the ‘size’ of the distinct dead zones (areas with 96% to 100% blocking) caused by the offset 1 interfering network is smaller compared to the distinct dead zones produced by the offset 2 network, the overall network speech service performance for the offset 1 case is also affected by the areas of the network that had poor quality before ACI was introduced.

In Figure 11 (d) there are more regions of light blue (3 to 4% blocking) than in Figure 11 (c). The reason for this can again be attributed to the location of the dead zones. In Figure 11 (c) the distinct dead zones are located in areas of the network that previously suffered from poor performance, and perhaps more importantly it is in these areas at the perimeter of the serving areas of each sector that users will receive a significant proportion of the BS power. By blocking users in these areas, the power that would have been assigned to these users can now be assigned to other users in other parts of the network. As a consequence, the speech service blocking probability in other parts of the network is better than in the equivalent locations in Figure 11 (a) and Figure 11 (d).
4.2.5 Impact of ACI on the QoS for the Data Services

Recall that a mixture of services was simulated using MACcdma - 80% of users use the speech service, 15% utilise the 64 kbps data service and the remaining 5% of users are assumed to use the 144 kbps data service. We have already examined how ACI affects the performance of the speech users in a rural network. Let us now consider the effect ACI has on users of the data services. The QoS results are presented in Figure 12 and Figure 13, for the 64 kbps and 144 kbps data services, respectively. As demonstrated earlier for the speech service, the co-sited QoS results for the data service closely match the QoS for the victim network without adjacent channel interference (‘no ACI’ results).

![Figure 12](image)

**Figure 12** Victim network 64 kbps QoS results when subjected to ACI produced by three different adjacent channel rural networks. Refer to Section 4.2.1 for a description of the adjacent channel network configurations.
At first sight the offset 2 results are unexpected. The QoS appears to get worse as the ACP is increased. Indeed for both data services, the victim network that is afflicted by ACI from the offset 2 network appears to outperform the victim network without ACI for ACP values up to about 43 dB. In order to understand the mechanisms causing these results, we need to examine these statistics more closely and also look at other ways of quantifying the performance of 3G networks.

We will explain the results displayed in Figure 12 by examining blocking probability plots for the 64 kbps service assuming an ACP value of 33 dB (Figure 14). The blocking probability for the victim network without ACI modelled is shown in Figure 14 (a). The plots in Figure 14 (c) and Figure 14 (d) show the percentage blocking for the offset 2 and offset 1 interfering scenarios, respectively.
Earlier we demonstrated that for the offset 2 scenario the location of the dead zones helped improve the network performance in other locations for speech users. The location of the dead zones meant that speech users in other areas could benefit by being assigned more power. This power can also be allocated to data users and improve the blocking performance

**Figure 14**  
Victim network 64 kbps service blocking probability for the offset 1 and 2 adjacent channel rural network configurations for an ACP value of 33 dB. Also the blocking probability when no ACI is present is shown. Refer to Section 4.2.1 for a description of the adjacent channel network configurations.
in areas not containing dead zones. If we compare the plots in Figure 14 (a) and Figure 14 (c), the latter plot has more dark blue areas (less than or equal to 2% blocking) than the former plot. This was an unexpected result because we would not expect the introduction of additional interference to actually improve the performance of one of the victim network’s services.

If the ACP value were increased for the offset 2 scenario, then the speech service dead zones would diminish in size. This means that there would be less power available to improve the performance experienced by other users in the network, regardless of the service type. Eventually, a point is reached when the ACP value is sufficiently high to make the impact of ACI negligible and the dark blue curve approaches the brown area in Figure 12.

Figure 14 (d) shows the blocking probability for the offset 1 scenario. The distinct dead zones for this case (areas with 96% to 100% blocking) are not located in the worst part of the network and no significant power saving is achieved by blocking users in these locations. As a consequence, the overall performance of the 64 kbps service with no ACI [Figure 14 (a)] is similar to the performance of the network with ACI at offset 1 adjacent site locations [Figure 14 (d)]. The main differences between the two plots are the small dead zones at the adjacent site locations in Figure 14 (d). If the ACP value were increased, then these small dead zones would shrink further and the network performance would improve as a result and converge to results similar to those presented in Figure 14 (a). This explains the increase in QoS for the 64 kbps service as a function of ACP for the light blue curve in Figure 12.

For completeness the blocking probability plots for the 144 kbps service are shown in Figure 15. These plots help explain the trends of the offset 1 and offset 2 curves in Figure 13, following the same line of argument put forward for the 64 kbps service.
(a) no ACI.  
(b) Blocking Key.

(c) Offset 2, ACP 33 dB.  
(d) Offset 1, ACP 33 dB.

**Figure 15**  Victim network 144 kbps service blocking probability for offset 1 and 2 adjacent channel rural network configurations for an ACP value of 33 dB. Also the blocking probability when no ACI is present is shown. Refer to Section 4.2.1 for a description of the adjacent channel network configurations.
4.2.6 Alternative Measures of 3G Network Performance

In Sections 4.2.4 and 4.2.5 we demonstrated that the impact of ACI on the QoS of the speech and data services produced interesting results that in some instances were unexpected. There appears to be a symbiotic relationship between the performances of the services, i.e., degradation of the speech service can improve the performance of other services for low ACP values (up to about 43 dB). Indeed, for the offset 2 scenario the QoS actually decreased as the ACP increased. We would, however, expect the overall network capacity to improve as the ACP increases. Later in this section we will describe a method for quantifying the overall network performance. However, before describing this method, we will examine whether the QoS measure, as we have defined it, is an appropriate measure of the performance of each of the services.

The definition of QoS employed so far in this report is the percentage of the simulation area that has less than or equal to 2% blocking. In order to investigate this definition further, let us consider the blocking probability plots displayed in Figure 16 for the offset 2 adjacent channel network scenario. The key for each of these plots is shown in Figure 17. Note that the first band of the key (dark blue colour) encompasses the range of blocking probabilities between 0 and 2% inclusive. The plots in the left hand portion of Figure 16 correspond to an ACP value of 33 dB. Starting from the top of the figure and traversing the figure in a downward direction, the blocking probability plots for the three services are shown in order of increasing data rate. Similar plots are shown in the right half of Figure 16 for an ACP value of 63 dB.

Given the definition of QoS above, the QoS is the proportion of each plot that is coloured dark blue. Starting with the speech service, if we compare the plots in Figure 16 (a) and Figure 16 (b), then it is clear to see that the dead zones have decreased in size as the ACP is increased from 33 dB to 63 dB. This means that the proportion of the area coloured dark blue and hence the QoS also increases. The converse effect is observed for the data services in Figure 16 (c) to Figure 16 (f) inclusive, i.e., the proportion of dark blue area decreases as the ACP is increased. These trends were observed in the previous section. Now let us redefine the QoS to be the proportion of the area with less than or equal to 5% blocking (rather than less than or equal to 2% blocking). To reflect the change in definition of QoS, let us change the key from the one shown in Figure 17 to the one displayed in Figure 18. The blocking probability plots that are associated with the new key are shown in Figure 19.
(a) Speech (ACP 33 dB).
(b) Speech (ACP 63 dB).
(c) 64 kbps (ACP 33 dB).
(d) 64 kbps (ACP 63 dB).
(e) 144 kbps (ACP 33 dB).
(f) 144 kbps (ACP 63 dB).

Figure 16 Victim network blocking probability plots for the offset 2 adjacent channel rural network configuration. The blocking probability for each service is shown for ACP values of 33 dB and 63 dB. The blocking probability key is shown in Figure 17.
Figure 17  Blocking key with the first band defined as 0 to 2% blocking.

Figure 18  Blocking key with the first band defined as 0 to 5% blocking.
Figure 19   Victim network blocking probability plots for the offset 2 rural network configuration. The blocking probability for each service is shown for ACP values of 33 dB and 63 dB. The blocking probability key is shown in Figure 18.
Due to the redefinition of the key for Figure 19, the QoS is still the proportion of the area coloured dark blue. Going through the services, in turn, we see that the QoS for speech increases as the ACP is increased. This trend was also observed in Figure 16. The QoS for the 64 kbps service appears to follow a similar trend. This trend was not observed in Figure 16. Finally, for the 144 kbps service, there is no noticeable change in the proportion of the area coloured dark blue between the plots in Figure 19 (e) and Figure 19 (f). However, a difference was observed earlier between the plots in Figure 16 (e) and Figure 16 (f). These differences demonstrate that the relationship between QoS and ACP is dependent on the exact definition of QoS. Rather than further scrutinising the plots in Figure 16 and Figure 19, it is easier to understand this relationship by examining the probability distribution function (PDF) of the blocking probability for each service type. Figure 20, Figure 21, and Figure 22 show PDFs for speech, 64 kbps and 144 kbps services, respectively, for the simulation results area of the network (refer to Section 4.2.2 for a definition of this area). PDFs are shown for ACP values of 33 dB and 63 dB in each figure. The upper plots in each figure contain curves for the PDF and cumulative distribution function (CDF) for blocking rates in the range 0 to 10%. The lower plots in each figure only contain PDFs. These plots have expanded x-axis and reduced y-axis ranges.

Firstly, let us consider the blocking PDFs and CDFs for the speech service, as shown in Figure 20 (a). The PDFs and CDFs are similar for blocking probabilities of 2% and above for the two ACP values. The CDF for a blocking probability of 2% is equal to the QoS as originally defined. The QoS for both an ACP value of 33 dB and 63 dB is almost identical. Similarly, if we define the QoS as the proportion of bins\(^9\) with less than or equal to a blocking probability of 5%, then determining the QoS from the CDF graphs for a blocking probability of 5% gives similar results for the speech service (for both ACP values). We can observe from Figure 20 (b) that approximately 800 bins have a blocking probability of 100% for an ACP value of 33 dB. These bins, more or less, define the size of the light purple coloured dead zones in Figure 19 (a).

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\(^9\) Throughout this report we refer to a bin either as a radio coverage prediction bin, or a bin of a MACcdma output. A bin is a square that has a particular attribute (for example, a pathloss value or a blocking probability), and a radio coverage prediction or MACcdma output area consists of a regular grid of bins. The MACcdma output bin size is user-definable and sets the geographical bin size of various outputs produced by MACcdma. For all simulations presented in this report the output bin size was set to be equal to the coverage prediction bin size.
Figure 20  Blocking probability PDFs and CDFs for the speech service for the case in which ACI was produced by the offset 2 network.
Figure 21  Blocking probability PDFs and CDFs for the 64 kbps service for the case in which ACI was produced by the offset 2 network.
Figure 22  Blocking probability PDFs and CDFs for the 144 kbps service for the case in which ACI was produced by the offset 2 network.
The story is somewhat different for the 64 kbps data service. In Figure 21 (a), there is a clear shift between the two PDFs. The QoS based on the 2% blocking probability threshold is different for an ACP value of 33 dB and 63 dB. However, the CDFs for the two ACP values converge for high blocking probabilities. This means that the QoS is similar for the 5% definition of QoS. Similar conclusions can be drawn from the results given in Figure 22 for the 144 kbps service. It is also worth noting that for an ACP value of 33 dB, the proportion of bins that have 100% blocking increases for the data services, particularly for the 144 kbps service (compare the graphs in Figure 20 (b), Figure 21 (b), and Figure 22 (b)).

The most important conclusion to make is that varying the level of ACI that a network experiences (by varying the ACP value, for example) can have the effect of shifting the blocking probability distribution. This is especially apparent for the case when the adjacent channel network sites are located in the worst-case positions, ie, for the offset 2 adjacent network. This situation is unlikely to occur in practice, ie, not all adjacent channel sites are going to be located in the worst place from an ACI perspective. The shifts in blocking distribution observed here are not necessarily captured correctly by the measure of network performance used. Indeed, we have demonstrated that by slightly changing the definition of QoS, it is possible to paint quite a different picture.

It is also worth reiterating that we have simulated a mixture of services. The performance of each service is intertwined with the performance of the other services. Given that in our simulations 80% of the traffic consists of speech users and the remaining 20% is data traffic, it can be misleading to examine the performance of each individual service, when, for instance, the 144 kbps service only makes up 5% of the offered traffic. Therefore, we need a method of calculating the overall performance of the network.

In addition to network performance statistics produced over the entire simulation area, MACc dma also generates statistics on the performance of every sector in the network. These statistics include information on the number of calls served by each sector, and are divided into the number of speech calls, \( N_{speech} \), the number of 64 kbps data calls, \( N_{64kbps} \) and the number of 144 kbps calls, \( N_{144kbps} \). It is possible to combine the number of calls served by the network for each service type to compute the effective number of speech calls, \( N_{eff} \), served by a sector using the following equation.
The ratio of the downlink power required for a data service call compared to the power required for a speech service call is given by

\[
N_{eff} = N_{speech} + N_{64kbps} \left( \frac{P_{64kbps}}{P_{speech}} \right) + N_{144kbps} \left( \frac{P_{144kbps}}{P_{speech}} \right),
\]

(5)

Using Equations 5 and 6, the number of effective served speech calls can be evaluated per sector and the total number for all sectors within the simulation area can be computed. Note that a description of the parameters in Equation 6 is given in Appendix A. This appendix also contains the appropriate values for each of these parameters.
should not be considered as the general performance of a rural 3G network when subjected to ACI. In reality, some sites will be co-sited, others will be positioned in the worse possible place to cause ACI to another 3G network, and finally other sites will be positioned in varying positions relative to other 3G sites. Therefore, we would expect the overall network performance in a rural area to be somewhere between the offset 2 curve and co-sited curve, and most likely resembling the co-sited curve in practice. In Section 4.3 an urban 3G network is simulated using MACcdma. In this case a random location of sites is chosen and the results presented will be more representative of the actual expected performance of a 3G network when subjected to ACI.

![Overall network performance for the offset 1, offset 2 and co-sited rural network configurations. The ‘no ACI’ result is also shown as a thick brown line. The middle of the line is equal to the mean of ten simulations with the thickness equal to twice the standard deviation of number of served calls.]

Figure 23

One purpose of the rural analysis was to get an idea of the maximum separation between victim and adjacent network sites that produces a negligible performance degradation of the victim network. Figure 23 gives us an idea of this maximum separation. Take the offset 1 interfering network results as an example. For the UTRA FDD specification value for ACP, the capacity of the network is about 99.4% of the capacity without ACI. One could easily
perceive this as a negligible capacity decrease. For the ACP value expected of real 3G equipment, ie, 43 dB, there is no capacity degradation. Therefore, we can conclude that for adjacent channel sites located halfway between the worst- and best-case positions, there should be little or no concern regarding ACI problems. On a cautionary note, we should re-iterate that the perfect hexagonal arrangement of cells simulated in our rural network is normally never seen in practice.

4.3 Urban Scenario

We next describe the simulation methodology and results for the urban scenario. The location of sites in the urban victim and interfering networks, as we will describe in further detail later, were chosen to be representative of 3G networks. This means that the simulation results should be representative of an urban network As a consequence, we should be able to draw more solid conclusions from the results compared to our analysis of the hypothetical rural scenario investigated in Section 4.2.

4.3.1 Networks and Coverage Predictions

For the urban scenario coverage predictions were generated using MAC Ltd’s proprietary software radio planning tool, the NP WorkPlace. The NP WorkPlace allows sector antennas to be positioned on a digital map. Predictions can then be performed to identify the signal strength from the sectors at various location bins around the antenna. Our analysis was based on a coverage prediction area with dimensions 8 km × 8 km, giving a total area of 64 km². Figure 24 shows a building and vegetation plot from the NP WorkPlace for a small section of this 8 km × 8 km area; the buildings are coloured grey and the vegetation (trees and shrubs, rather than grass) is green. The map has been created to be representative of a typical European city.
4.3.1.1 Serving Network

Before simulating, the layout of the serving network had to be designed to cover the 8 km × 8 km urban area under consideration. Two important factors were the density of the cell sites and the positions of dead zones. We already stated in Section 3.1 that a suitable macrocellular site density is 4.2 sites per square kilometre. Similarly, MAC Ltd previously identified [26] that 226 microcells was an appropriate number of sites to cover a 25 square kilometre area, giving a density of 9.0 microcell sites per square kilometre. Therefore, in total we had 269 three-sectored macrocellular sites and 579 microcellular sites in our 64 square kilometre area.

The sites were placed within the urban area using the following technique. The first macrocell was placed randomly within the network area. The second macrocell was randomly placed in the network area with the constraint that it could not be closer than 250 metres to another macrocell. This value was based on the assumption that macrocells will not be placed too close to each other and was verified by observing the macrocell separation distances currently used by the GSM network operator, O₂, in the centre of London [28]. Only a few
macrocell sites were observed to be separated by less than 250 metres. The remainder of the macrocells were randomly placed, based on the same constraint, until the macrocellular network was complete. Next, microcells were placed using the same random process. Microcell locations were constrained so that no microcell could be any closer than 100 metres to another microcell. This limit was also based on our observations of the O₂ network. A further constraint was applied to the microcell locations in that they could not be less than 200 metres from a macrocell because it is unlikely that a network operator would put microcells close to a co-channel macrocell in a 3G network. After the sites were placed each was reviewed to ensure that it was in a suitable position, ie, macrocells should be on buildings and microcells should be at street level and on the edge of buildings. Figure 25 shows the same area as that shown in Figure 24, but this time the macrocells and the microcells are shown.

![Network Overlay View (Existing Network)](image)

**Figure 25** The sites as they were positioned on the urban map.

Notice that the three-sectored macrocells can be seen as three arrows pointing at 0, 120 and 240 degrees. The microcells are represented by the single arrows. Note also the red arrow in the centre left of Figure 25. This represents a collocated macrocell site, which will be discussed in Section 4.3.1.2.
A suitable antenna and transmit power for the macrocell sites was established after reviewing the data on the RA’s Site Finder website [29]. We established that Hutchison 3G’s UTRA FDD sites typically have an EIRP of 28.7 dBW. Thus, for each sector, we chose a 63-degree beamwidth antenna with a peak gain of 16 dBi and a transmit power of 43 dBm. This gives a maximum EIRP of 29 dBW. Similar values were used in previous work for the RA [26]. The antenna had four degrees of electrical downtilt and the centre of the antenna was five metres above the roof. The microcells were also assumed to be five metres high, but this time above the ground. The antenna was a dipole with no downtilt and the microcell’s transmit power was 37 dBm [18].

MAC Ltd’s proprietary radio prediction algorithms, MiniWorks and MicroWorks, were used to generate signal strength coverage plots for the macrocell sites and microcell sites, respectively.

4.3.1.2 Adjacent Channel Network

Next, the adjacent channel network was set up. In agreement with the RA we assumed that approximately 14% of the sites in a typical 3G network will be collocated, so the first 38 macrocell sites from the serving network were copied to the adjacent channel network. The remaining 231 macrocell sites were randomly placed in our map. We used the same constraints as before; however, apart from the collocated sites, we did not constrain the separations between the adjacent channel sites and the serving sites. The microcells were then placed using the same constraints as for the serving network, but we assumed that there were no collocated microcells and the adjacent channel microcells were placed independently of the serving microcells.

After all the adjacent channel sites were placed in the network they were repositioned onto suitable rooftops or street positions. Note that the collocated sites had exactly the same positions as the serving network equivalents. MiniWorks and MicroWorks were again used to generate signal strength coverage plots for the adjacent channel sites.

4.3.2 Simulation Area

The signal strength predictions were generated over a large area. However, simulations could only be run over a smaller area because simulations over the full area would not be valid at the edges of the map. This is because, if a real network were simulated, UEs at the edge of
the map would experience interference from BSs beyond the range of the map. These BSs cannot be modelled in the simulation because we do not have coverage predictions from BSs outside the map area. In addition, a UE at the edge of the map may be even better served by BSs off the edge of the map. This edge area is represented as the green area in Figure 26. A similar edge effect occurs for the results of the simulation. The performance of the UE at the edge of the simulation square will not be valid because we do not model the effect of UEs outside of this square. This edge area is the brown region in Figure 26. A smaller square in the centre of the map, highlighted in pink, is the area from which the simulation results were extracted. The reasons for the pink, brown and green areas in Figure 26 are similar to the reasons given for the equivalent areas used for the rural network (refer to Figure 8).

![Figure 26](image)

*Figure 26*  Specific areas within the simulation process.

Note that the size of the pink area was 4 km by 4 km, and the square defining the brown region had dimensions of 6 km by 6 km, and the entire area was 8 km by 8 km. Simulation results were obtained for the pink area. The traffic density map was defined for the brown and pink areas and coverage predictions were obtained for all areas contained within the 8 km by 8 km area.
4.3.3 QoS Definition for the Urban Scenario

For the urban network it was decided to define the QoS as the percentage area with less than or equal to 2% blocking for the speech service. Note that alternative definitions of QoS were also analysed, such as the percentage area with less than or equal to 5% blocking. Recall that for the rural network results in Section 4.2.6, the results relating to the offset 2 scenario showed that the 5% definition of QoS produced different results than the 2% definition of QoS. The main reason for this difference was due to the relative positioning of the adjacent channel sites compared to the victim network sites. All adjacent channel sites were located at the worst-case positions of the rural victim network, which caused a change of the blocking distribution for the data services. Refer to Section 4.2.6 for an explanation of this phenomenon. These shifting effects were less apparent for the urban network results presented here because the location of adjacent channel sites was essentially random and there was not a fixed relationship between the position of the victim network sites and the interfering network sites. In others words, in the urban network not all of the adjacent channel sites were located in the worst-case positions. Instead, by chance some were located in poor positions, whilst 14% were in the best possible locations, ie, collocated with the victim network sites. The remainder were located at a range of positions. Therefore, the network-wide changes in blocking distribution evident in the rural network with adjacent channel sites located in the offset 2 positions were not observed in the urban network. As a consequence, we found that the 5% QoS results followed similar trends to the 2% QoS results. Therefore, in subsequent sections only the 2% QoS results will be presented.

4.3.4 Determining the Offered Traffic Density Level

Adopting a methodology similar to that applied for the rural network in Section 4.2.3, the offered traffic density level was determined for the urban network to provide 95% QoS for the speech service, ie, percentage area with less than or equal to 2% blocking. This traffic level was determined for the victim urban network before any ACI was introduced from the adjacent interfering network. As Figure 27 shows, an offered traffic density level of 134 Erlangs per square kilometre was required to provide the necessary QoS.
4.3.5 Accuracy of Results

Compared to the rural scenarios evaluated in Section 4.2, fewer snapshots needed to be evaluated for each \textit{MACcdma} simulation for the urban case. Many more sectors are simulated for the urban scenario compared to the rural scenarios. Also the offered traffic density was higher for the urban network. The number of snapshots required to produce reasonable results was governed by these two factors. As a consequence, all of the urban \textit{MACcdma} results presented in this section were run for 50 snapshots. To illustrate the variability of the QoS results based on 50 snapshots, \textit{MACcdma} was run 12 times for an offered traffic density level of 134 Erlangs per square kilometre. Table 12 shows the mean and standard deviation (stdev) of the QoS for the three service types considered.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{qos_plot}
\caption{QoS for various traffic densities. Each data point represents the result of one \textit{MACcdma} simulation performed for 50 snapshots.}
\end{figure}
As explained in Section 4.2.3 for the rural network, these values for the accuracy of the QoS results are used in many of the graphs presented in this report to demonstrate the statistical validity of the results.

<table>
<thead>
<tr>
<th></th>
<th>64 kbps</th>
<th>144 kbps</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>95.05%</td>
<td>92.97%</td>
</tr>
<tr>
<td><strong>Stdev</strong></td>
<td>0.05%</td>
<td>0.16%</td>
</tr>
</tbody>
</table>

Table 12 Accuracy of QoS results generated by MACcdma for the victim network without ACI modelled. The results are based on 12 repeated simulations of MACcdma where each simulation was evaluated for 50 snapshots.

As explained in Section 4.2.3 for the rural network, these values for the accuracy of the QoS results are used in many of the graphs presented in this report to demonstrate the statistical validity of the results.

4.3.6 Impact of ACI on QoS for each Service Type

The QoS for the victim urban network with the effects of ACI included are shown in Figure 28 for all service types. For the data services, an ACP value of 37 dB is sufficient to make the effect of ACI negligible. The y-axis scale is not appropriate to determine the ACP level to make the ACI negligible for the speech service. Figure 29 shows the speech service results with a more appropriate scale. Bear in mind that each data point of the speech service curve is the result of one MACcdma simulation. There is a small probability that all of the data points for ACP values in excess of, say, 37 dB are equivalent to the no ACI results. However, even if this is not the case, then it is safe to say that for ACP values between 39 dB and 41 dB, the QoS of the speech service for the network is only slightly degraded compared to the network without ACI.

In Section 4.2.6 we demonstrated that in addition to examining the performance of the individual service types, it is also important to analyse the performance of the network as a whole. We will consider these results later in Section 4.3.9.
Figure 28    QoS results for all three service types.

Figure 29    QoS results for the speech service.
In the meantime we will consider another method of analysing the results. One approach of interpreting the results is to quantify the difference in blocking performance of the network close to adjacent channel sites. One can draw circles around adjacent channel sites and compare the level of blocking in the regions contained by the circles with and without the ACI being simulated. Caution should be taken when using this approach because, as we demonstrated for the rural scenario, the effects of ACI are not necessarily restricted to areas in the vicinity of the adjacent sites. Sometimes the occurrence of a dead zone in a network can improve the performance of the network elsewhere. Therefore, the most important analyses are those that evaluate statistics across the whole network. Having said that, the occurrence of a dead zone, however small in size, may be in a location that is in a particularly important area for a network operator. As a consequence, we will examine the performance of the network in the vicinity of adjacent network sites to assess how the network performance in these areas is related to the level of adjacent channel protection.

The performance measure to be adopted is the composite blocking probability within 50 m of the adjacent sites. The composite blocking probability is defined as the number of bad bins divided by the total number of bins. Note that fractional bad bins are allowed as part of this definition. For example, if the blocking probability in a bin is 50%, then it is counted as half a bad bin.

The composite blocking probability for the speech service within 50 m of the adjacent sites is shown in Figure 30 as a function of the adjacent channel protection level. Once again the results are shown for a victim network without ACI. Also, consistent with earlier analyses, the brown line indicating these results is centred on the mean of 12 simulations and the thickness of the line is equal to twice the standard deviation of the variation between simulations. The accuracy of these results is good as shown by the thinness of the brown line in Figure 30. The results with ACI converge to the results without ACI for increasing ACP. For the UTRA FDD specification value of ACP, indicated by the vertical red line in Figure 30, the blocking probability has increased from about 4% (without ACI) to about 8% (with ACI). For an ACP value of 43 dB, the blocking probability increased from approximately 4% to around 5%.
The blocking probability results close to the adjacent site locations are shown for the 64 kbps and 144 kbps services in Figure 31 and Figure 32, respectively. The trends for the curves are similar to the trend observed for the speech service. For ACP values of 33 dB and 43 dB, there is a similar step increase in blocking probability for all services. Indeed, for an ACP value of 43 dB, which is the expected ACP value for real 3G equipment, the incremental increase in blocking probability is about 1% within 50 m of the adjacent channel network sites for all services. One could argue either way whether this is an acceptable degradation in the performance of the network in these areas. It is worth putting these results in perspective. The overall network QoS statistics for each service given in Figure 28 and Figure 29 show little or no degradation in performance for an ACP value of 43 dB, and even for an ACP value of 33 dB it can be argued that the QoS degradation is negligible across the entire network.

**Figure 30** Composite blocking probability for the victim network within 50 m of the adjacent network sites for the speech service.
Figure 31  Composite blocking probability for the victim network within 50 m of the adjacent network sites for the 64 kbps service.

Figure 32  Composite blocking probability for the victim network within 50 m of the adjacent network sites for the 144 kbps service.
4.3.7 Effect of Increasing the Minimum Coupling Loss

One of the possible ACI mitigation techniques is to increase the minimum coupling loss between cell sites and UEs. At 2 GHz the NP WorkPlace applies a minimum coupling loss of approximately 50 dB for microcells and a much higher value is generally predicted for macrocells. In this study we are mostly interested in the adjacent channel interference caused by microcells because of the relatively small isolation between microcells and UEs. Techniques can be used to increase the minimum coupling loss between microcell sites and UEs, such as through the use of antennas with a small vertical beamwidth or by raising the height of antennas. These examples are considered further in the mitigation techniques section of the report (Section 5.5). Suppose that it was possible to increase the minimum coupling loss to 60 dB or 70 dB. In Figure 33 we show the QoS for the speech service for minimum coupling losses of 60 dB and 70 dB. In addition the results with no further imposed minimum coupling loss restriction (blue curve), ie, the approximate 50 dB minimum coupling loss predicted for microcells and a higher value for macrocells predicted by the NP WorkPlace, is shown.

![Figure 33](image-url)

**Figure 33** QoS for speech for different minimum coupling loss values.
These results clearly show that increasing the minimum coupling loss has almost no impact on the overall network performance for the speech service. Figure 34 shows the QoS results for the 64 kbps service. There appears to be more variability in the simulation results for this service type. This is expected because the offered traffic for the 64 kbps service is only 15% of the total offered traffic. More snapshots would have to be run to reduce the variability of the 64 kbps results. Given the relative inaccuracy of the 64 kbps QoS results compared to the speech service results, it makes it difficult to distinguish between the performance of the 64 kbps service across the entire network for alternative minimum coupling loss values. The variability of the 144 kbps results shown in Figure 35 is more pronounced than the 64 kbps QoS results.

Figure 34 64 kbps QoS for different minimum coupling loss values.
We can conclude that using various methods to increase the minimum pathloss has little impact on the overall network performance for the speech service. Although the results for the 64 kbps and 144 kbps data services are masked somewhat by the variability of the results, we would expect the trends for these services to be similar to that of the speech service. This does not mean that increasing the coupling loss does not have the potential to significantly improve the network performance in areas close to adjacent network sites. We can demonstrate this by only examining the blocking probability in an area within 50 m of adjacent network sites, rather than across the whole network. Figure 36 shows these results for the speech service for various minimum coupling loss values. The graph clearly shows that increasing the minimum coupling loss to 70 dB clearly benefits the victim network in the vicinity of adjacent network sites for speech users. The same conclusion can be made for the other service types. In Figure 37 and Figure 38 the blocking probabilities within 50 m of the adjacent sites are displayed for the 64 kbps and 144 kbps services, respectively. A minimum coupling loss of 60 dB does offer an improvement over the standard network configuration (‘predicted coupling loss’ curve in the figures), but a 70 dB minimum coupling loss almost makes the effects of ACI negligible for ACP values in excess of 33 dB.

![Diagram showing 144 kbps QoS for different minimum coupling loss values.](image)

**Figure 35** 144 kbps QoS for different minimum coupling loss values.
Figure 36  Composite blocking probability for the victim network within 50 m of each site for the speech service.

Figure 37  Composite blocking probability for the victim network within 50 m of each site for the 64 kbps service.
4.3.8 Effect of ACI Produced by Different Site Classifications

The results presented in Figure 36, Figure 37 and Figure 38 are the composite results for within 50 m of all adjacent channel sites within the simulation results area of the network. It would be interesting to produce the equivalent results for different classifications of adjacent channel sites. For instance, we could examine the blocking probability only in the vicinity of adjacent network macrocell sites, or collocated sites. The latter blocking probability results are shown in Figure 39 for the speech service. Not surprisingly, we observe that for collocated site positions ACI has no effect on the performance of the network in the vicinity of these sites. Although the equivalent results for the other services are not shown in this report, the results do resemble those of the speech service.

Figure 38 Composite blocking probability for the victim network within 50 m of each site for the 144 kbps service.
We have also produced similar statistics for adjacent channel macrocell sites. The results are shown in Figure 40 and repeated in Figure 41 with an expanded y-axis scale. The first point to note is that increasing the minimum coupling loss to 60 or 70 dB has no impact on the speech service performance for the victim network. Secondly, if we look at the absolute blocking levels in the vicinity of adjacent macrocells compared to the blocking near all sites (as shown by the dark blue curve in Figure 36), then we can conclude that adjacent network macrocells are not the main source of ACI. Once again, to illustrate the points above we have only included the results for the speech service, but all services exhibit the same trends. Macrocell sites tend to have reasonable isolation between the antennas and the users at street level. Antennas are often set back on the tops of buildings and UEs close to a macrocell site are not usually in the boresight of the antennas (except possibly for some in-building users). These factors help to keep the minimum coupling loss at relatively high levels compared to microcells. In Section 5.5 we calculated the minimum coupling loss for an example macrocell to be 58.8 dB. This is almost 10 dB more than the value calculated for a standard microcell of 49.5 dB (also calculated in Section 5.5).

**Figure 39** Composite blocking probability for the victim network within 50 m of the collocated sites for the speech service.
Figure 40  Composite blocking probability for the victim network within 50 m of the macrocell sites for the speech service.

Figure 41  Composite blocking probability for the victim network within 50 m of the macrocell sites for the speech service (different y-axis scale compare to the previous figure).
On the subject of microcells, the blocking probability within 50 m of the adjacent microcells in the simulation results area is shown in Figure 42 for the speech service. Increasing the minimum coupling loss dramatically improves the performance of the speech service in areas close to adjacent network microcells. Comparing the dark blue curve with the one displayed in Figure 40 (for macrocell sites only), it is clear that the ACI caused by adjacent network microcells is greater than that caused by macrocells.

![Figure 42](image)

**Figure 42** Composite blocking probability for the victim network within 50 m of the microcell sites for the speech service.

For example, microcells cause a composite blocking probability of approximately 8.5% within 50 m of each site for an ACP value of 33 dB, whereas macrocells cause a blocking probability of lower than 5.5%. Furthermore, increasing the minimum coupling loss has a pronounced effect on the ACI caused by microcells. This was not observed for the macrocells. Indeed, only minimum coupling losses of maybe 80 or 90 dB would have produced a reduction in the ACI produced by macrocells in the adjacent interfering network. Clearly for an interfering network with a reasonable density of microcells, it is the microcells that are going to cause most of the ACI problems rather than the macrocells. However, for macrocells in an adjacent channel network that do cause a problem, it certainly would be an option to increase the minimum coupling loss to increase the protection. As described in
Section 5.5, operators of both networks would benefit from increasing the minimum coupling loss.

4.3.9 Impact of ACI on Overall Network Performance

An important part of the rural network analysis in Section 4.2 was the results relating to the overall network performance of all services considered together. A method was derived for computing the total number of effective speech calls served by the network. The number of 64 kbps and 144 kbps calls were translated into an equivalent number of speech calls and added to the actual number of speech calls. The same method can be used to compute the number of effective speech calls served by the urban network and the results are shown in Figure 43. These results clearly support some of the earlier urban results. For ACP values of more than 33 dB, the network performance with ACI is similar to the performance without ACI.

![Figure 43](image)

**Figure 43** Total effective number of speech calls served by the urban network with and without ACI.

Although we have presented some interesting urban simulation results in this section, particularly those relating to the effect of minimum coupling loss on reducing the ACI generated by adjacent channel microcells, it is the overall network performance that is most
important to a 3G operator. We have clearly shown here that for the UTRA FDD specification value of ACP, ie, 33 dB, there is little or no overall degradation in network performance produced by ACI.

4.4 Comparison Between Uplink and Downlink Statistics

So far in Section 4 we have considered the overall blocking statistics produced by MAC\textit{cdma}. These statistics include those users that are blocked due to insufficient uplink or downlink resources. We have not analysed uplink and downlink statistics separately because we observed for all of our simulations that the introduction of ACI produced downlink blocking in the victim network and only a small amount of uplink blocking. This is what we would expect for a downlink-limited CDMA system. For completeness, in Figure 44 we show the average uplink and downlink blocking probabilities\textsuperscript{10} as a function of ACP value for a rural victim network with ACI produced by the offset 2 network that had sites located in the worst-case positions.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure44.png}
\caption{Comparison of the average downlink and uplink blocking for the speech service. ACI was produced by the offset 2 rural network.}
\end{figure}

\textsuperscript{10} These averages are the mean of the uplink and downlink blocking PDFs. Examples of blocking PDFs were given earlier in Figure 20, Figure 21, and Figure 22 for the rural scenario.
As we would expect, the downlink blocking decreases with increasing ACP value. Also, given that the downlink is the limiting link, we observe that the uplink blocking is negligible for all ACP values. Although, the uplink blocking statistics were not scrutinised for both urban and rural simulations carried out as part of this study, the uplink blocking was never seen to be a dominant factor compared to the downlink blocking statistics.

5  Dead Zone Mitigation Techniques

We identified a number of potential techniques for combating ACI during our study and have investigated these further. In this section we present a summary of the different techniques and define a set of metrics that we used to measure their relative merits, such as feasibility or anticipated effectiveness. Following this, we discuss each technique in more detail, and explain the current state of the art, when applicable, and describe the potential performance benefits and implementation issues of each.

5.1  Summary of ACI Mitigation Techniques

There are, broadly, three ways to combat ACI, namely:

1. reduce the amount of ACI transmitted by the BS and UE transmitters, or increase the tolerance of their receivers to ACI (ie, increase ACLR and/or ACS);

2. increase the SIR of the wanted signal, either by boosting the wanted signal power or increasing the rejection of co-channel interference; and

3. using higher layer network functions to avoid situations in which high ACI is experienced.

These three categories of solutions will work at different layers of the network, ie, at the physical layer at RF, at the physical layer in the baseband processing, and in the higher layer protocols, respectively. In general, solutions that fall into Category 2 are not specific to mitigation of ACI. Any technique that can be used to decrease the uplink and the downlink interference equally will be viewed as a means to increase the overall system capacity, and given that any such solution would increase implementation costs, no operator would want to dedicate an overall increase in capacity to overcoming ACI. However, if a particular technique was found to offer greater benefit for the downlink, say, and if the perception is
that the downlink is affected most by ACI, then a particular Category 2 solution could be viewed as an ACI mitigation technique. We will see that some of the ACI mitigation techniques proposed fall into Category 2.

The ACI mitigation techniques we identified for further research have been grouped into the categories described above, although in some cases this is somewhat subjective and a particular technique may be viewed as belonging to more than one of these categories. The techniques examined are as follows.

Category 1

- Improved Hardware Design
- Operator Cooperation
- BS Desensitisation
- Increased Minimum Coupling Loss
- Repeating Adjacent Channel Signals

Category 2

- Interference Cancellation
- Smart Antennas (BS & UE)
- Increased Site Density
- Placing Sites in Traffic Hotspots

Category 3

- Call Admission Control
- Bit Rate Relegation
- Hard Handover
- Inter-operator Roaming

Each technique is discussed in more detail in Sections 5.7 through 5.14. We explain whether a particular technique is equally effective at combating uplink and downlink ACI. We also consider whether a technique is effective against a few strong sources of ACI, or provides a general improvement in terms of tolerance to interference. Furthermore, we consider whether solutions are equally applicable for cities and rural environments, or whether a solution
provides a bigger improvement in certain types of environments. Some of the techniques listed above are not considered feasible or effective, but they are included in the list and discussed briefly for completeness. Before our more detailed discussions, however, we provide an overview of the feasibility and potential benefit offered by each technique.

5.1.1 Classifying ACI Mitigation Techniques

It is useful to define metrics that can be used to compare different ACI mitigation techniques. We have classified each of the ACI mitigation techniques considered according to the following characteristics.

**Own Network Benefit**

Specifies whether deploying a particular mitigation technique in one network lessens the effect of ACI for that same network.

**Other Network Benefit**

Specifies whether deploying a particular mitigation technique in one network lessens the impact of ACI for other networks.

**Operator Independence**

A subjective measure of the extent to which operators would be required to cooperate for the particular mitigation technique to be effective.

- 0 = real-time network inter-operability required (e.g., inter-operator handovers)
- 1 = cooperation required with planning and installing physical equipment (e.g., site sharing)
- 2 = cooperation required with planning network configurations (e.g., frequency planning)
- 3 = sharing of network configuration information required (e.g., frequency assignments)
- 4 = no cooperation required

**Feasibility**

A subjective measure of the feasibility of a particular mitigation technique, based on the increase in cost and/or complexity of its implementation.

- 0 = impractical or inefficient (or technology not currently available)
- 1 = significant complexity, cost, or development required
- 2 = requirements of the solution comparable with current state-of-the-art technology
- 3 = implementation relatively straightforward
Effectiveness

A subjective measure of the anticipated effectiveness of a particular mitigation technique.

0 = little impact
1 = some improvement
2 = significant improvement
3 = solves problem

A summary of the mitigation techniques is presented in Table 13 with metrics chosen based on the classifications above. Also the techniques are grouped into the three categories described at the beginning of this section. For each ACI mitigation technique we have considered the application of the particular technique to a victim network only (the ‘own network’) and have considered the interfering network (the ‘other network’) to be unmodified, i.e., not to have the technique in place. The exceptions to this are the operator cooperation techniques, which, by definition, require both networks to have the technique in place. The effectiveness score we have divided into uplink and downlink scores, since some techniques will be asymmetric in this respect. Furthermore, we have scored the effectiveness irrespective of whether the benefit is to the ‘own network’, the ‘other network’, or both, so the effectiveness columns should be read in conjunction with the two network benefit columns.

Note that we have omitted the bit rate relegation and call admission control solutions from the table, because we do not consider them to be viable solutions. Our reasons are discussed in more detail in Sections 5.12 and 5.11, respectively. Note also that we have split the interference cancellation, smart antennas, improved hardware design and operator cooperation solutions into subcategories to provide greater insight into their benefits.

It can be seen that those solutions scoring highest in effectiveness require more operator cooperation (i.e., have a lower operator independence score) than other techniques. Furthermore, these techniques also generally benefit both networks. One exception to this is improved ACLR (particularly for the downlink), which requires no cooperation and also benefits only interfering networks. Of these techniques that require operator cooperation, only one technique (frequency planning) also scores highly for feasibility, although use of repeaters and inter-operator roaming score moderately well.
<table>
<thead>
<tr>
<th>Category</th>
<th>Mitigation Technique</th>
<th>Own Network Benefit</th>
<th>Other Network Benefit</th>
<th>Operator Independence Feasibility</th>
<th>Effectiveness (Uplink)</th>
<th>Effectiveness (Downlink)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Improved Hardware Design (BS ACLR)</td>
<td>Yes</td>
<td>4</td>
<td>1</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>Improved Hardware Design (UE ACLR)</td>
<td>Yes</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Improved Hardware Design (BS ACS)</td>
<td>Yes</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Improved Hardware Design (UE ACS)</td>
<td>Yes</td>
<td>4</td>
<td>0</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>Operator Cooperation – Collocation</td>
<td>Yes</td>
<td>Yes</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>Operator Cooperation – Frequency Planning</td>
<td>Yes</td>
<td>Yes</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>Operator Cooperation – Channel Spacing</td>
<td>Yes</td>
<td>Yes</td>
<td>2</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>BS Desensitisation</td>
<td>Yes</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Increase Minimum Coupling Loss</td>
<td>Yes</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Increase Minimum Coupling Loss</td>
<td>Yes</td>
<td>4</td>
<td>2</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>Repeating Adjacent Channel Signals</td>
<td>Yes</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>Repeating Adjacent Channel Signals</td>
<td>Yes</td>
<td>1</td>
<td>2</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Interference Cancellation (BS)</td>
<td>Yes</td>
<td>4</td>
<td>2</td>
<td>1 or 2(^{11})</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Interference Cancellation (UE)</td>
<td>Yes</td>
<td>4</td>
<td>2</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Smart Antennas (BS) – Uplink Techniques</td>
<td>Yes(^{12})</td>
<td>4</td>
<td>1</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Smart Antennas (BS) – Downlink Beamforming</td>
<td>Yes(^{12})</td>
<td>4</td>
<td>1</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Smart Antennas (UE) – Downlink Beamforming</td>
<td>Yes(^{12})</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Smart Antennas (UE) – Uplink Beamforming</td>
<td>Yes(^{12})</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Increased Site Density</td>
<td>Yes</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Place Sites in Traffic Hotspots</td>
<td>Yes</td>
<td>Yes</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Hard Handover</td>
<td>Yes</td>
<td>4</td>
<td>2</td>
<td>2(^{13})</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Inter-operator Roaming</td>
<td>Yes</td>
<td>Yes</td>
<td>4</td>
<td>2</td>
<td>2(^{13})</td>
</tr>
</tbody>
</table>

Table 13 Summary of mitigation techniques.

5.2 Improved Hardware Design

The ACP that can be expected from typical 3G equipment was investigated earlier, and we showed that current models exceed the ACS and ACLR requirements of the UTRA FDD

\(^{11}\) In the presence of a small number of dominant interferers.

\(^{12}\) Although beamforming benefits the ‘own network’, the benefit to the other network is greater in terms of ACI mitigation.

\(^{13}\) The impact of the solution would depend on the frequency plan as well as which combinations of network operators were collocated on the same building. Using hard handover to solve an adjacent channel interference problem with one neighbour may create a problem for another neighbour.
specifications by a considerable margin. We have also seen from the results of our simulations that further increases in ACP can reduce the size of dead zones. The ACLR and ACS performance of the UE is the dominant factor in the overall ACP of the system, so can improvements in the RF design of the UE realistically be expected? This would seem unlikely without a change in the specifications. Indeed, as UMTS hardware design matures (in the UE in particular), it is likely to be optimised for size and cost, both of which will possibly cause the RF performance to be compromised so that it does not exceed the specification values by such a large margin.

Receiver ACS performance of the UE is governed largely by the IF filters employed. These devices will typically be SAW filters [19] with a bandwidth of 5 MHz and having 30-40 dB rejection at a 5 MHz offset from the band centre. The complexities of SAW filter design are beyond the scope of this brief discussion; however, it is clear that filters having greater adjacent channel rejection are available for BS use, but are considerably larger than those intended for UE use. Although integration of analogue RF front-end modules is progressing [30], use of filters with greater out-of-band rejection to improve ACS will inhibit the miniaturisation of handsets in the future.

Transmitter ACLR performance is governed by the linearity of the power amplifier (PA) employed in the front end. Adjacent channel leakage can be reduced by “backing off”, or reducing the output power of the amplifier, but requires use of a higher power amplifier than would otherwise be required. This will have power consumption implications that may be acceptable at the BS but are unlikely to be so at the UE where battery life is critical. A second possibility is amplifier linearisation, where a predistorter is employed before the PA to compensate for the non-linear characteristics of the amplifier. These techniques have been shown in Reference [31] to improve the ACLR by up to 17 dB for a UMTS BS transmitter. However, for the predistortion process to remain accurate, estimation of the PA characteristics should be adaptive to compensate for the effects of temperature and ageing. This extra complexity may prove prohibitive for the incorporation of linearisation in the UE transmitter.

5.3 Operator Cooperation

As discussed elsewhere in the report, the most effective method of avoiding ACI is to ensure that all operators’ BSs are collocated. There are other areas of cooperation that might be
appropriate; for example, when different carriers are used by operators for different purposes, eg, in hierarchical network configurations, the operators could elect to use their carriers in a manner that ensures that each operator has the carrier devoted to microcells at the same end of their spectral allocation (or when they have three carriers, in the centre). This approach would enable each operator with two carriers to have one carrier, the microcell carrier, with a greatly reduced ACI.

Other strategies involve adjusting the spacing between carriers so that a larger guard band is achieved between carriers. Figure 45, taken from the UK TAG Update Report [32] shows the effects of adjusting the channel separation on adjacent channel interference ratio (ACIR).

![Figure 45](image.png)

**Figure 45** Curves showing variation of ACIR with Carrier Spacing (The Nokia submission is the upper curve, the Ericsson submission is the lower curve). This graph was taken directly from the UK Tag Update Report [32].

At 5 MHz separation we observe an ACIR of 30 dB. Although decreasing the channel separation from 5 MHz results in a rapid reduction in ACIR, increasing the separation results in a slow increase in ACIR. At 5.5 MHz, the ACIR increases to 32 dB, and by 7 MHz it still increases to only 35 dB (following the Ericsson curve). Consequently, a small increase in channel separation will provide very little benefit. Thus increasing channel separation between operators is unlikely to offer a resolution to the problem of dead zones.
5.4 BS Desensitisation

One way of protecting a BS from ACI is to introduce uplink attenuation. This will have the undesired consequence of raising the noise floor, and therefore will require greater transmit powers by the UEs. However, if the cell is not coverage-limited (this being the case for microcells and picocells), this increase in power is less important, as the power rise does not affect pole capacity. Note that although such desensitisation will increase the co-channel interference to other BSs in the network, as the UE transmit powers will be higher, it may also result in an increase in ACI to the uplink of BSs operating on an adjacent channel because the powers are greater than they might otherwise be.

5.5 Increased Minimum Coupling Loss

If collocation is impractical one solution to reducing or eliminating dead zones is to design the sites such that the coupling loss to nearby UEs is maximised without compromising the pathloss to UEs at the cell edge. This can be achieved by mounting the antennas as high as possible to increase the pathloss to a UE below, and having a narrow beam directed toward the outer reaches of the cell [24].

For a typical macrocell we considered an antenna similar to a Jaybeam type 5044110, which is a sector antenna developing a gain of 17 dBi with a downtilt of 10º and a vertical beamwidth of 8º. With this antenna mounted at a height of 15 m, the minimum coupling loss (MCL) to a UE at a height of 1.5 m was 58.8 dB assuming free space propagation. This maximum occurred a distance of 70 m from the BS. If the height of the BS were increased to 30 m, then the MCL increases to 65.3 dB, and the distance increases to 150 m. An antenna of similar size, and therefore similar vertical beamwidth but with less downtilt will develop a larger MCL; however, higher gain would be developed toward the horizon and hence more inter-cell interference would be generated.

For a typical microcell we assumed an antenna similar to a Jaybeam type 5027, which is a patch antenna developing a gain of 4.5 dBi with a vertical beamwidth of 100º. With this antenna mounted at a height of 5 m, the MCL to a UE at a height of 1.5 m was 49.5 dB, assuming free space propagation. This maximum occurred a distance of 5 m from the BS. If the height of the BS were increased to 15 m, then the MCL increases to 61.3 dB, and the distance increases to 19.5 m. If we were to replace the microcell antenna with the macrocell antenna, but maintain the same power into the microcell antenna and sensitivity,
(simplistically by introducing a 12.5 dB attenuation in the feed), then the MCL would be 71.3 dB (58.8 dB + 12.5 dB). In this way we gain 10 dB in MCL. Thus, raising the antenna height, and using antennas with narrower vertical beamwidths increases the MCL. Increasing the MCL causes the powers of nearby UEs to rise, but these UEs would be at very low power, so the effect on intra-cell interference is small. The advantage is that the increase in MCL provides increased protection from UEs transmitting on adjacent channels. Furthermore, the increase in MCL reduces the level of downlink ACI suffered by UEs operating on adjacent channels; and so, increasing the MCL offers significant benefits for both networks. In essence we are using desensitisation only where required.

In Section 4.3.7 we described the effect of MCL on the performance of an UTRA FDD urban network as determined by simulation using MACcdma. We showed that the overall performance of a network subjected to ACI did not change as the MCL was increased. However, we did show some interesting results in localised areas in which ACI was being produced from adjacent channel microcells. These results showed that increasing the minimum coupling loss for microcells to 70 dB almost removed the dead zones caused by these microcells, assuming an ACP value of 33 dB.

We have certainly shown that increasing the MCL is an effective solution. However, we must question the practicalities of using such a technique. There are obvious repercussions of installing, at microcell sites, relatively large macrocell panel antennas instead of small microcell patch antennas. For instance, site acquisition is made much more difficult, and there may be serious effects on the performance of the network, ie, the design of the network may be far from ideal.

5.6 Repeating Adjacent Channel Signals

The adjacent channel problem arises because the pathloss from a UE to the BS operating on the adjacent channel is considerably less than the pathloss from the UE to the serving BS. If a means of reducing the pathloss from the UE to the serving BS were to be introduced, then the adjacent channel problem could be mitigated. One device used for reducing pathloss is the repeater.

Let us assume that the repeater shares its serving antennas with the adjacent channel BS. In this case we can ensure that the repeated signal is always received at a level above the ACI.
For example, assuming an ACP of 33 dB, we could consider repeating the signal at the adjacent channel BS at a level 23 dB below the adjacent channel power, thus giving 10 dB downlink margin. If the adjacent channel BS transmits at 43 dBm, then the repeater will transmit at 20 dBm, ie, 100 mW. This means that a UE served by the adjacent channel BS would experience downlink ACI that is 56 dB (43 dBm – (20 dBm – 33 dB)) below the wanted signal level. This should provide adequate protection for the adjacent channel network. Considering the converse situation, the downlink ACI produced by the adjacent channel BS is 10 dB (ie, the downlink margin) below the wanted signal received by a UE served by the repeater. This protection is not as high as the protection provided to the adjacent channel network; however, it would be sufficient to significantly improve the downlink performance for the serving network compared to the performance of a similar network without the repeater installed. The uplink signal, of course, would be received at the repeater, and uplink power control would act to reduce the transmit power of a UE as it approaches the adjacent channel BS. Note that no handover occurs, the UE moves seamlessly into the repeater coverage area and so it is always protected from the ACI.

There are of course some significant problems with this approach, and these arise from the backhaul. We can consider two basic categories of repeater, namely the on-frequency repeater, and all other types. A block diagram of the on-frequency repeater is shown in Figure 46. For this category of repeater the signal is transmitted by the donor BS and received by the donor antenna. The received signal is amplified by the repeater and retransmitted from the repeater serving antenna. In the reverse direction, the signal is received at the repeater serving antenna, amplified and retransmitted via the donor antenna to the donor BS.
The key requirements of the on-frequency repeater are that

- the isolation between the repeater serving antenna and the donor antenna is greater than the repeater gain to prevent oscillation;
- the delay caused by the repeater is small so that the direct paths and repeated paths may be combined to provide a diversity gain; and
- the additional noise introduced by the repeater should be minimised to prevent capacity and coverage loss at the donor cell.

For other repeater types, the first requirement, ie, the isolation requirement, is eliminated since the transmission to and from the donor BS occurs via a different channel, either on a different frequency or via a different medium, eg, optical fibre. In other words, it is not possible for the repeater to receive an attenuated version of its transmitted signal. We shall therefore consider only the on-frequency repeater, since it is the most difficult type to implement.

Since the purpose of the repeater is simply to combat ACI and **not** to provide additional coverage, we can arrange that the target $E_b/I_0$ at the repeater is considerably higher than that needed at the donor BS. Let us call the difference between the repeater $E_b/I_0$ and donor BS $E_b/I_0$, the $E_b/I_0$ margin. The collocated adjacent channel BS would, more or less, see an interfering UE (served by the repeater) as another intra-cell interferer if the $E_b/I_0$ margin was
set to the ACP value of 33 dB. This situation is far better than if a repeater were not used, in which case a UE would be observed by the adjacent channel BS as a rogue UE that is not utilising power control.

Given the argument outlined above, it would be sensible to place an upper limit on the $E_b/I_0$ margin and restrict the margin to the ACP of the link between adjacent channel BS and served UE. We could opt for an $E_b/I_0$ margin of 20 dB, for example. Enforcing such a margin would increase the target received power at the repeater. This means that the degradation in SIR introduced by the repeater is small (due to the thermal noise produced by the amplifier), and so the noise rise at the donor BS is small. The other advantage of a high target received power at the repeater is that the gain of the repeater need not be too high and consequently, the isolation requirement is eased.

Now let us consider the link budget for this repeater. Firstly, we will examine the downlink.

### 5.6.1 Downlink Link Budget

In the downlink we must ensure that the SIR of the repeated transmission is sufficient for the UE to successfully decode the signal. It would be sensible to limit the gain of the repeater to 30 dB so that oscillation does not occur due to feedback between the donor and repeater serving antennas (ie, the isolation between these antennas should easily be more than 30 dB). We suggested earlier that the output power of the repeater should be 20 dBm to provide a 10 dB margin on the downlink. This means that the received level at the port of the donor antenna would have to be $-10$ dBm to achieve the output power of 20 dBm (given that the assumed repeater gain is 30 dB). Let us assume a donor antenna gain of 20 dBi, and a donor BS EIRP of 55 dBm. Such a scheme would limit our pathloss between the donor BS and donor antenna to $55 + 20 - ( -10 ) = 85$ dB. In general, the donor and donor BS antennas will have clear line-of-sight to one another, and therefore, we use a free space propagation model to compute the maximum separation between the donor BS and the repeater location. This separation is 212 m at 2 GHz. Such a small separation is insufficient for removing dead zones at the cell edge of the donor BS. For example, in the rural network analysed in this report, we assumed a cell radius of 5.6 km. At this distance, the free space pathloss is 113.4 dB, so for a repeater located at the cell edge, we would have to overcome at least 113.4 dB. Given our assumed values for antenna gains and EIRP of the donor BS, the received level at the port of the donor antenna (input of the repeater from the donor side) would be $55 + 20 - 113.4 =$
−38.4 dBm, and so to achieve our desired repeater transmit power of 20 dBm, we require a repeater downlink amplifier gain of 58.4 dB. Such a high gain requires an even higher isolation between the donor antenna and repeater serving antenna, ie, an isolation of more than 58.5 dB is required between the two antennas.

Note that the EIRP of the repeater (from the repeater serving antenna) is 40 dBm, assuming an antenna gain of 20 dBi for the repeater serving antenna. The maximum pathloss given in Table 2 for a speech downlink link budget was 150 dB for an EIRP of 44 dBm, if we assume no UE body loss. For our repeater EIRP of 40 dBm, the maximum pathloss reduces to 146 dB. The downlink range (corresponding to this pathloss) provided by the repeater should be reasonable.

The link budget for the downlink discussed above is summarised in Table 14.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Formulae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Donor BS max traffic channel power</td>
<td>35</td>
<td>dBm</td>
<td>a</td>
</tr>
<tr>
<td>Donor BS antenna gain</td>
<td>20</td>
<td>dBi</td>
<td>b</td>
</tr>
<tr>
<td>Donor BS EIRP</td>
<td>55</td>
<td>dBm</td>
<td>c=a-b</td>
</tr>
<tr>
<td>Pathloss from donor BS to donor antenna</td>
<td>113.4</td>
<td>dB</td>
<td>d</td>
</tr>
<tr>
<td>Donor antenna gain</td>
<td>20</td>
<td>dBi</td>
<td>e</td>
</tr>
<tr>
<td>Power at port of the donor antenna</td>
<td>-38.4</td>
<td>dBm</td>
<td>f=c-d+e</td>
</tr>
<tr>
<td>Repeater downlink amplifier gain</td>
<td>58.4</td>
<td>dB</td>
<td>g</td>
</tr>
<tr>
<td>Repeater transmitter power</td>
<td>20</td>
<td>dBm</td>
<td>h=g+f</td>
</tr>
<tr>
<td>Repeater serving antenna gain</td>
<td>20</td>
<td>dBi</td>
<td>j</td>
</tr>
<tr>
<td>Repeater EIRP</td>
<td>40</td>
<td>dBm</td>
<td>k=h+j</td>
</tr>
<tr>
<td>Adjacent site max total downlink power</td>
<td>43.0</td>
<td>dBm</td>
<td>m</td>
</tr>
<tr>
<td>Downlink ACP</td>
<td>33</td>
<td>dBm</td>
<td>n</td>
</tr>
<tr>
<td>Downlink margin</td>
<td>10.0</td>
<td>dB</td>
<td>p=n-(m-h)</td>
</tr>
</tbody>
</table>

Table 14 Repeater link budget for the downlink.

5.6.2 Uplink Link Budget

The uplink presents less of a problem. The repeater will add noise to the signal, but we need to ensure that this noise does not significantly affect the capacity of the donor cell. Table 15 shows an example link budget for the uplink. Let us walk through the link budget calculation starting from the top and working down.
Assuming a noise figure at the donor BS of 5 dB, we have a thermal noise floor of −169 dBm/Hz. On the uplink we can assume a noise rise of 6 dB due to inter-cell and intra-cell interference at 75% loading (refer to Section 3.1). Hence, the revised donor BS noise

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Formulae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal noise density</td>
<td>-174</td>
<td>dBm/Hz</td>
<td>a</td>
</tr>
<tr>
<td>Donor BS noise figure</td>
<td>5</td>
<td>dB</td>
<td>b</td>
</tr>
<tr>
<td>Donor BS receiver noise power density</td>
<td>-169</td>
<td>dBm/Hz</td>
<td>c=a+b</td>
</tr>
<tr>
<td>Uplink interference margin</td>
<td>6</td>
<td>dB</td>
<td>d</td>
</tr>
<tr>
<td>Revised donor BS receiver noise power density</td>
<td>-163</td>
<td>dBm/Hz</td>
<td>e=c+d</td>
</tr>
<tr>
<td>Acceptable donor BS receiver noise rise</td>
<td>0.1</td>
<td>dB</td>
<td>f</td>
</tr>
<tr>
<td>Revised donor BS receiver noise power density (inc noise rise)</td>
<td>-162.9</td>
<td>dBm/Hz</td>
<td>g=e+f</td>
</tr>
<tr>
<td>Noise power density at donor BS arising from repeater</td>
<td>-179.3</td>
<td>dBm/Hz</td>
<td>h=e+10log[10^{(E_b)}-1]</td>
</tr>
<tr>
<td>Pathloss from donor BS to donor antenna</td>
<td>113.4</td>
<td>dB</td>
<td>j</td>
</tr>
<tr>
<td>Donor BS antenna gain</td>
<td>20</td>
<td>dBi</td>
<td>k</td>
</tr>
<tr>
<td>Transmitted noise EIRP density from the donor antenna at the repeater</td>
<td>-85.9</td>
<td>dBm/Hz</td>
<td>m=h+j-k</td>
</tr>
<tr>
<td>Donor antenna gain</td>
<td>20</td>
<td>dBi</td>
<td>n</td>
</tr>
<tr>
<td>Noise power density at port of donor antenna</td>
<td>-105.9</td>
<td>dBm/Hz</td>
<td>p=m-n</td>
</tr>
<tr>
<td>Repeater noise figure</td>
<td>10</td>
<td>dB</td>
<td>q</td>
</tr>
<tr>
<td>Repeater noise power density</td>
<td>-164</td>
<td>dBm/Hz</td>
<td>r=a+q</td>
</tr>
<tr>
<td>Maximum allowable uplink gain of repeater</td>
<td>58.1</td>
<td>dB</td>
<td>s=p-r</td>
</tr>
</tbody>
</table>

Table 15  Repeater link budget for the uplink.\(^{14}\)

Assuming a noise figure at the donor BS of 5 dB, we have a thermal noise floor of −169 dBm/Hz. On the uplink we can assume a noise rise of 6 dB due to inter-cell and intra-cell interference at 75% loading (refer to Section 3.1). Hence, the revised donor BS noise

\(^{14}\) The 10log(12200) factor (in the bottom row of the table) converts the effective isotropic radiated energy per bit, $E_b$ (-160.5 dBm/Hz) to the equivalent signal power using the relationship, $P = E_b R_b$, where $P$ is the signal power and $R_b$ is the data rate.
floor is −163 dBm/Hz. We will allow the repeater to raise this noise floor by no more than a further 0.1 dB bringing the total noise level at the donor BS to −162.9 dBm/Hz. This is equivalent to linearly adding a further −179.3 dBm/Hz of noise power spectral density, arising from the repeater, to the noise floor of −163 dBm/Hz. As calculated above, if we assume a pathloss of 113.4 dB to a repeater at the edge of our donor cell, the transmitted noise EIRP from the donor antenna at the repeater becomes −85.9 dBm/Hz. This calculation assumes that the donor BS antenna gain is 20 dBi. Taking into account the donor antenna gain, also 20 dBi, the output of the repeater (or port of donor antenna) should transmit no more than −105.9 dBm/Hz towards the donor cell. If the repeater amplifier has a noise figure of 10 dB, then its noise floor will be −164 dBm/Hz, and therefore the uplink gain of the repeater should be no more than 58.1 dB.

Let us now consider the uplink signal power. If we require an $E_b/I_0$ at the donor BS of 7.1 dB, for example, then we need an $E_b$ of −155.8 dBm/Hz to overcome the $I_0$ of −162.9 dBm/Hz. To achieve this $E_b$ at the donor BS, we must transmit this signal from the donor antenna at the repeater with an effective isotropic radiated energy per bit of −62.4 dBm/Hz. Given that the transmitted noise PSD from the donor antenna was calculated earlier to be −85.9 dBm/Hz, we have a transmitted $E_b/I_0$ of 23.5 dB. Assuming that we have an uplink repeater amplifier gain of 58.1 dB and a donor antenna gain of 20 dBi, then we have an uplink effective isotropic radiated energy per bit of −140.5 dBm/Hz. We note that this level is some 15.3 dB greater than that required at the donor site (−155.8 dBm/Hz).

Once we consider the repeater serving antenna gain (also 20 dBi) we can accept an uplink effective isotropic radiated $E_b$ of −160.5 dBm/Hz. If we assume that the UE could transmit at a maximum power of 21 dBm using the 12.2 kbps service, then the isotropic pathloss may be no more than $21 - (−160.5) - 10\log(12200) = 140.6$ dB. This maximum pathloss will ensure that the uplink range provided by the repeater is reasonable.

Note that the cost of off-the-shelf repeaters that meet the requirements for the solution discussed above is relatively inexpensive. For example, at the time of writing UMTS repeaters cost approximately £1500 to £8000 [33]. Although there would be other costs involved with a repeater solution, the costs would not be prohibitive, ie, it is a workable solution given current technology.
In summary, an on-frequency repeater is workable although the donor antenna at the repeater and the serving antennas at the repeater will have to be carefully arranged to obtain isolation between the two antennas that is at least, say, 15 dB greater than the repeater amplifier gain, ie, of the order of 75 dB. This would provide a significant margin to prevent oscillation from occurring.

5.7 Interference Cancellation

As each CDMA receiver has to deal with co-channel interferers transmitting in the same bandwidth (albeit using different spreading codes), CDMA systems are inherently interference-limited. On the uplink each UE transmits asynchronously such that its signal arrives at the BS corrupted by the characteristics of the mobile radio channel. On the downlink, although the signals for different UEs are summed synchronously before transmission, the downlink signals are corrupted by mobile radio channel dispersion, which destroys the code orthogonality of the spreading codes for the different UEs.

Conventional CDMA receivers, such as the matched filter, detect the signal of the desired user by matching the received signal with a known replica of the spreading code of the desired user. RAKE receivers improve on this design by exploiting multipath diversity; matching a known replica of the spreading code of the desired user with the received signal at different delays in order to achieve multipath gains.

However, matched filters and RAKE receivers do not actively try to reject interference from other users. In an effort to improve the performance of CDMA receivers, multi-user receivers that actively mitigate against interfering signals have been proposed. Although these receivers have been developed to combat co-channel interfering signals, there is potential to exploit these receivers for ACI mitigation.

5.7.1 Multi-user Receivers

The optimum CDMA receiver was first proposed by Verdú [34], who showed that the receiver is capable of recovering a wanted signal in the presence of interference, provided that the spreading codes of the wanted and interfering signals are known, along with the amplitude, phase and timing information of the wanted and interfering signals. Since then, numerous papers have been published suggesting sub-optimum receivers for recovering a
wanted signal in the presence of interfering signals. These receivers can be broadly divided into two categories, ie, non-blind receivers and blind receivers.

5.7.1.1 Non-blind Multi-user Receivers

With non-blind receivers *a priori* information about all the signals, desired and interfering, is required. The information required includes the spreading codes and mobile radio channel estimates for all the signals. This information allows the receiver to estimate the interfering signals and remove the impact of these signals from the composite received signal, leaving only the desired signal. Typically, these receivers require large amounts of processing power and tend to be appropriate for BS receivers because a BS knows the spreading codes and has the channel estimates for all the intra-cell UEs.

Linear versions of the non-blind receivers include the decorrelating and minimum mean square error (MMSE) receivers [35, 36]. With decorrelating receivers, a matrix is constructed using the spreading codes and channel information of all the signals that make up the composite received signal. This matrix is then inverted and applied to the received signal in order to recover all the signals, including that of the desired user. As the name implies, these receivers remove the correlation between the various signals, but they do so at the expense of enhancing the receiver noise. The MMSE receivers construct the same matrix, but include in that matrix the effect of the noise variance and the energy levels of the different signals. The aim of MMSE receivers is to minimise the mean square error between the output signal of the receiver and the transmitted signals. These receivers also attempt to decorrelate the different signals from each other but aim to achieve a balance between decorrelation and noise enhancement.

Non-linear versions of non-blind receivers include interference cancellation receivers [37, 38]. With interference cancellation receivers the spreading codes and channel information of the interfering signals are used to produce estimates of the interfering signals, so that the interfering signals can be cancelled from the composite received signal, leaving the desired signal in the residual. The performance of these receivers depends on the accuracy of the signal estimation process, but the cancellation process can be performed iteratively to successively reduce the interference and produce better estimates for the next cancellation stage. Any type of CDMA receiver can be used in the signal estimation process, including the matched filter or the MMSE receivers.
In a simulation study that compared different non-blind receivers [39], it was found that with perfect power control in an additive white Gaussian noise (AWGN) channel, the linear receivers provided a threefold capacity improvement compared to the capacity provided by a matched filter, whilst the non-linear receivers provided a fourfold capacity improvement. When the bit error rate performance of the receivers was analysed and compared against the single-user bound (ie, the performance with no interference), it was found that the non-blind multi-user receivers followed the single-user bound closely with a degradation varying between 0.5 dB to 1 dB.

In the presence of a dominant interferer with a power rising to 30 dB above the power of the wanted signal, the multi-user receivers provided a great improvement over the matched filter. The matched filter performance suffered a large degradation in the presence of strong interference, whilst the multi-user receivers were able to closely follow the single-user bound, ie, the multi-user receivers (with the exception of the parallel interference cancellation receiver), were able to almost completely cancel the dominant interferer from the received signal.

The multi-user receivers were also evaluated in flat Rayleigh fading channels, and two-path frequency-selective Rayleigh fading channels (with no dominant interferer). In this case, the matched filter showed large performance degradations with no significant improvement when the received SNR of the desired signal was increased. When perfect channel estimation was assumed, the performance of both the linear and non-linear receivers closely followed the single-user bound. For example, in a system with 10 users, a processing gain of 31 and the flat Rayleigh fading channel (assuming perfect channel estimation), a SNR value of approximately 13 dB was required to achieve a bit error rate of $10^{-2}$ with the multi-user receivers, whilst the matched filter was not able to achieve a bit error rate of $10^{-2}$.

However, when channel estimation errors were introduced, the interference cancellation receivers (ie, non-linear receivers) did not improve once the received SNR increased beyond a certain threshold, whereas the linear receiver performance showed continual improvement with increasing SNR (although both types of receiver still performed much better than the matched filter). This indicates that non-linear receivers, which utilise a signal estimation and regeneration process, require good channel estimates for effective interference cancellation. Similarly, when the performance with the frequency-selective Rayleigh fading channels was analysed (with channel estimation errors), it was found that the RAKE receiver (the
conventional receiver for frequency-selective channels) had an irreducible bit error rate of \(4 \times 10^{-2}\). At this bit error rate the multi-user receivers gave performance gains of approximately 7 dB compared to the matched filter.

5.7.1.2 Blind Multi-user Receivers

Blind receivers [40] are so-called because they do not require any information about the interfering signals. These receivers only need a priori information about the wanted signal, ie, the spreading code and channel information, and were developed in order to provide interference mitigation capabilities for a UE receiver with lower complexity. These receivers usually model the interfering signals as random signals and estimate the statistics of these signals in order to mitigate against them. Most blind receivers are based on the MMSE optimisation criterion and aim to optimise the receiver such that the square of the error between the output signal and the transmitted wanted signal is minimised. Typically, blind receivers are implemented using adaptive algorithms that require a convergence period in order to optimise the receiver for the desired signal. The adaptive algorithm also has to be able to track the varying conditions of the mobile channel.

In one study [41] that compared two different versions of blind receivers with the matched filter, the simulation results showed that bit error rate performances of at least an order of magnitude better than the conventional matched filter could be obtained for a synchronous AWGN CDMA system with a processing gain of 64 and 16 users in the system. In this case the power ratio between each interferer and the desired user was 14 dB. For a system with the same processing gain, the desired user and three very strong interferers, ie, a power ratio of 26 dB between each interferer and the desired user, similar performance gains were obtained.

It is difficult to achieve the same performance gain with a blind MMSE receiver as that achieved with a non-blind MMSE receiver that has information regarding all the interferers. In general, blind receivers show a degradation of at least 2-3 dB compared to the non-blind MMSE receiver [42, 43]. However, in general terms, the BER performance of a blind receiver still shows at least an order of magnitude improvement over the conventional matched filter. It is difficult to quantify accurately the performance gains that multi-user receivers provide compared to the conventional matched filter or RAKE receiver, because in realistic channel conditions with fading multipath channels the conventional receiver is not able to achieve sufficiently low error rates for direct comparisons with multi-user receivers.
A receiver that combines non-blind and blind multi-user estimation techniques has been proposed [43] for the scenario in which a BS has all the required information about its intra-cell UEs but no information about the inter-cell UEs. This so-called partially blind receiver initially uses the information on all the intra-cell users, ie, spreading codes and channel information, in order to obtain estimates of the intra-cell interfering signals. These estimated interfering signals are then subtracted from the received composite signal and blind estimation is performed on the residual signal in order to provide a good estimate of the desired signal. This receiver showed an improvement over the blind MMSE receiver that had no information about any of the interfering signals, including the intra-cell interferers.

Simulation results were presented for a CDMA system with a processing gain of 31, 12 intra-cell UEs received at equal power, and 12 inter-cell UEs received at 36% of the power of the intra-cell UEs. In order to achieve a bit error rate of $10^{-2}$, the blind MMSE receiver required a SNR value of approximately 11 dB, whilst the partially blind MMSE receiver needed a SNR value of approximately 9 dB. The matched filter was unable to achieve the bit error rate of $10^{-2}$. The study also presented the results for an ideal scenario, in which the known intra-cell interferers could be cancelled perfectly leaving only the inter-cell interference for the blind component of the receiver. The results showed that a SNR value of 7 dB was needed to obtain a bit error rate of $10^{-2}$.

In order to gain an approximate comparison between the matched filter, blind and non-blind receivers for this scenario, the results showed that at the bit error rate floor of $4 \times 10^{-2}$ for the matched filter, the blind MMSE receiver provided a gain of approximately 5 dB compared to the matched filter, whilst the non-blind MMSE receiver gave an additional 2 dB gain above that of the blind receiver. It should be noted that as the matched filter had an irreducible error floor, the gains of the blind and non-blind receivers improved as the desired bit error rate decreased.

### 5.7.2 Using Interference Rejection to Counter ACI

Given sufficient processing power and information about the wanted and interfering signals it should be possible to use interference rejection to remove ACI from the received signal. However, we must accept that processing power is limited, and it is unlikely that real-time information about the spreading codes allocated to users of adjacent channel systems would be available. Although it may be possible for a BS to deduce the spreading codes being used
by adjacent channel UEs (and generate channel estimates for those interfering signals), no such equivalent information will be available at the UE. Therefore, only blind interference rejection techniques could be used at the UE, and although there is a possibility that non-blind or partially blind interference rejection techniques could be used at the BS, we must be realistic about what can be achieved with interference rejection in terms of mitigating against ACI.

5.7.2.1 Downlink ACI Mitigation

For the downlink, at power-on a UE located in a dead zone (created by adjacent channel signals from a nearby BS) will not be able to obtain any information about its home network. Hence the UE will not be able to register with its network to make a call, and interference rejection will offer no benefits.

Interference rejection may be able to offer benefits for a UE that moves into a dead zone whilst in-call. When there is no ACI present, a serving BS is just able to allocate sufficient power to enable a UE at the cell boundary to decode the wanted signal in the presence of the intra-cell and inter-cell interference. The total interference received by the UE is a combination of the downlink power allocated to the other intra-cell users (which is no longer orthogonal to the wanted signal due to radio channel dispersion) and the power transmitted by several of the neighbouring BSs. No single source of interference dominates, because at the cell boundary the UE is normally a reasonable distance from each of the two, three (or more) nearest BSs (one of which is the serving BS). Note that we are assuming here that the serving BS and the nearest BSs all have similar cell loading.

In the presence of ACI, when a UE is at the boundary of the dead zone, it is also effectively at the boundary of its own cell (although the cell boundary has moved following the introduction of ACI). At the boundary of the dead zone the serving BS is just able to allocate sufficient power to enable the UE to decode the wanted signal in the presence of the same-system (intra-cell and inter-cell) and the adjacent channel system interference. If the dead zone boundary is close to the position of the cell boundary when there is no ACI, it is likely that no single source of interference will dominate (as when there is no ACI). On the other hand if an adjacent channel BS is located at the boundary of the serving cell, then as a UE approaches the adjacent channel BS it is likely that the ACI will dominate. Therefore, given that there is potential for ACI to dominate over other sources of interference, it is unclear
whether the published simulation results for co-channel interference rejection can be directly applied to the mitigation of downlink ACI. Clearly, more research would have to be carried out in this field to obtain a better understanding of the potential gain of utilising interference rejection when a UE is subjected to high levels of ACI relative to the co-channel interference level.

We discount the ability to use non-blind interference rejection of the same cell users, because we assume that the UE will not have sufficient processing power, and it will not have channel estimates for the other UE signals. For cases in which the ACI dominates (ie, when a UE approaches the adjacent channel BS moving further into the nominal dead zone area), the gains from non-blind rejection of the same cell users will diminish. Therefore, the preferred option is to use blind rejection of all unwanted signals.

From the review of blind interference rejection techniques in Section 5.7.1.2, we know that blind interference rejection techniques may be capable of boosting the wanted signal by somewhere in the region of 4-5 dB, or in effect, increasing the ACP value by 4-5 dB. However, we do not know that this gain would be achieved consistently, and the gain may be affected by the relative levels of co-channel and adjacent channel interference.

5.7.2.2 Uplink ACI Mitigation

A UE that is creating uplink ACI is located within the service area of its own serving BS, and also within the service area of the adjacent channel BS. As a result of the finite ACP, any UE that is creating uplink interference is normally transmitting at relatively high power (ie, a reasonable distance from its serving BS) and well within the service area of the adjacent channel BS. To the nearby adjacent channel BS, the UE appears as a rogue same cell user that is not utilising uplink power control. It is well known that power control is crucial to the operation of CDMA systems, because if a user at a given location transmits at twice the required power, it consumes the capacity resources of two users. Therefore, if not controlled or mitigated, uplink ACI can have a dramatic effect on the operation of a CDMA network.

The effect of uplink ACI will be lessened because the UEs will be distributed over each BS’s service area, and although UEs may cluster in one particular area it is likely that only a few UEs will create significant levels of uplink ACI. Furthermore, and more importantly, downlink ACI will ensure that UEs cannot encroach too close to an adjacent channel BS.
before the UE loses connection to its home network. In fact, under normal circumstances it is likely that a requirement to mitigate against uplink ACI probably exists only if measures are introduced that enable UEs to mitigate against downlink ACI.

Uplink interference rejection could be used to decrease the amount of uplink ACI, most of which is likely to be generated by a UE close to its downlink dead zone boundary, or somewhat within its downlink dead zone boundary if the UE is able to mitigate against downlink ACI (or in the less likely scenario that a UE’s uplink data rate significantly exceeds its downlink data rate). As the BS will not know the spreading codes, nor have channel estimates for the other system’s UEs, the only real solution is to use blind interference rejection. However, blind interference rejection typically suffers a 2-3 dB degradation compared to non-blind rejection. Therefore, if interference rejection is employed for the uplink, it would be better to first consider non-blind rejection of the same cell users followed by implementing blind rejection of the other-cell co-channel users and/or the inter-system adjacent channel users. Several approaches have indicated that combining non-blind rejection of same cell users and blind rejection of out-of-cell users provides gains of 2-3 dB above that of a completely blind approach [42, 43]. Further analysis would be required to determine whether cancelling the other-system adjacent channel signals provides greater gain than cancelling the same-system other-cell signals.

If one or more UEs are able to operate close to an adjacent channel BS and can tolerate the downlink ACI, the uplink ACI could significantly affect the uplink capacity of the adjacent channel BS. In this case, it may be possible for the BS to deduce the spreading code of the adjacent channel UEs and cancel their signals directly using non-blind cancellation techniques. The bit error rate results quoted in Section 5.7.1.1 indicate that non-blind techniques could almost completely cancel high power interfering signals from the received signal. For example, results in Reference [39] and [43] indicate that gains of approximately 7 dB or more can be achieved. However, the effectiveness of these techniques would rely on being able to obtain accurate channel estimates of the adjacent channel signals.

Interference cancellation techniques are currently being standardised for GSM [44], and it seems likely that they will be used to increase the capacity of 3G systems. In terms of ACI mitigation, it may be possible to use non-blind multi-user detection to cancel strong uplink signals, but only if accurate channel estimates of the adjacent channel signals can be obtained.
5.8 Smart Antennas

The term ‘smart antenna’ encompasses a number of techniques using multiple antenna elements [45, 46], from relatively simple switched beam arrays, through transmit and/or receive diversity, phased array beamforming and fully adaptive arrays. In general radio links employing these will use an antenna array at one end of the link with a single antenna at the other. In a cellular system with antenna arrays at the BS and a single antenna at each UE, the uplink can be described as single input, multiple output (SIMO), while the downlink can be described as multiple input, single output (MISO). Adding multiple antenna elements at both ends of the link creates an advanced multiple input, multiple output (MIMO) system that can increase the effective bandwidth of the channel substantially, by transmitting multiple data streams simultaneously via different spatial channels [47, 48]. MIMO techniques are currently in their infancy and are some way away from practical use in 3G cellular systems. In this short examination of the application of smart antenna techniques to ACI mitigation in UTRA FDD, we will limit our discussions to the MISO and SIMO cases. The following subsection (Section 5.8.1) considers the use of multiple antenna elements at the BS, while the subsequent subsection (Section 5.8.2) summarises the results of an earlier study on multiple antenna elements within handsets.

The UTRA specifications make provision for the use of smart antennas by defining pilot symbols that are multiplexed into the dedicated traffic channels and by including feedback (FBI) bits in the uplink dedicated physical control channel (DPCCH). Dedicated pilot symbols allow spot beams to be formed for individual UEs. (The UE does not have to separately monitor any common pilot channels that are broadcast to all users across the cell or sector.) The FBI bits allow limited use of closed loop downlink beamforming methods. In addition, open loop transmit diversity is possible using space-time block coding-assisted transmit diversity (STTD).

5.8.1 Smart Antennas at the BS

Smart antennas can be grouped into the following categories.

Selection diversity, in which two or more antenna elements are employed (usually separated by a distance of $\lambda/2$) with patterns that cover the whole cell or sector. The element having the highest received signal power or signal-to-interference-plus-noise-ratio (SINR) is selected as the receive antenna. The occurrence of deep fades is therefore reduced because the
probability of all antenna elements being in a fade simultaneously is much less than the fading probability for a single element. This offers little direct mitigation of ACI, but will improve the link budget somewhat by reducing the required fast fading margin.

*Beam-switched antennas,* which employ several antenna elements with narrow beamwidths, for example four elements with nominal beamwidths of 30º in a 120º sector. This technique exploits the angle of arrival of the main signal component, and will reject any interference that does not arrive from a similar angle.

*Beam-steered arrays* (or phased arrays), in which an array of antenna elements is employed, with the phase offset between individual antenna elements adjusted to steer a single beam in the direction of each UE.

*Adaptive arrays,* in which a similar array is used, but with both the relative phase and weight of each element adjusted in order to synthesise multiple beams that may be steered towards individual multipath components, and multiple nulls that may be steered towards interference sources. An *M* element adaptive array is able to generate *M* lobes, with *M*-1 nulls.

A small number of systems are currently in use in second generation (2G) networks and manufacturers have adapted them for use in UMTS. Current systems are generally of the switched beam type, with beam-steered and fully adaptive arrays still in development.

5.8.1.1 Uplink Beamforming

In the uplink the antenna array at the BS will attempt to maximise the received signal-to-interference-plus-noise-ratio by optimising the antenna beam pattern. In theory, an *M*-element antenna array will provide an *M*-fold increase in antenna gain, reduce the number of interfering signals by a factor of *M*, and will increase the system capacity *M*-fold [45]. In a single cell, the performance improvement can be measured by the relative increase in cell radius, which will be equivalent to *M*\(^{1/\alpha}\) with a simple pathloss rule, where \(\alpha\) is the pathloss exponent. This applies whether the array is a switched beam, phased array or adaptive array type. The theoretical range and/or capacity gain will not, however, be realised in full for a number of reasons.

Performance will differ for TDMA and CDMA systems because the interference characteristics will be somewhat different. In CDMA there will be many co-channel intra-cell
and inter-cell interferers, from which signals will be received at the BS with similar powers. However, in a TDMA system there will be fewer, but more dominant, co-channel interferers. With a large number of evenly distributed interferers, the performance of a switched or beamformed array will be comparable to a fully adaptive array. For reasons of reduced complexity, switched beam arrangements have been favoured for CDMA systems. However, with the introduction of uncoordinated ACI into the UTRA FDD system, the interference characteristics are somewhat different in that additional dominant interferers are introduced when an adjacent channel UE on a different network is transmitting with relatively high power close to the BS. In this case it could be expected that the additional interference nulling capabilities of fully adaptive arrays would be advantageous.

The distribution of interferers and the angular spread of different multipath components arriving at the BS antenna will vary according to the environment under consideration. In street-level urban microcells, for example, signals will propagate along the street canyons and their angle of arrival at the BS will not be evenly distributed. It is highly likely under these circumstances that a wanted signal will arrive at the BS from a similar direction as that of a strong interfering signal and will therefore be difficult to distinguish. With small angular spread, switched beam and adaptive arrays will have similar performance; however, as the spread is increased, fully adaptive arrays will outperform switched or beam-steered types because they are able to form multiple beams to combine multipath components from different directions of arrival. Typical angular spreads range from 1° to 30° in macrocells, whilst are generally much wider in indoor picocells (360°) [46]. The use of adaptive arrays could therefore be more beneficial in picocells than in macrocells, where a switched beam arrangement may suffice.

The use of a RAKE receiver to provide multipath diversity gain means that some of the smart antenna gain is already realised. There are two approaches to combining the RAKE receiver fingers with the antenna array [49]. In the simpler of the two, a common beamformer is used in front of the RAKE receiver, providing the same antenna pattern for each of the RAKE fingers. A more complex finger beamformer applies a separate antenna weighting vector for each RAKE finger, allowing individual beams to be formed for different multipath components more effectively. Therefore, the finger beamformer will perform better than a common beamformer under conditions of wide multipath angular spread.
For fully adaptive arrays there is a range of possible algorithms that may be used to optimise the complex antenna element weight vector. A detailed discussion of these and their relative merits is beyond the scope of this study. A number of different methods were compared under the auspices of the TSUNAMI (II) project\textsuperscript{15} [50], in a field trial using modified GSM1800 BS installations.

A number of studies have been reported in the literature involving simulations of different adaptive antenna configurations, although little has been reported on their direct impact on ACI. The performance gain for CDMA systems has been reported in terms of SINR increase, range increase or capacity increase, in the presence of co-channel intra-cell interference or intra-cell and inter-cell interference in the case of multi-cell studies. The simulation results show varying increases in performance with the adaptive antennas, depending upon the number of antenna elements, the type of system simulated and the environment assumed for each.

Analytical results reported in Reference [51] compare combinations of adaptive arrays and sectorisation in a multiple cell arrangement. For a given number of users, potential improvements in BER of two and three orders of magnitude are shown. The number of supported users was found to increase between two and four times for different techniques, for a BER of 10\textsuperscript{-3}. Using analytical techniques and simulation, similar capacity improvements are reported in References [52] and [53].

Blogh and Hanzo [54] simulated a pedestrian microcellular environment with 150 m cells, using two- or four-element adaptive arrays at the BS, with a sample matrix inversion optimisation method. Capacity increases of between 27\% and 56\% for the two-element array and between 88\% and 156\% for the four-element array were seen when compared to an omni-directional antenna. In a later study [55] the combination of adaptive antennas with adaptive modulation showed further potential gain.

Zhang et al. [56] simulated the uplink performance using a six-element array, with maximal ratio combining (MRC). Considerable increases in BER performance were shown with increasing SNR. At –12 dB SNR an order of magnitude increase was reported, whilst at -8 dB

\textsuperscript{15} Technology in Smart antennas for UNiversal Advanced Mobile Infrastructure – Part 2.
SNR three orders of magnitude were observed when compared to an omni-directional antenna.

Winters and Gans [57] compare adaptive and phased arrays and quantify their performance gain in terms of range in a single cell system. It is shown that the range increase achievable with phased arrays is limited by the angular spread of the received signal. With an angular spread of just 3° and a 100-element array it is shown that the range may be increased 2.8-fold and 5.5-fold for a phased array and an adaptive array, respectively. Furthermore, the range increase of the 100-element phased array may be achieved with an adaptive array of only 10 elements.

A small number of adaptive antenna field trials have been performed, eg, [50, 58], most notably for the TSUNAMI (II) project. The results obtained from a test bed employing a modified GSM1800 BS with an eight-element adaptive antenna are described. The test bed was operated by Orange PCS in Bristol, in a rural macrocellular environment. Numerous antenna weight optimisation algorithms were compared, and all were found to offer an improvement in SNR of 7-8 dB for the uplink in a single cell. In terms of range, however, the useable cell radius was found to increase by between 0.7% and 15%.

It is rather difficult to relate the results of these studies and trials directly to mitigation of ACI and dead zones. By treating adjacent channel interferers on the uplink simply as adding to the total co-channel interference, it could be assumed that performance gains of adaptive antennas would be similar in the presence of ACI. The gain in SINR or capacity of the adaptive antenna could be traded directly against the capacity loss caused by ACI. Strictly, this is unlikely to be the case, as the interference generated by adjacent channel UEs will have different characteristics. It is more likely that there will be one or more dominant interferers as adjacent channel UEs move close to the victim BS, compared to the co-channel interferers when power control ensures that the received power at the BS is similar for all users. In addition, implementation issues such as the increased antenna and mast size required for antenna arrays; the potential requirement for power in addition to RF feeds to the masthead; and extensive calibration requirements may prove prohibitive compared to the potential gains offered.
5.8.1.2 Downlink Beamforming

Our simulations have shown that the dead zone problem is most acute on the downlink, where well-defined areas of high call blocking can occur in the vicinity of adjacent channel cell sites. Mitigation against ACI on the downlink using smart antennas at the BS involves optimisation of the transmit antenna pattern. A beam can be directed to a UE and only the traffic channel assigned to this user needs to be transmitted together with an individual pilot channel. This means that the intra-cell interference is reduced and also increased signal power can be steered towards the desired UE. Downlink beamforming does not increase the rejection of other interferers (including inter-cell interference), although downlink beamforming employed in adjacent channel cells will reduce the interference generated, ie, there is less chance of the adjacent channel network downlink beams being in the direction of a UE served by the victim network.

A further difficulty with transmit beamforming is that it requires prior knowledge of the downlink channel, which can only be established from a received signal over that channel. There is a large volume of research into beamforming for the uplink, but relatively little in the area of downlink beamforming. Array optimisation for the downlink can be achieved in either an open or closed loop manner. In open loop methods the downlink channel characteristics are estimated based upon the channel seen by the BS receiver on the uplink. This may differ considerably from the downlink channel due to the frequency difference between uplink and downlink in a FDD system, and because the channel characteristics may change over the time between reception on the uplink and transmission on the downlink. Koutalos and Thompson [59] have assessed an open loop algorithm for downlink beamforming for FDD and conclude that the accuracy, and therefore performance gain, of the method reduces not only with increasing frequency separation but also with increasing numbers of antenna elements.

Closed loop methods require some form of feedback from the UE to allow the BS to adjust the antenna array weights. This can require high feedback data rates to track the instantaneous downlink channel effectively. Averaged feedback reduces this data rate, but at the expense of increased optimisation and settling time, and reduced ability to track fast-moving UEs effectively.

At the current time, downlink beamforming methods are not well developed, and appear to offer only limited benefit due to the difficulties of downlink channel estimation and feedback,
particularly in the case of FDD systems. In the future, these techniques may improve sufficiently for practical use; however, they currently have limited potential for use in mitigating dead zones.

5.8.2 Smart Antennas at the MS

In an earlier study for the Radiocommunications Agency [26] the use of adaptive antennas in 3G handsets was investigated. The implementation difficulties of this new technology mean it is still some way from practical use, although advances in miniature antennas and the continual increase in the processing power of semiconductor devices suggest that it will be feasible in the future. Simulations were performed using MACcdma to establish the likely benefit that using adaptive arrays for the UE receiver would have on network capacity, required BS density, achievable data rates and mitigation of ACI.

Initially, a review of the current state-of-the-art in miniature antenna arrays revealed that the expected gain in SINR compared to a single omni-directional antenna would be variable, conforming to a lognormal distribution. Conventional diversity combining techniques were found to provide between 6 dB and 9 dB gain in SINR, whilst interference rejection combining (IRC) was found to provide up to 23 dB. Furthermore, it was established that the potential gain provided depended on the number of strong interferers present and whether the UE was in line-of-sight (LOS) of its serving BS. A statistical model of the adaptive antenna array performance was incorporated into the simulation, based upon a lognormal distribution with mean and variance set according to the number of interferers present and the LOS or non-LOS condition.

Monte Carlo simulations were performed using a fictional UMTS network deployed over a 25 km² area of Central London. A similar but uncoordinated network operating on an adjacent radio channel was also created to examine the effects of ACI. In a similar manner to the simulations within the present study, a quality of service was defined as the percentage of the simulation area with a call blocking probability of 2% or less. It was found that the network capacity at a QoS of 95% was increased by approximately one third, and also that the improvement in QoS compared to an omni-directional antenna increased with increasing offered traffic. The increased capacity could be translated into a reduction in BS density for the same network capacity, and it was found that use of the adaptive antennas allowed a
reduction of between 8% and 15% in the number of BSs required to serve the simulated area, depending upon how well the network was optimised.

Additionally, the appearance of dead zones in the network around the cell sites of the adjacent network was investigated. Although the overall network capacity was not significantly affected by the introduction of ACI from the adjacent network, it was found that areas of high call blocking appeared around cell sites in the adjacent network. The areas within a radius of 50 m of adjacent cell sites were examined in isolation and it was found that the composite call blocking probability within these areas was reduced from 12.00% to 3.57% when adaptive antennas were employed. This equates to a reduction in size of the dead zones to less than a third of that with omni-directional antennas on the handsets.

It was concluded that the use of adaptive arrays in handsets may be possible in future systems. However, due to the physical difficulties of fitting multiple antenna elements on a small handset, practical array size would be limited to perhaps two elements and would therefore offer limited performance. In this case either maximal ratio combining (MRC) or interference rejection combining (IRC) could be employed, but IRC would only provide rejection for one strong interferer.

5.9 Increased Site Density

Increasing the site density has the advantage of increasing the system link margins required for coverage. In other words, the pathloss between a BS and a UE at the edge of the BS’s serving area would be lower. This means that more downlink power can be assigned to a UE to combat ACI, or on the uplink, a UE can increase its power to overcome uplink ACI at the BS. It is unlikely that an operator will increase site density principally as a measure to reduce the effects of ACI because it is associated with massively increased cost. If we require a 10 dB increase in margin, then assuming a path loss exponent of 3.5, we require a reduction in site radius of 48%, which means that the coverage area would fall by 73%, and therefore we would require 270% more sites. As a consequence, an operator is more likely to only increase site density as a capacity enhancement method.
5.10 Place Sites in Traffic Hotspots

Placing sites in traffic hotspots is a successful strategy for maximising the capacity of a network, especially a CDMA network. If a site placed near a hotspot is not fully loaded, then the total downlink transmit power will be reduced, and therefore fewer adjacent channel UEs will be affected by downlink ACI. Also the uplink ACI caused by served UEs will be reduced. If all operators take this approach, this ultimately leads to collocation, which is the best strategy for avoiding ACI. For this statement to be true, the traffic hotspots of each network would have to be in similar geographical locations. This may not necessarily be the case, especially if operators target different types of customers with different network usage characteristics. A particular operator may, for instance, target a particular class of users that use high data rate services in geographical areas not common to the traffic hotspots observed in other networks. This situation could arise, for example, if an operator wanted to differentiate its service offering from that of other operators.

5.11 Call Admission Control

Call admission control (CAC) accepts calls only if they do not degrade the performance of existing calls. One would not expect that a CAC algorithm would have knowledge of the conditions at BSs of other operators in order to determine the effect that admitting a call might have on their performance. Furthermore, CAC algorithms generally do not consider the effects on other sites in the same network, let alone a different network, and therefore we think it unlikely that this could provide a strategy to reduce ACI.

5.12 Bit Rate Relegation

Bit rate relegation is a means of mitigating the effects of ACI, because the increased processing gain available from the use of a lower bit rate can be used to increase the energy per information bit, and thus overcome increased interference. It is not really a solution to the problem but merely an amelioration of the consequences – essentially, in conditions of significant ACI, the data rates are reduced, to ensure that some information is conveyed rather than none. The consequences of bit rate relegation rather depend on the service being provided and the period for which the ACI is excessive. For example, a high data rate, low delay service could become unusable, whereas a non-real time file transfer would be barely affected by a short reduction in bit rate. Similarly, for lower rate services such as speech, a
reduction in bit rate associated with a reduction in quality when in ACI may be preferable to dropping the call. It is important to be aware that if the transmissions become highly asymmetric, the downlink on the serving system may adapt to ACI by reducing bit rate, but the uplink may not. Therefore, a UE may cause excessive uplink ACI to an adjacent BS, forcing it to reduce its bit rate and/or coverage area.

5.13 Hard Handover

One approach to alleviate the dead zones caused by ACI would be to move the affected user to a different carrier that is unaffected by the ACI. For example, an operator may have 10 MHz of paired spectrum devoted to UTRA FDD, which contains two carriers, A₁ and A₂. If a UE on carrier A₂ passes too close to a BS belonging to another operator that uses carrier B₁ such that B₁ is adjacent to A₂, then a dead zone for carrier A₂ is formed around the other operator’s BS. Since carrier A₁ must be separated from B₁ by approximately 5 MHz (i.e., a gap of 5 MHz or a separation of 10 MHz between carrier frequencies), the interference suffered from the other operator on carrier A₁ is less, and therefore, the dead zone, if any, is smaller.

The specification for ACLR at the UEs is 33 dB with 5 MHz separation and 43 dB with 10 MHz separation [5]. The ACS at the UE is 33 dB with 5 MHz separation. The ACS value is not specified for 10 MHz separation. Therefore, for the purpose of this analysis, let us assume an ACS of 50 dB for a separation of 10 MHz. If we assume that the UE performance is the dominant cause of ACI, we observe that moving to the second adjacent channel from the first adjacent channel buys an increase in ACLR of 10 dB and an increase in ACS of 17 dB. Assuming free-space propagation the dead zone radius on the downlink (dominated by UE ACS) would decrease by a factor of 7, and the dead zone radius on the uplink (dominated by the UE ACLR) would decrease by a factor of 3.2. In this way the area of the downlink dead zone would decrease by at least 98.0%, and the uplink dead zone area would decrease by 90%. In fact, the consequence may be that the dead zones disappear entirely if the UE cannot get sufficiently close to the BS antennas of the other network.

We need to address the mechanism for such a hard handover. There are two parts to performing a hard handover to avoid ACI. The first part is to be able to determine that such a handover is likely to improve the interference, and the second is to actually perform the handover.
5.13.1 Determining that a Hard Handover is Required

In principle, determining that an inter-frequency handover is required in the presence of adjacent channels involves measuring carriers other than the one currently used for communication. To facilitate these measurements, UTRA includes the compressed mode of operation, which opens a gap in the transmissions to allow the hardware to be retuned to make measurements on an alternative carrier. The physical layer is capable of a large number of different measurements in all modes of operation [60], with the important measurements for determining dead zones being common pilot channel (CPICH) $E_b/N_0$ and received signal strength indicator (RSSI). The measurement procedures are described in the radio resource control (RRC) specifications [61]. We can suggest two strategies, one involving measurements on an alternative carrier and the second involving measurements on the adjacent channel. Let us consider the former approach first.

The RRC specifications describe ‘measurement events’, which are triggers that provoke the transmission of a measurement report to the radio access network (RAN). Measurement event 2a occurs when there is a “change of best frequency”. Measurement event 2b occurs when “the estimated quality of the current frequency is below a certain threshold and the estimated quality of a non-used frequency is above a certain threshold”. These measurement events could be used to trigger a hard handover. Fundamentally, if ACI becomes significant on the current frequency, a served UE’s call quality will deteriorate. If an alternative carrier is being monitored then, when it is advantageous to switch, the measurement event will occur and the RAN can initiate the hard handover.

The second approach would be to monitor the RSSI on the adjacent carrier. Once this RSSI exceeds the RSSI of the current frequency by a significant margin, the hard handover procedure could be initiated. This second approach would allow handover due solely to ACI; however, there is no guarantee that the new carrier is not corrupted, ie, the call quality on the new carrier is unknown. The first approach appears to be better as we can be sure that the UE transfers to a carrier that is better than the current carrier, and this is the correct behaviour for mitigating any form of interference.

5.13.2 The Hard Handover Mechanism

Hard handover is used to transfer an ongoing call from one frequency to another, and involves the reconfiguration of the RRC [61]. Fundamentally, the radio access network can
instruct the UE to transfer the ongoing call to a specified cell on a specified frequency using RRC procedures that are described in the RRC specification [61].

5.13.3 Handover to GSM

Each of the 3G operators can also provide service on an existing GSM network. For four of the 3G operators this is their own GSM network; in the case of Hutchison this is O₂’s GSM network. UEs experiencing excessive downlink ACI from an adjacent channel BS can hand over to GSM until the UE moves to a location where downlink ACI is not a problem. As downlink ACI should trigger calls to hand over to GSM, as long as the downlink and uplink data rates are similar, downlink ACI-triggered handovers to GSM should also minimise the amount of uplink ACI generated by UEs. This provides a complete workaround for voice and low-to-medium data rate services that can be supported by general packet radio service (GPRS) or enhanced general packet radio service (EGPRS). However, as it is unlikely that a 3G video conference call could hand over to GSM, this solution is not all-encompassing. Furthermore, in the strict sense an ACI mitigation technique should provide a means to manage ACI whilst calls continue to be served by the 3G network system. Handing calls to a different system operating in a different frequency band is not really solving the problem of ACI in the present 3G frequency allocation.

5.14 Inter-operator Roaming

From a physical radio propagation perspective, the optimum approach to dealing with a strong adjacent channel interferer would be to hand over to the BS generating the interference. From a layer 3 perspective this appears to be possible; however, it requires significant inter-RAN communications. UTRA has been designed to interface with alternative radio access technologies, eg GSM and cdma2000, and roaming is supported. For example, roaming between UTRA and GSM is currently supported, as exemplified by Hutchison 3G in the UK using the GSM network of O₂ to provide near-ubiquitous voice coverage [62]. Furthermore, O₂ and T-Mobile plan to share 3G infrastructure in some areas of the UK [63] using inter-operator roaming. Ideally, inter-operator handover could also be supported. The complexity of such handover lies in the backhaul, switching and billing rather than in the radio interface. Obviously, if inter-operator handover were implemented, such that one could hand over to the lowest pathloss BS, then this would eliminate the ACI problem. Unfortunately, this is unlikely to be a viable solution since operator differentiation becomes
difficult, the handover and roaming signalling traffic between operators will become significant, and the design of appropriate inter-operator tariffs is likely to be complex.

One advantage is that agreement would only be necessary between operators with neighbouring frequency allocations. O₂ and T-Mobile have already agreed to share network infrastructure. A combination of hard handover and inter-operator roaming would mean that they could also mitigate against ACI even if the two neighbouring operators were co-located at a site unused by the victim operator.

6 Summary and Conclusions

In this report we described the results of our investigation into dead zone problems that can occur between adjacent channel UTRA FDD operators. We began by examining the nature of a dead zone and how it is caused by ACI between uncoordinated networks. We undertook a campaign to estimate the uplink and downlink ACP values of typical 3G equipment. Through a combination of making measurements of handsets, conducting a literature search, contacting operators and equipment manufacturers, we estimated that the ACP value on the uplink and downlink for typical 3G equipment is 43 dB. This value is 10 dB better than the UTRA FDD specification value of 33 dB.

In order to simulate the effects of ACI, we constructed a set of basic link budgets for the uplink and downlink of a representative victim and interfering network. The link budgets were used to model specific scenarios within a UTRA FDD network. Three scenarios were considered; a dense urban network, a rural network and a fast-moving UE (travelling along a motorway or on a train).

For the urban scenario a link budget analysis showed that dead zones would not occur on the uplink or downlink in urban areas for the speech service. These results were masked somewhat by the choice of the propagation model used for the basic urban link budget analysis. However, we did provide a qualitative argument suggesting the possibility of dead zones occurring if a UE is not in line-of-sight of its serving BS.

The rural results indicated that the worst-case downlink dead zones could have a radius of 650 m for the speech service. This dead zone size was calculated assuming that the 3G equipment meets the ACP specification value of 33 dB. A smaller 330 m radius dead zone on the downlink was calculated assuming an ACP value of 43 dB (estimated ACP for typical 3G
equipment). Given that the rural cell radius was set at 5.6 km, this dead zone size is relatively small compared to the total cell area. Uplink results were also obtained for the rural scenario that indicated more of an impact from ACI on the uplink compared to the downlink. However, the worst-case scenario analysed on the uplink is not likely to occur often in practice. Therefore, we concluded that the impact of ACI on the uplink is likely to be not as significant as on the downlink.

The fast-moving UE link budget analyses showed that depending on the UE speed and whether the interfering site is a microcell or a macrocell, the time spent in a dead zone was between 5 and 59 seconds. This was once again a worst-case set-up with the adjacent channel site halfway between two serving sites. The proportion of time in the dead zone varied between 2.5% and 11%, which was the time in a dead zone divided by the time it takes to travel between two serving sites. Clearly, not all adjacent channel sites are going to be located halfway between serving sites. Therefore, the percentages above are on the pessimistic side. We also showed that if an ACP value of 43 dB is assumed, then the worst-case time in a dead zone is 33 seconds.

Caution should be used in the interpretation of the results produced by the basic link budget analyses because they are limited in that they can only highlight a small number of specific scenarios. The link budget analyses cannot indicate the likelihood that these example situations will occur in reality. For this reason, we would like to place more emphasis on results obtained from simulations of urban and rural environments. This brings us to one of the core parts of the study - the results of MACcdma simulations. A hexagonal rural network was simulated using MACcdma. ACI was introduced by an adjacent channel network. We demonstrated that if the adjacent channel network was co-sited with the serving network, then no ACI occurred. We also showed that if the adjacent channel network is located in the worst-case locations, ie, equidistant from the nearest three victim network sites, then the dead zones were the most severe. The size of the dead zones for this scenario was similar to the size calculated by the rural link budget analysis for the downlink.

We also unearthed some interesting dynamics between the performance of the speech, 64 kbps and 144 kbps services for this worst-case set-up. This was due to the fact that the ACI introduced dead zones into the network in areas that were particularly poor, in terms of blocking, before the introduction of ACI. The increased blocking in the poor areas of the network meant that the power not used to serve these dead zone areas could be used to
improve the performance in other areas and for other services. Overall, the introduction of ACI caused the performance of the speech service to degrade but this was somewhat offset by an improvement in the performance of the data services. Still, as expected, the introduction of ACI caused the overall capacity of the network to degrade slightly.

We also modelled the ACI from another adjacent channel rural network with sites positioned in between the worst-case and best-case (collocated) positions. In this case the dead zones did not appear in locations of the network that had poor performance before ACI was introduced. As a consequence, all services were affected in a similar way by ACI. Also, because the adjacent channel sites were not located in the worst positions, the size of the dead zones produced was smaller compared to the dead zones created by the worst-case adjacent channel network configuration. The capacity of the victim network was found to be about 99.4% of the capacity without ACI modelled. From an ACI perspective, these adjacent channel site locations should cause no concern to operators.

A more realistic network was simulated for the urban scenario using MACcdma. The site density, minimum site spacing and many other important factors were carefully chosen to represent a real 3G network. Also, accurate urban predictions were generated using the NP WorkPlace, which is a radio planning tool specifically designed for predicting coverage from sites in urban areas. A number of sites were collocated (14%) with the adjacent channel sites and the remainder of sites randomly located. Given these factors, extra importance should be given to the urban MACcdma results. With this in mind, it was shown that for the specification value of ACP (33 dB), the overall capacity of the urban network in the presence of ACI was similar to the capacity without ACI. This means that, considering the network as a whole, the problem caused by ACI is negligible. It does not mean that dead zones do not exist. Indeed, we demonstrated the presence of dead zones by examining only the victim network statistics within 50 m of adjacent channel sites and the analysis showed that ACI did degrade the performance in these areas. However, given that only a small subset of adjacent channel sites in a real network are going to be located in the worst-case interfering positions, ie, at the extremity of the serving area of sites, then in the grand scheme of things the effect of the dead zones is negligible.

Operators may still want to employ various ACI mitigation techniques to dampen the effect of ACI in certain important parts of their network. The MACcdma results demonstrated that interfering microcells were the main source of ACI due to the close proximity of microcell
antennas and UEs at street level. In other words, microcells tend to have lower minimum coupling losses than macrocells. We suggested methods of increasing the minimum coupling loss of microcells, such as through the use of low vertical beamwidth panel antennas rather than the traditional microcell patch antennas. Although this approach is not the most practical, it certainly is effective. Indeed, if a minimum coupling loss of 70 dB can be achieved, this was shown to reduce to an almost negligible level the effects of ACI produced by microcells.

We also investigated other ACI mitigation techniques in depth. A summary table was produced that rated each mitigation method according to a number of different metrics, including degree of operator cooperation required, feasibility and effectiveness. Apart from the minimum coupling loss technique, the other techniques that scored well in terms of effectiveness included the use of repeaters, inter-operator roaming and collocating sites. There does appear to be a trade-off between the effectiveness of the solution and the required degree of operator cooperation. Excluding the minimum coupling loss solution, all of the techniques listed above require a high level of operator cooperation.

Note that if our results had indicated that there was a significant degradation in overall network performance caused by ACI, then more reliance would need to have been placed on the widespread use of ACI mitigation techniques. Instead, the most likely situation is that operators may need to use these techniques to solve a relatively small number of problems caused by ACI.

In conclusion, we have demonstrated that the dead zone problem has a relatively minor impact on the overall performance of 3G networks. However, in the areas that dead zones occur, we highlighted a number of remedies to overcome the problems caused by these dead zones. It is clear that a reasonable level of operator cooperation is essential to ensure maximum benefit from the most effective of these remedies.
References


7. Email correspondence with Yannick Li, Nortel Networks, 31 July 2003.

8. Email correspondence with Howard Benn, Motorola (and 3GPP TSG-RAN4) and Edgar Fernandes, Motorola, 21 August - 9 October 2003.


Appendix A  MAC\textit{cdma} Parameters

MAC\textit{cdma}'s input parameters are entered on different pages of the Configuration Editor. This section is organised to present the parameters as they are entered into the Configuration Editor.

A.1 Simulation

This group of parameters controls the operation of the simulation, ie, they do not relate directly to the network being simulated.

A.1.1 Number of Simulation Snapshots

This is the number of static snapshots that are used to build up a picture of network performance. A higher number increases the statistical validity of the result, but also increases run time. Generally a value of 50 was used for urban simulations and 1000 snapshots were used for rural simulations.

A.1.2 Global Traffic Scale Factor

A scale factor applied to all traffic values in the simulation. This can be varied depending on the traffic density we want to simulate.

A.1.3 Output Bin Size

The resolution of the output plots. We used the same resolution as the coverage predictions, ie, 5 metres for the urban analysis and 100 metres for the rural analysis.

A.1.4 Output Statistics Area

A 4 km $\times$ 4 km area at the centre of our 8 km $\times$ 8 km urban map was used. A circle of radius 14.55 km of the rural map was used.
A.2 Network

This group of parameters relates to the network as a whole, ie, parameters that affect every base station or every UE.

A.2.1 Orthogonality Factor

The proportion of the same-cell BS transmit power that is seen as interference at the receiver. A typical value of 0.4 was used.

A.2.2 Pilot Channel Required $E_c/I_0$

The required ratio of energy per chip to interference power spectral density. A typical value of -16 dB was used.

A.2.3 Attenuation of Extra Interference

Attenuation applied to the additional downlink interference that is specified by an additional interference map file to represent the adjacent channel interference (ACI). The value of 33 dB for adjacent channel protection (ACP) specified for UTRA FDD with a 5 MHz carrier offset was used\(^{16}\). Also a range of other ACP values was used.

A.2.4 RAKE Efficiency Factor

The proportion of the wanted signal that is captured by the RAKE receiver. This value was set to 0.5.

A.2.5 Downlink Noise Figure

The noise figure of the UE receiver. A typical value of 9 dB\(^{17}\) was used.


A.2.6 Downlink Line Loss
Additional loss that should be added to all downlink connections to model cable and connector losses. A typical value of 7 dB was used (4 dB plus 3 dB body loss).

A.2.7 Uplink Noise Figure
The noise figure of the base station receiver. A typical value of 5 dB\textsuperscript{18} was used.

A.2.8 Uplink Line Loss
Additional loss that should be added to all uplink connections to model cable and connector losses. A typical value of 6 dB was used (3 dB plus 3 dB body loss).

A.2.9 Maximum Traffic Channel Power
The maximum downlink power that can be allocated to a single user. We used a typical value that is 1 dB below the pilot channel power. We assumed that the maximum total downlink power for a macrocell is 43 dBm and the relative pilot channel power, as described in Section A.2.11, was 0.1, which means that the maximum traffic channel power was set to 32 dBm. Likewise, we assumed a maximum total downlink power of 37 dBm for a microcell, which means that the maximum traffic channel power was set at 19 dBm.

A.2.10 Minimum Traffic Channel Power
The minimum downlink power that can be allocated to a single user. The value was set to -40 dBm.

A.2.11 Relative Pilot Channel Power
The proportion of maximum total downlink power that is allocated to the pilot channel. A typical value of 0.1 was used.

A.2.12 Relative Common Channels Power

The proportion of the maximum total downlink power that is allocated to the common control channels (excluding the pilot channel). If, from Section A.2.11, 10% of the downlink power is dedicated to the pilot channel and, from Section A.2.13, 76.8% of the downlink power is in the traffic channel, we are left with a relative common channels power setting of 0.132.

A.2.13 Relative Total Traffic Power

The proportion of the maximum total downlink power that is available for allocation to traffic channels. A typical value of 0.768 was used.

A.3 Services

The service parameters define the 3G service types active to be modelled. A set of output plots was produced by the simulation for each service type defined. We defined the service mix shown in Table A.1, where the entries in the second row show the proportion of users that use each service. The definition of the remaining parameters follows.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Voice (12.2 kbps)</th>
<th>Medium Rate Data (64 kbps)</th>
<th>High Rate Data (144 kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion of Users (%)</td>
<td>80</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>Max UE Transmit Power (dBm)</td>
<td>21</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>SHO Enabled</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>No. of Secondary Uplink Channels</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Uplink Processing Gain</td>
<td>315</td>
<td>60</td>
<td>27</td>
</tr>
<tr>
<td>Uplink Required $E_b/I_0$ (dB)</td>
<td>5</td>
<td>2.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Uplink Channels of this Type</td>
<td>1 (1)</td>
<td>1 (1)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>Uplink Source Activity Factor</td>
<td>0.5 (1.0)</td>
<td>0.8 (1.0)</td>
<td>0.8 (1.0)</td>
</tr>
<tr>
<td>Uplink Transmit Cycle</td>
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<td>0.025 (1.0)</td>
<td>0.025 (1.0)</td>
</tr>
<tr>
<td>Uplink Relative Power of Secondary Channel (dB)</td>
<td>-2.69</td>
<td>-9.54</td>
<td>-9.54</td>
</tr>
<tr>
<td>No. of Secondary Downlink Channels</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Downlink Processing Gain</td>
<td>315</td>
<td>60</td>
<td>27</td>
</tr>
<tr>
<td>Downlink Required $E_b/I_0$ (dB)</td>
<td>5</td>
<td>2.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Downlink Channels Of This Type</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Downlink Source Activity Factor</td>
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<td>0.8</td>
<td>0.8</td>
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<tr>
<td>Downlink Transmit Cycle</td>
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<td>0.975</td>
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Table A.1: Service specific parameters that were used for the simulations. Numbers in brackets refer to secondary channel values.

A.3.1 Max UE Transmit Power

The maximum transmit power capability of UE using this service.

A.3.2 SHO Enabled

Enables UEs of this service to use soft handover (SHO).

A.3.3 Processing Gain

The processing gain, given by the chip rate of 3.84 Mchip/s for UTRA FDD divided by the bit rate of the service.
A.3.4 Required $E_b/I_0$
The required ratio of energy per traffic channel bit to the interference power spectral density.

A.3.5 Channels of this Type
The number of physical channels of this type. For example, a UTRA call can have up to six traffic channels.

A.3.6 Source Activity Factor
The proportion of time for which a transmitting source is active when nominally engaged in transmissions.

A.3.7 Transmit Cycle
The proportion of time for which a service is nominally engaged in transmissions.

A.3.8 Relative Power
The transmit power of a secondary channel relative to the instantaneous power of the associated primary channel.

A.4 Call Admission Control
Some parameters relate to the call admission control (CAC) algorithm used in the network. The purpose of a CAC algorithm is to prevent new users accessing the network if their transmissions would adversely affect the quality of ongoing calls. The CAC assessment can be based either on the current network status, or an attempt can be made to predict the impact of the new call. CAC algorithms can operate on the downlink, uplink or both.

A.4.1 Call Admission Control Algorithm
The “downlink predictive transmit power, uplink predictive SIR CAC” algorithm was used. New call attempts are accepted if a certain power headroom exists at the target base station, including the power that will be allocated to the new call, and if no existing UE attached to
the target base station has their uplink $E_b/I_0$ reduced beyond the specified value as a result of interference generated by the new call.

**A.4.2 Downlink Power Headroom**

This value is the minimum margin required below the maximum traffic channel power for a new user to be allowed onto the network. This value was set to 1 dB.

**A.4.3 Maximum Reduction in Uplink $E_b/I_o$**

This value is the maximum degradation allowed in the existing users’ uplink $E_b/I_0$, beyond which a new user will be allowed access to the network. This value was set to 0.5 dB.

**A.5 Soft Handover**

The final group of parameters relates to how the SHO algorithm is implemented.

**A.5.1 Uplink Margin**

The $E_b/I_0$ target for each uplink in the active set can be reduced by this amount. A typical value of 2 dB was used.

**A.5.2 Maximum Active Set Size**

The maximum number of BSs in the Active Set. A typical value of three was used.

**A.5.3 Add/Drop Threshold**

The difference between the $E_c/I_0$ of the serving and candidate cells for the candidate cell to be added to/dropped from the active set. A typical value of 3 dB was used.

**A.5.4 Add/Drop Hysteresis**

This value is subtracted from the Add/Drop Threshold when adding candidates to the active set, and added when removing candidates from the active set. A typical value of 0.5 dB was used.
A.5.5 Replacement Hysteresis

When the active set is full, a further candidate replaces the weakest cell when its $E_c/I_0$ exceeds that of the weakest cell by this amount. A typical value of 0.5 dB was used.
Appendix B  MACcdma Data Sheet
MACcdma - CDMA Network Simulator

MACcdma is a simulation module for 2G and 3G CDMA networks, including UMTS and cdma2000. The tool can be integrated with the NP WorkPlace or configured to operate as a stand-alone tool taking pathloss information from other planning tools.

**Customer focus**

MACcdma is a static Monte Carlo simulator that builds up a statistical view of network performance based on the results of numerous sample snapshots. Advanced algorithms are used to ensure that MACcdma mimics the behaviour of real network scenarios. For example, special consideration is given to power control, call admission control, soft handover and base station power allocation. This means that MACcdma can be relied upon to give a clear indication of the grade-of-service that will be offered to customers.

**Multiple services**

Mobile networks are now multi-service, supporting web browsing, file transfer, video conferencing, etc, as well as traditional voice and text services. MACcdma can simulate an unlimited number of service types. Each takes its own parameters and traffic information, and a separate set of outputs is generated for each case.

**Useful outputs**

Key outputs from MACcdma include plots of mobile transmit power, pilot quality (highlighting areas of pilot pollution) and soft handover zones. CDMA networks are inherently interference limited. New users can often be added to the network, but existing users may suffer as a result. Call admission control algorithms are used to determine when new call attempts should be allowed to access the network and when they should be blocked. Plots of call blocking probability produced by MACcdma are crucial for evaluating the true network capacity.

- Provides detailed performance evaluation of UTRA FDD and cdma2000 networks
- Stand-alone package that integrates with the NP WorkPlace and other radio planning tools
- Supports multiple service definitions with many parameters specified on a per-service basis
- Includes models of realistic soft handover, power control and call admission control algorithms
- Accurately models intercell interference
- Outputs include blocked and dropped call probabilities, pilot strength, reverse transmit power and soft handover regions, all on a per-service basis
- Combined with NP WorkPlace coverage predictions, the performance of the CDMA network inside buildings can be investigated

The transmit power of speech users in a multi-service network.
MACcdma output plots can be viewed in the NP WorkPlace or in MapInfo Professional™. Also, a wealth of statistical information is written to file following each simulation. This enables the performance of individual cells in the network to be analysed in detail.

**Technical Specification**

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Technologies modelled¹</td>
<td>UTRA FDD, cdma2000</td>
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<td>Definable services</td>
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<td>Input file formats supported⁴</td>
<td>NP WorkPlace</td>
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<td>Output file formats supported</td>
<td>NP WorkPlace, MapInfo</td>
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<tr>
<td>Intersystem interference modelling?</td>
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“Display and Continue” function permits interim results to be displayed while calculations continue

Output files (per service) each calculated within the mix of services defined:

- $E_c/I_0$
- Soft handover zones
- Mobile transmit power
- Blocking
- Outage
- Enhanced summary file

MACcdma runs on Microsoft Windows™ operating systems

¹ Other technologies may be supported in the future
² Future enhancements will include additional algorithms and the ability for third party algorithms to be included through an open interface
³ Different handover algorithms provided for each of UTRA FDD and cdma2000
⁴ Support for other file input formats on request
If you would like any further information on MACcdma, the NP WorkPlace or any of MAC Ltd’s extensive range of consulting and training services, then please do not hesitate to contact

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Multiple Access Communications Ltd is an independent consulting and product design company operating in cellular, cordless, wireless LAN, wireless local loop, satellite telecommunications and private and special mobile radio markets.

We operate internationally, particularly in the USA, Europe and the Far East. Our customers include network operators, equipment manufacturers, government organisations and semiconductor houses. We are dedicated to understanding our clients’ problems and aspirations, and producing high quality, innovative solutions in response.

Multiple Access Communications Ltd is a Full Member of ETSI and the TETRA MoU Association.