Final Report

on

Semi-Smart Antenna Technology Project

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Disclaimer

This report was commissioned by Ofcom to provide an independent view on the use of Smart Antennas to improve efficient use of the radio spectrum in the UK. The assumptions, conclusions and recommendations expressed in these reports are entirely those of the Authors and should not be attributed to Ofcom.

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EXECUTIVE SUMMARY

Over the last few years, a wide variety of 'smart' antenna technologies have been proposed as potential techniques for improving the spectrum efficiency of cellular radio systems. 'Smart' in this context, means either using antennas with multiple radiating elements to increase the directivity of the antenna beam so as to enhance the signal at the intended receiver without causing interference to other radio users, or using multiple receive/transmit antenna channels simultaneously in order to increase reliability and hence data capacity of the link.

Although these 'smart' techniques have been well-researched and documented, to date there has been little wide-spread implementation of this technology in cellular radio systems in the UK. In recognition of this fact, Ofcom awarded this work to a consortium of Queen Mary University of London, Lucent Technologies and BSC Associates Ltd, to analyse the current situation with regard to smart technologies in the UK and the barriers to their introduction, to propose an alternative and demonstrate its benefits and to make recommendations on how Ofcom can assist the markets to increase spectrum efficiency by using these techniques.

This report is in three parts. The first part studies the current state of the art of smart antenna technology in general. The information is derived from published technical papers and reports, discussions with mobile radio operators worldwide and experience of the design of antenna systems for mobile radio base stations. The aim was to understand where the technology is and where we think it may be heading.

The conclusions derived from this part of the study shows that there is little doubt in the industry that the adoption of smart-antenna techniques can increase the utility of radio communications in theory, providing both enhanced data rates and improved coverage and spectral utilisation. However, it is argued that the administrative, technical and financial risks involved in implementing this technology are not trivial. In particular, the regulatory environment of the industry and the current technical standards adopted in the mobile radio industry may not provide the most promising environment for the adoption of these techniques. Since roll-out of both 2G and 3G networks in the UK is well-advanced, there is an understandable reluctance to introduce new technologies into a deployed system without clear and tangible benefit. For networks currently being planned for deployment, it is promising to learn that the smart antenna techniques in SCDMA systems are currently in service in a limited set of base stations in China (mostly rural and suburban environments). The Chinese 3G standard TD-SCDMA system was engineered to enable the use of smart antennas in the network from the start, but the implementation of the networks using this air interface is proving much more difficult than expected.

The second part of this study examines whether a semi-smart technology, pioneered in the military sector by QMUL, can overcome the limitations identified in existing smart antenna systems. The semi-smart antenna approach is based on the use of shaped-beam antenna pattern synthesis aided by artificial intelligence (AI) techniques. The term semi-smart antenna has been coined to denote its lower complexity with respect to conventional smart antennas. The basic principle of this approach is based on utilising a cooperative load balancing scheme to dynamically shape cellular base station antenna coverage according to traffic needs. Here, heavily loaded cells are reduced in size to match the
available capacity by contracting the radiation pattern around the area of peak traffic, while adjacent cells cooperatively expand their radiation patterns to compensate for coverage loss. The cooperative pattern shaping process is based on AI techniques and completely avoids the need for central optimisation which would take prohibitively long times. The semi-smart process offers coverage pattern updates of the order of every 30 seconds.

This project substantiated the expected improvements in system capacity offered by deploying the semi-smart antenna into cellular base stations with lower infrastructural modifications and cost than those needed by other smart antenna technologies. Extensive studies were conducted to establish the network level performance of semi-smart antenna systems. These were undertaken using a sophisticated network simulator developed at QMUL over the last 5 years, which we believe offers industry leading simulation performance. A novel optimisation technique was developed in parallel with the extension of the system level of simulation into the aspects of spatially heterogeneous demand, differentiated services, non-uniform topography and comparisons with using antenna down-tilting to control coverage. The performance simulation of the semi-smart antenna system for heterogeneous demands indicated a significant decrease in blocking and dropping rates, i.e., an increase of the capacity, both in the uplink and downlink. An analysis of the system’s ability to support different classes of customers and services showed that differentiation is achieved between all three classes while still achieving increased capacity and lower blocking rates. Results obtained from simulating different scenarios in a real topographic environment revealed that very similar and even better performance can also be achieved. Some preliminary simulation work also indicated that the semi-smart antenna technique has true potential to support efficient networks without the need for conventional network planning.

As part of this study, we also considered practical implementation of the technology. A novel cylindrically-conformal base station antenna array with appropriate feed network was designed and tested. The new design is simple, robust, light and small in size (low profile), and most importantly operates efficiently in providing dynamic radiation coverage in the azimuth plane. Software was developed for radiation pattern synthesis and management of the semi-smart hardware for the real-time control of pattern coverage. The study was further extended to verify the concept of down-tilting as a means of array amplitude control. In this part of the study, extensive electromagnetic modelling was carried out on linear arrays. Also, a brief review is given of non-mechanical phase shifters, the key components in semi-smart antennas, and the potential technologies which might be used in future to replace the current mechanical methods, but still retain their excellent low-level of intermodulation product generation.

In the last phase of work, we examine a number of technical, economic, regulatory and other factors which influence the deployment of smart antennas in general and suggest a possible way for wireless networks to advance in this area. It is also suggested that the financial and environmental constraints to the adoption of enhanced techniques could be resolved to the benefit of the community at large by the adoption of a different model for the ownership and operation of services for future networks, more similar to that now employed in the broadcast industry. Combined with the specific choice of technical standards that can make best use of the techniques of multiple antennas, this could lead to a significant advance in network engineering.
This part of the study have shown that there are significant advantages to installing smart antenna techniques in terms of spectrum efficiency and hence the provision of new radio services to users in the crowded cellular spectrum. However, these advantages are only likely to be realised if operators have a clear migration path from current practice and are not discouraged from investing by the spectrum regulatory environment. From our studies, it appears that the proposed low-cost semi-smart technique offers an excellent migration path for the improvements of cellular networks at minimum complexity and cost, when compared to conventional smart-antenna techniques.
### ACRONYMS

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<th>Acronym</th>
<th>Description</th>
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<td>3GPP</td>
<td>3rd Generation Partnership Project (<a href="http://www.3gpp.org">www.3gpp.org</a>)</td>
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<tr>
<td>BOA</td>
<td>Bubble Oscillation Algorithm</td>
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<td>BTS</td>
<td>Base Transceiver Station</td>
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<tr>
<td>CAC</td>
<td>Call Admission Control</td>
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<tr>
<td>CIR</td>
<td>Carrier-to-Interference Ratio</td>
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<td>CPRI</td>
<td>Common Public Radio Interface</td>
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<td>CSI</td>
<td>Channel State Information</td>
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<tr>
<td>CST</td>
<td>Computer Simulation Technology (CST GmbH)</td>
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<td>DAIC</td>
<td>Dual Antenna Interference Cancellation</td>
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<tr>
<td>DAS</td>
<td>Distributed Antenna System</td>
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<tr>
<td>EIRP</td>
<td>Effective Radiated Power</td>
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<td>FDD</td>
<td>Frequency-Division Duplex</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile communications</td>
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<tr>
<td>HSDPA</td>
<td>High-Speed Downlink Packet Access</td>
</tr>
<tr>
<td>HSUPA</td>
<td>High-Speed Uplink Packet Access</td>
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<tr>
<td>ICNIRP</td>
<td>International Committee on Non-Ionising Radiation Protection</td>
</tr>
<tr>
<td>IEEE-802.11</td>
<td>A standard specification for WLANs (qv)</td>
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<tr>
<td>MIMO</td>
<td>Multiple-Input, Multiple-Output</td>
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<tr>
<td>MKP</td>
<td>Multidimensional Knapsack Problem</td>
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<td>MS</td>
<td>Mobile Station</td>
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<tr>
<td>NPT</td>
<td>Network Planning Tool</td>
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<td>OFR</td>
<td>On-Frequency Repeater</td>
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<td>PIM</td>
<td>Passive Intermodulation</td>
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<td>QC</td>
<td>Quantisation Cell</td>
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<td>RET</td>
<td>Remotely Controlled Electrical Tilt</td>
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<td>RF</td>
<td>Radio Frequency</td>
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<td>RNC</td>
<td>Radio Network Controller</td>
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<td>SAIC</td>
<td>Single Antenna Interference Cancellation</td>
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<tr>
<td>SINR</td>
<td>Signal to Interference and Noise Ratio</td>
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<td>SFB</td>
<td>Switched Fixed Beam (antenna)</td>
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<td>SFIR</td>
<td>Spatial Filtering for Interference Reduction</td>
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<td>SDMA</td>
<td>Space Division Multiple Access</td>
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<td>SRR</td>
<td>Slit Ring Resonator</td>
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<td>SSDT</td>
<td>Site Selection Diversity Transmit</td>
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<td>TDD</td>
<td>Time Division Duplex</td>
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<td>TDMA</td>
<td>Time Division Multiple Access</td>
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<td>QC</td>
<td>Quantisation Cell</td>
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<td>UE</td>
<td>User Equipment</td>
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<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunication System</td>
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<td>WLAN</td>
<td>Wireless Local Area Network</td>
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1 INTRODUCTION

Wireless networks face ever-increasing demands on their spectrum and infrastructure resources. Increased minutes of use, capacity-intensive data applications and the steady growth of worldwide wireless subscribers mean carriers will have to find effective ways to accommodate increased wireless traffic in their networks. Smart antennas have emerged as potentially a leading technology for achieving highly efficient networks which maximise capacity and improve quality and coverage.

Smart antennas can provide greater capacity and performance benefits than standard antennas because they can be used to customise and fine-tune antenna coverage patterns that match the traffic conditions in a wireless network or that are better suited to complex radio frequency (RF) environments. Furthermore, smart antennas provide maximum flexibility by enabling wireless network operators to change antenna patterns to adjust to the changing traffic or RF conditions in the network.

There is little doubt regarding the ability of smart antenna technologies to make more efficient use of spectrum in wireless systems and to enhance overall quality of service to wireless users. Commercial deployments of smart antenna arrays for macro-cellular base stations have already appeared in some countries, but various issues are still hampering the wide adoption of the technology in today’s systems.

In July 2005 Ofcom issued an invitation to organisations to tender for a 12-month investigation into the recent developments of smart antenna technologies. A project team comprising Queen Mary College, University of London (QMUL), Lucent Technologies and BSC Associates Ltd proposed to address all the issues raised in the Call through a study on a semi-smart antenna system. The semi-smart antenna approach is based on the use of shaped-beam antenna pattern synthesis aided by artificial intelligence techniques. The term semi-smart antenna has been coined to denote its lower complexity with respect to conventional smart antennas. The basic principle of this approach is based on utilising a load balancing scheme to shape cellular coverage according to the traffic needs. Here, heavily loaded cells are reduced in size to match the available capacity by contracting the radiation pattern around the area of peak traffic, while adjacent cells expand their radiation patterns to compensate for coverage loss.

Each partner in the project team is an international leading player in its own field. The Communications Group of QMUL has extensive experience and expertise in smart antenna technology research, especially through its experience of leading two EC-IST intelligent antenna/networking projects: SHUFFEL and ADAMANT and a recent research contract for the U.S. Navy. Wireless Research Lab of Lucent Technologies is an international leading player in modern wireless communications technology research. It has pioneered many wireless communication technologies, including the smart antenna system and the MIMO system. BSC Associates Ltd is an SME, specialising in consultancy on antennas and radio communications systems worldwide.
1.1 Objectives and Work Packages
The main objective of the project is to demonstrate an improvement of system capacity by deploying the semi-smart antenna into cellular base stations without introducing substantial infrastructural modifications.

The work was divided into three work packages (WPs), each led by one of the participating partners.

WP1 aimed to identify the key obstacles in the development of proposed smart antenna systems and to address the breakthroughs needed to overcome these obstacles. The study involved a detailed evaluation of the technical, standard and business issues raised by employing smart antenna systems and suggesting possible solutions.

WP2 involved the study of semi-smart antenna systems and traffic load balancing algorithms. The study involved development of a novel optimisation algorithm and system level simulations on 3G UMTS/W-CDMA networks using real topological traffic data. The study also covered the hardware aspects of this technology and built a prototype system to demonstrate the feasibility of this technique.

Finally, WP3 studied the regulatory issues and additional benefits of deploying such systems. The study involved an extensive literature survey and discussions with UK/EC and Chinese network operators and antenna manufacturers.

1.2 Report structure
The structure of this report reflects the studies conducted on each work package specified in the proposal.

Chapter 2 presents a general study of conventional smart antenna systems. The chapter introduces the smart antenna technology, highlights the state-of-the-art and examines the obstacles to the deployment of smart antennas.

The basic concept of semi-smart antenna technology and some background work are given in Chapter 3.

Chapter 4 presents a computer simulation of a semi-smart antenna system and the methodologies developed for this purpose. It covers the performance evaluation of the semi-smart antenna system in real terrain and traffic conditions and other realistic network scenarios.

In Chapter 5, the study is extended to the hardware aspects of semi-smart antenna technology. In association with the assessment of different implementations, a prototype system has been developed and tested at QMUL.

Chapter 6 compares the semi-smart antenna system with other systems and analyses the gain in spectrum efficiency.

Finally, Chapter 7 presents the overall conclusions drawn in this study.
Appendix A gives the details of one of the most important algorithms developed in the simulation study of the semi-smart system.

Appendix B lists our review of research literature describing practical and theoretical work on a wide variety of algorithms and methods of implementation.
2 REVIEW OF SMART ANTENNAS IN MOBILE RADIO SYSTEMS

This chapter provides an overview of the state of research and investigations into smart antennas and their potential utility in commercial mobile radio networks. The information is derived from published technical papers, discussions with mobile radio operators worldwide and experience of the design of antenna systems for mobile radio base stations over the past 15 years.

As there are many hundreds of papers that were consulted in order to complete this study, it is not practical to refer to them all here in the text. Instead, the general conclusions are presented with key paper references. Appendix B lists a bibliography of the subject to which the interested reader may refer for more details.

2.1 Introduction

There is an extensive literature describing the application of a wide variety of algorithms to the outputs of antenna or individual antenna elements. This literature extends over at least 40 years, during which time there has been enormous progress in digital signal processing techniques. Antennas embodying these techniques are generally referred to as smart antennas because their characteristics are adapted to the signal regime in which they are situated. Although some authors distinguish between smart, intelligent and adaptive antennas, the terms are effectively synonymous.

The adoption of smart antenna techniques has been seen by many investigators as capable of offering significant advantages in terms of improved coverage, increased network capacity and enhanced use of spectral resources, yet to date they have not been applied commercially in mobile radio systems. While a number of demonstration systems have been built and some ‘smart’ antennas have been deployed, it is clear that in mobile radio systems their potential promise has not been fully realised.

To place the work carried out in the course of the present project into context, we have examined a number of the technical, economic and other factors which influence the present situation. We have also tried to come to some conclusions about potential benefits which could be achieved by the adoption of smart antennas.

2.2 Smart antenna systems

2.2.1 Early technologies

Early work on smart antennas pre-dates the widespread availability of digital techniques and is mostly related to systems in which antenna beams were created using phase shifters and power dividers realised in physical hardware. The systems were adaptive in the sense that the direction of the main beam of an antenna (and perhaps also some pattern nulls) were provided with appropriate means of adjustment which could be controlled by some characteristic of the transmitted or received signal. At first, motor-driven analogue devices were used to control the currents in antenna elements; these were succeeded by systems using PIN diodes controlled by computers that became able to respond with increasing
speed to changing requirements in the signal environment. In these systems, radiation patterns were shaped by directly processing either the RF signal or an IF or base-band signal derived from it. In later and more advanced systems, the vectors controlling the currents in antenna elements were calculated by a digital process and the available phase and amplitude weights were quantised to suit the number of available control steps and degrees of freedom.

2.2.2 Digital techniques

In recent years it has become possible to convert the signals received from each antenna element into digital data streams. The RF signals may be converted to a suitable IF, or mixed down directly to base band before being converting into I and Q components in the digital domain. This technique is often referred to as digital beamforming; it is extremely powerful and makes possible the use of a wide variety of powerful signal processing algorithms.

In addition to forming beams to optimise the reception of incoming signals (the uplink in terms of a mobile radio base station), corresponding processes are applied to the outgoing signals (the downlink). After signal processing and conversion to RF, the signals are amplified and applied to the antenna elements.

There are important differences between the processing of the incoming and outgoing signals. A smart receiving antenna system is a closed-loop device; parameters of the received signal (C/I ratio, BER or other metrics) are directly used to control the processing of the incoming signals from the array elements. Control of the outgoing signal can use some of the information derived from the processing of the incoming signal, but in mobile radio systems the receive and transmit frequencies are often different and it is not possible to derive the optimum processing parameters for the transmitted signal by processing the received signal. Consequently, one needs to convey information back from the Rx to Tx in order to utilise optimum transmit beamforming. In legacy systems, this can be problematic due to the limited number of spare bits in each frame to convey this information.

2.2.3 Multiple antenna techniques

A conventional antenna array comprises one or more antenna elements connected directly together by RF transmission lines with fixed characteristics. The elements are usually suitable for both transmission and reception.

All the systems considered in this report have the shared feature that more than one antenna is employed at the base station, and that some form of intelligence is used to determine how the signals from each element are combined. Several possible broad strategies are available:

a. The signals from each antenna are selected so that the one providing the best signal is used for reception. Alternatively, signals received at several antennas are combined so that all the received energy is added together. Diversity systems work in this way, but they are not usually regarded as smart antenna systems. Several different forms of diversity systems can be defined on the basis of the way decisions are made about combining the available signal outputs from the antenna arrays.
b. The signals from each antenna may be adjusted according to some algorithm to point the main beam in a direction that can be selected on the basis of some knowledge of the direction of the mobile station relative to the base station. The beam direction may be variable continuously (a beam-steered antenna) or in steps (a switched fixed beam antenna) – in the latter case the beams may simply be created by different antennas pointing in different directions.

c. The radiation pattern of the whole group of antennas can be changed from moment to moment on the basis of real-time information about the signals being received or transmitted. This is probably what most people think of as a smart antenna.

d. The characteristics of the group of antennas can be changed on the basis of information about current traffic requirements. Because traffic demands change much more slowly than individual signals, the time available to change the antenna characteristics is much longer. This is what we define as a semi-smart antenna, discussed in Chapter 3, 4 and 5 in this report.

e. The same basic signal is transmitted from each antenna in the group but each is modified in some way so that it is appropriately processed on reception (transmit diversity).

f. Different information is transmitted simultaneously from different antennas, each signal being coded so the receiver can put together the whole signal ensemble. Such techniques include MIMO (multiple-input, multiple-output) and related space-time coding systems.

2.3 Classes of smart antennas
A typical mobile radio base station uses three antennas oriented mutually at 120° in azimuth and having individual 3-dB beamwidths of around 65°. Alternative schemes have been proposed in which each 120° sector is served by an array of multiple antennas provided with a passive beamforming network able to form several separate narrow beams spread across the sector. These switched fixed beam antennas have been shown to provide increased total capacity in the cell, as they reject interference coming from many directions and provide more gain – at least near beam centres – than would be achieved by the standard wider-beamwidth sector antenna. Antennas of this type have been marketed in the USA and elsewhere, but have not been sufficiently successful to capture a significant share of the market and a number of products have been withdrawn from sale.

There are various methods of combining the outputs of several antennas forming a broadside array. The methods can be broadly classified as:

- **Switched fixed beam arrays.** These arrays operate as described above. They are the simplest to understand and require minimum hardware to create and manage the multiple beams. The same beam is chosen for the uplink as the downlink. It will be appreciated that several beams will be needed to serve dispersed users. The apparent simplicity of this technique is
compromised by the need to identify individual users and steer beams towards them.

- **Direction finding arrays.** These arrays are connected to a processor which determines the effective bearing of the incoming signals and forms a single beam in the determined direction, enhancing the signal-to-interference plus noise ratio (SINR) of a wanted signal. Information on the direction of arrival of the uplink signal is used to steer the corresponding downlink signal. Multiple beams are formed to serve multiple dispersed users.

- **Optimum combining arrays.** The processing for these arrays adds all the available signal power – which may be contained in a number of components dispersed in angle of arrival and with differing phase and amplitude – in such a manner as to optimise the SINR. This technique provides excellent uplink characteristics, but the downlink signal can only be pointed in the direction of the average or maximum incoming signal unless there is feedback from the mobile. Once more, serving multiple users requires a complex system.

- **Space division multiple access** (SDMA). In this scheme the processing creates a number of spatially separate beams within each sector (Figure 2-1). Each beam is directed at a different user who can share channel resources (such as the frequency, spreading code or burst time) with the other users. The extent to which sharing is possible depends on how narrow and well-defined the individual beams are and the amount of scattering in the radio propagation environment which limits the minimum angle of arrival possible. SDMA requires a more intelligent and dynamic version of a beam-forming array with multiple concurrent inputs/outputs.

![Figure 2-1: The concept of an SDMA system. The users can share spectral resources because they are served by different beams provided by the antenna](image)

- **Spatial filtering for interference reduction** (SFIR) This scheme operates by using spatial (angular) separation of wanted and unwanted signals; as well as adding wanted signal components it forms nulls in the direction of interfering signals. This approach may allow closer frequency re-use than would conventionally be obtained with fixed antennas.
• **Opportunistic beam forming** is a cross layer technique that can be applied to a system in which a beam can be formed and randomly steered over a sector. If there is a large number of users in the sector it is probable that for some of them the beam configuration and propagation conditions are such that the signal path from the base station is optimal at the moment the beam intersects the MS. Data is then fed at the highest possible rate to the users. It is reported that this apparently haphazard method can provide significant gains in system performance [2]-[3].

Tsoulos [1] provides a summary of the advantages and disadvantages of these schemes, as shown in Table 2-1.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switched fixed beams</td>
<td>Easily deployed Tracking at beam switching rate</td>
<td>Low gain between the beams Limited interference suppression False locking, shadowing, interference and wide angular spread</td>
</tr>
<tr>
<td>Direction finding</td>
<td>Tracking at angular rate of change No reference signal is required Easier downlink beamforming</td>
<td>Lower overall CIR gain Susceptible to signal modelling inaccuracies, needs calibration Concept is not applicable to small cell, non line-of-sight environments.</td>
</tr>
<tr>
<td>Optimum combining</td>
<td>Optimum gain in SINR No need for accurate calibration Performs well even when the number of elements is smaller than the number of signals</td>
<td>Difficult downlink beamforming with FDD Needs a good reference signal for optimum performance Requires frequent updating as the target moves and signal conditions change</td>
</tr>
<tr>
<td>SDMA</td>
<td>No need for revised frequency planning to exploit capacity gain Single cell deployment is possible for local capacity gain</td>
<td>Requires discrimination between intracell SDMA users More complex radio resource management (angle and power)</td>
</tr>
<tr>
<td>SFIR</td>
<td>No need for major air interface changes Only minor changes to radio resource management</td>
<td>Relies on intelligent intracell handover Large deployments are necessary to exploit the full capacity potentials</td>
</tr>
</tbody>
</table>

Table 2-1: Summary of alternative smart antenna schemes

The shared characteristic of all smart antenna schemes for mobile radio base stations is that they are able to form one or more adaptive beams (and/or nulls) in the azimuth plane. To achieve this they must comprise several antennas spaced apart in the azimuth plane. If the objective is to process the potentially large number of signal components arriving from wanted and unwanted stations, it is necessary that the antenna has a sufficient physical
extent in the azimuth plane (measured in wavelengths) to allow the separate resolution of the signal components that can contribute to the result. As the number and spacing of arrayed elements increases it becomes possible to form narrower beams and nulls, and the available capacity and coverage advantages increase. Unfortunately, increasing the number of antennas also increases the cost, complexity and visual impact of the array.

2.4 Current practice in mobile radio networks
In considering the possible advantages to be obtained by the application of smart antenna it is important to understand the practices that are in current use to optimise transmission in mobile radio networks. If smart antenna systems are to be adopted in mobile radio networks they must exhibit clear performance and/or economic advantages relative to the systems already in use. A major error made by some proponents of smart antennas has been to compare their performance with that of simple antenna systems which are seldom used in real networks.

2.4.1 Receive diversity
Each sector of a typical current-generation base station is usually equipped with a two-branch diversity receiving system fed from either:

- a single dual slant-polarised antenna, or
- two separate vertically-polarised antennas

The radio equipment configuration associated with space and polarisation diversity antenna configurations is the same. The universal adoption of a 2-branch diversity system for the uplink receiver provides very significant protection against spatial fading, improving the link budget by 4–6dB relative to a single antenna. A fuller explanation and a comparison of space and polarisation diversity is provided in [4].

2.4.2 Common transmit and receive antennas
In both GSM and UMTS systems it is standard current practice to combine both transmitters and receivers into common antennas. This system can be used when more than two transmitters are installed, but then requires combiners to permit a group of transmitters and receivers to feed each antenna. This universally adopted arrangement, in which multi-channel transmitters and receivers share access to a common antenna, provides significant advantages but creates a major constraint to the design of smart antenna systems for FDD systems.

The advantage of using common transmit/receive antennas is reduced cost, reduced physical profile for the antenna system and reduced mechanical requirements for their support. The familiar single-pole base station with three dual-polar antennas relies entirely on this method of operation. Older practice with separate transmit and receive antennas for space-diversity systems required three or four antennas to serve each sector.
2.4.3 Tower-mounted low-noise amplifiers
To improve up-link performance a low-noise amplifier is connected directly to the antenna to establish a low noise figure for the receive system (typically the noise figure for these amplifiers is only a little greater than 2dB for a system with built-in duplex filter to bypass the transmitter signal). Compact multiband units are now available.

2.4.4 Common antennas for different bands and systems
Networks which previously operated GSM systems in the 900MHz and 1800MHz bands have reduced the visual profile and tower-rental costs for their antennas by installing antennas providing combined facilities for all their assigned bands. Dual-polar antennas are currently available for various band combinations including:

- 900 + 1800MHz, often with combined inputs
- 900 + 1800 + 2100MHz (all with separate inputs)
- (900 + 1800) + 2100MHz (with separate inputs for GSM and UMTS)
- 1800 + 2100MHz (broadband antennas)

A dual-polar tri-band antenna is a complex device. It contains six independent multi-element antenna arrays and makes very intensive use of the physical space it occupies.

2.4.5 Intermodulation in multi-frequency systems
The successful operation of multiple transmitters into a common antenna requires great linearity of all components between the channel combining filters and the antenna to avoid the generation of passive intermodulation (PIM) products. These are spurious signals which can cause interference to other spectrum users. If the multi-channel antenna is shared with receivers, generated PIM can potentially mask incoming low-level receive signals and effectively desensitise the receivers.

The requirement for extremely low PIM levels has driven a number of aspects of base station antenna design; the standard specification required by network operators is for PIM levels to be lower than -143dB relative to 2 x 20W input (transmitter) signals. These low levels are difficult to achieve and are many orders of magnitude below the intermodulation products produced by any active devices such as amplifiers or PIN-diode switches.

2.4.6 Elevation pattern shaping
Typical base station sector antennas have a vertical aperture of 8–14 wavelengths long (a physical aperture between 1.3m and 2.5m). It has been normal practice since the advent of digital systems that these antennas provide shaped elevation radiation patterns with suppressed sidelobes above the main beam. The main beam is usually tilted downwards both to ensure maximum power is directed into the served area and also as a means of limiting the area over which the spectrum used by one base station can cause interference to other base stations.
2.4.7 Antennas with remotely adjustable electrical tilt
As a more recent development, base station antennas are now available with remotely-
controlled beamtilt. Many 3-G networks and some 2-G networks are now being equipped
with these antennas. Although the full remote control facilities are not always being
installed at the time of roll-out, the potential for network-wide control of base station
footprint by remote down tilt control will soon be available in many networks. Remote
electrical tilting ability has also recently been standardised within 3GPP, providing a new
interface (called the luant interface) between the Node B and the RNC (Radio Network
Controller) systems within a UMTS network [5]. With this facility a certain degree of
adaptivity is becoming available, and this development is closely allied to the present
project.

2.4.8 Six-sector and other alternative sectorisation schemes
Where additional capacity is required (usually in urban areas) base stations have been
equipped with six sectors and antennas with 45-degree azimuth beamwidth. In this case
each antenna is associated with a different set of radio equipment, so transfer of a moving
user from one antenna beam to another is accomplished by handoff from one cell to
another, rather than by antenna switching. The use of six-sector base stations has been
shown to allow improved frequency re-use with a corresponding increase in spectral
efficiency [6].

2.4.9 Microcells and picocells
Many networks make use of very small cells (known as microcells and picocells) to
provide coverage in areas such as traffic hotspots and gaps in coverage which are unserved
by the local macrocell base station. These small cells usually employ low-gain antennas
mounted low down or within buildings and other structures to limit their coverage area.
This technique can be highly spectrally efficient, but is relatively expensive to install.

2.4.10 Underlay/overlay schemes
Mobile radio networks often employ a hierarchy of cells with many small cells within an
area covered by large ‘umbrella cells’, sometimes operating in an alternative frequency
band – for example a 900MHz umbrella cell may cover an area also served by several
smaller 1800MHz cells. This technique requires intelligence to be applied to the
management of users and network resources at the network level.

2.4.11 Distributed antenna systems
In a distributed antenna system (DAS) a single base station feeds several separate antennas,
usually placed low down in the built environment. This is another spectrally efficient
technique allowing the use of intelligent management of local resources by the network.


2.5 Recent innovations
As well as the techniques described above, further methods for the improvement of capacity, coverage and spectral utilisation are currently being implemented in mobile radio networks.

2.5.1 Remote radio heads
A further level of intelligent control can be introduced into a network by using the concept of a distributed base station. In this a single network interface controls a set of transceivers which – instead of being co-located and combined into a single antenna – are physically separated and feed separate antennas. This technique is in an early stage of adoption but the agreement on a standard interface (CPRI) indicates that its importance is widely recognised in the industry. CPRI is an initiative driven by Ericsson, Huawei, NEC, Nortel and Siemens whose purpose is to define a publicly available specification for the interface between the radio equipment control and the radio equipment.

2.5.2 4-branch diversity
The replacement of two existing space diversity antennas by two dual-polar antennas offers the possibility of further increasing receive system performance by using a 4-branch configuration – this is a simple substitution and leaves the visual profile of the base antennas almost unchanged.

2.5.3 Transmit diversity
Transmit diversity is now standardised within 3GPP for UMTS and is in course of being implemented. This is an open-loop technique that improves the performance of the downlink – especially important when downlink data rates are high and high-level modulation is used (as with HSDPA). It makes further use of the existing diversity pairs of base station antennas, so no additional antennas are needed.

2.5.4 Single antenna interference cancellation
Single antenna interference cancellation (SAIC) is a new method by which a mobile increases the downlink reliability by a technique of demodulating both wanted and unwanted signals and increasing the available data rate by software processing. It has been standardised by 3GPP.

2.5.5 Dual antenna interference cancellation
Dual antenna interference cancellation (DAIC) is a proposed technique for the improvement of downlink performance in which the mobile terminal is provided with two antennas and performs interference cancellation by processing two RF signals.
2.5.6 Base station antennas with azimuth beamwidth control

Base station antennas with remotely adjustable azimuth beamwidth and beam pointing direction are under development by antenna manufacturers. These may be seen as providing a simpler version of the control provided by the current semi-smart proposal and such antennas could be incorporated into the current proposal.

2.5.7 MIMO

MIMO techniques have not been established in public mobile radio networks, but there is clearly potential for their adoption. If UEs (User Equipments) can accommodate two antennas for DAIC, then in principle they can also be used for MIMO.

2.6 Cases of deployed smart antenna system (Antennas for SCDMA/TD-SCDMA systems in China)

A narrow band CDMA network known as ‘SCDMA’ and operated by Beijing Xinwei Telecoms Technology is already in operation and uses smart antennas on the 450MHz and 1900MHz bands. Antennas for both the new and existing systems were examined at first hand during a visit to Beijing Xinwei and an antenna manufacturer in China [7].

Commercial products are available from several major Chinese antenna manufacturers in the form of vertically-polarised planar arrays comprising between 4 and 8 columns of vertical dipole elements and circular arrays of 4 or 8 elements. These arrays are of conventional height (typically 1.3–1.8m high at 1.8–2.2GHz).

In the 1800MHz band the planar arrays are between 300mm and 600mm wide. Taking an example of an 8-element array, the azimuth beamwidth of each column is 120° at -3dB; the synthesised beam has a 3-dB beamwidth of around 12° and can be scanned over 60° relative to the array axis. The output of each element column is connected directly to a port at the base of the antenna and is also connected through the branch arm of a directional coupler to a calibration port. The array is connected by 8 standard flexible coaxial cables to the beam-forming electronics. In the downlink, eight separate small power amplifiers are used – one 2-watt amplifier for each column – so the total RF (and DC) power is much reduced compared with a conventional system, which would use one 128W amplifier to achieve the same EIRP from a single column of elements. For reception, the gain of the array is 9dB higher than that of a single column.

The beam-forming algorithm in use by SCDMA sums the power received in different azimuth directions and applies nulls to interfering signals. Using an 8-column array they report that the average downlink beamforming gain is found to be 21dB, and exceeds 18dB in 92% of cases in which there is no line-of-sight path to the mobile. (The gain is defined relative to a single column with one power amplifier, so doubling the number of columns would be expected to increase the EIRP by 6dB – twice the power and twice the directivity – so 8 columns increases the EIRP by 18dB.)
Typical circular arrays comprise eight columns of very basic collinear microstrip dipoles. The columns are end-fed to provide a simple low-cost unit, but as a result these antennas suffer very restricted bandwidth and there is little control over elevation pattern shaping. The 8-column array is housed in a single cylindrical radome approximately 350mm in diameter. The feed arrangements for the omnidirectional arrays are similar to those for the directional arrays, with main and calibration outputs as well as access to a single omni-directional beam.

The smart antennas available at present do not provide elevation pattern tilt control and its addition would add very considerably to the complexity of the systems because each azimuth beam may require a different elevation tilt.

All the antennas currently available are vertically polarised. The results for beamforming gain quoted above indicate that an effective angle-diversity gain of 3dB is being achieved, but this replaces the spatial diversity or polarisation diversity gains being realised with conventional systems (5–6dB). The discrimination against co-channel interference on both the up- and downlinks more than compensates for this; some of the additional link margin is currently used to reduce the cost of the low-loss cables and TMAs found in conventional systems. All the antennas currently in production are passive, with the smart beamforming cards contained in the base station electronics, situated close to the antenna.

The standards for the TD-SCDMA system adopted for general use in China have been engineered to enable the use of smart antennas in the network. The implementation of networks using this air interface continues to be delayed but information is now available regarding smart antennas to be used in the system [8].

The Chinese experience of smart antennas in the new TD-SCDMA system will be very instructive and will show what can be achieved in a high-capacity TDD system. However, nearly all European based cellular systems are FDD based and (as discussed in Section 2.8) this will considerably complicate the design and reduce the benefits of a smart directional antenna system.

No evidence was found of any intention by different networks in China to share base station locations (it is currently common for the base station structure to carry the name of the operator which owns it). The planar arrays described above are large, but they have adequate bandwidth to provide operation over several channels; alternatively, antennas for several operators could be mounted on a single structure. The current omnidirectional antenna has a ‘top-mounted’ format, so a structure cannot be shared and the narrow bandwidth of the current generation of antennas (15MHz) precludes their sharing by operators with significantly different frequency spectrum assignments.

2.7 Issues in deploying smart antennas in mobile radio networks

Any smart antenna system proposed for use in existing networks must show significant advantages in terms of cost, performance and environmental acceptability relative to established current practice and the new techniques now being introduced.
There is little doubt that smart antennas would be adopted if the potential advantages claimed for them could be realised in practice with no corresponding disadvantages. The commercial and practical realities that influence the possible adoption of smart antennas in mobile radio systems relate to:

- The nature of the radio environment;
- The selection of transmission standards;
- The relative practicability and costs of other available techniques that can be adopted to increase the coverage and capacity of networks;
- Environmental considerations – size and visual profile;
- Practical concerns about complex outdoor electronics systems;
- Business and cost issues;
- Regulatory concerns.

These considerations interact with one another and it is difficult to place them in a clear order of priority.

A mobile device with which communication is established is known as a mobile station (MS) in a GSM system and a user equipment (UE) in UMTS terminology. A base station is known as a base transceiver station (BTS) in GSM and a Node-B in UMTS. To avoid duplication the UMTS (IMT-2000, 3G) terms will generally be used in abbreviations in the discussion below. Many of the comments relate to both systems and specific comments are made where a generally comparable situation does not exist between them.

The radio frequency environment issue will be addressed in this section. Other issues will be discussed separately in later sections.

### 2.7.1 The radio frequency environment

Mobile radio networks operate in a complex radio environment and the techniques which can be used for antennas – especially smart antennas – are strongly determined by the imperfect and highly variable character of that environment.

### Path loss between the mobile and the base station

In an ideal environment there would be a smooth relationship between the signal strength at any point and the distance between the point and the base station. In practice this relationship is often very chaotic. Figure 2-2 shows path loss as a function of distance as measured in an urban cell in Toronto [9].
Three distinct mechanisms are usually identified as being responsible for this chaotic relationship:

- Distance-dependent path loss;
- Shadowing by terrain features and buildings (seen as *slow fading* by a moving user);
- Multipath fading (seen as *fast fading* by a moving user).

**Distance-dependent loss**

Distance-dependent loss is sometimes called *spreading loss* and is addressed by choosing an appropriate spacing between base stations and the provision of enough RF power, receiver sensitivity and antenna gain to provide coverage of the terrain round the base station. If we include the loss that occurs beyond line-of-sight propagation, then we can reduce the transmission loss and increase the coverage of the base station by increasing the antenna height. The disadvantage is that we will probably increase the level of signals received in adjacent cells, impairing frequency re-use and reducing the spectral efficiency of the network.

The typical dependence of propagation loss on distance $d$ in the mobile radio environment is usually assumed to be proportional to about $d^{3.8}$. Even in a city built on level terrain this
severely limits the distance to which coverage can be extended from a base station even by using a very directional high-gain antenna.

**Shadowing**

Shadowing is the obstruction of some parts of the intended coverage area by terrain features or major fixed structures. It can be reduced to some extent by careful choice of the base station location, but apart from raising the base station antenna there is little that can be done to overcome it. Severe shadowing loss may make it necessary to fill a coverage hole with an additional cell or microcell.

**Multipath fading**

Multipath fading is caused by the arrival at the base station of signals from a mobile which have travelled by different paths, having been reflected from a scattering objects such as buildings, cars and terrain features. The UE is typically within 2m of the ground and these scatterers are typically close to the UE, so at the base station the direct and scattered signals arrive with a small angular spread. To reduce the effect of multipath fading it has been standard practice for many years for the base station to receive two samples of the incoming signal, either at two spatially separate locations, or in two orthogonal polarisations [10]. In the case of spatial diversity the separation between the antennas at the base station effectively defines the angle within which signals will be separately resolved and can cause independent (uncorrelated) fading at the position of the antennas. In the case of polarisation diversity the correlation of the signals received at the base station does not depend on the spatial separation of the scatterers, but on the different polarisation characteristics of scattered signals.

The adoption of smart antenna techniques does not necessarily remove the effects of multipath fading [11]. If a smart antenna is situated in a position of temporarily low net signal it cannot produce a satisfactory output. Either the elements of the smart antenna must be sufficiently spaced to make it unlikely that fading across the array is correlated – that is to say that the width of the array must be sufficient to allow the resolution of the separate multipath components – or dual-polar operation must be adopted in accordance with present base station practice. Both techniques require additional hardware and processing and substantially increase the cost of the system.

**Angular spread**

In rural environments the direct and scattered signals arrive at the base station with a small angular spread – typically less than 5° – but in urban environments, especially when the mobile is close to the base station, the angular spread may be as large as 20–30°. SFB arrays or other smart antennas which effectively manipulate narrow beams may be unable to receive all the angularly-dispersed signal components and may in some circumstances provide a lower total signal power than a simple sector antenna.
**Delay spread**

Signals travelling between the mobile and the base station by different routes will not only arrive from different directions but will experience different propagation times. The time difference between the arrival of the first signal component and the last significant component is known as the delay spread.

A standard RAKE receiver used in a CDMA system has the property that it can add together the power contained in signal components with various relative propagation delays. In introducing a smart antenna to the system it is important that the capabilities of the RAKE receiver are not degraded; any narrow beam must remain in place for a sufficiently long period that all significant time-dispersed signal power is received. The system has no *a priori* knowledge of either the total dispersion or the propagation delay of the largest component of the signal – it is sometimes wrong to assume that the largest component has the shortest delay.

**Doppler spread**

The signals from moving users are characterised by frequency shifts caused by the familiar Doppler effect. In a multi-path environment the signals transmitted by different paths from a moving mobile will experience different Doppler shifts and the total frequency span between the significant signal components is known as the Doppler spread. (A user travelling away from the base station towards a significant scatterer will present the base station with a direct signal having a negative Doppler shift; but depending on the relative direction of scatters it may be associated with reflected signals with a positive shift.)

Processing signals with different Doppler shifts consumes a significant amount of time: smart antennas which act as narrow filters in the frequency domain or change characteristics too quickly may be unable to cope with the Doppler spread from a fast-moving user.

**Co-channel interference**

In general any signal will be received together with signals from other users sharing the same frequency. In a CDMA system the other users (both singly or together) will contribute to a raised noise level determined by the spreading gain, but in other systems a single interfering signal will more directly impair the ability of the receiver to correctly demodulate the wanted signal.

**Dynamic range**

The power level transmitted by each mobile is dynamically controlled by the base station to ensure that signals from different mobiles arrive with almost the same signal power. It would therefore seem that there is no significant problem of a smart antenna being
required to process signals with a wide dynamic range. The minimum received signal level will be that from a mobile located at the margin of the cell, having a signal level which can – by only a small margin – be decoded against thermal noise in the base station receive chain. In busy conditions a higher signal level will be needed, as the threshold will be raised by external noise and interference.

In practice, the highest receive signal levels may be caused by mobiles situated close to the base station but connected to other neighbouring cells. This mobile may be transmitting at maximum power on a channel adjacent to that used by the nearby base station with a limited channel filtering. This is a classic ‘near/far’ situation, and the resulting dynamic range must be handled by the whole receive chain without any consequent desensitisation or rise in receiver noise.

A further consideration arises when the base stations of two or more networks are closely co-located. In this situation the strong interfering signal is on the base station transmit frequency, but the powerful incoming signal must neither disrupt the control algorithms, nor give rise to intermodulation products generated either by the antenna system or by the transmitters.

**Noise**

As with all receiving systems the sensitivity and throughput of the system is limited by noise. This is not just a threshold effect – the data rate that can be obtained is directly proportional to the available signal-to-noise ratio.

### 2.7.2 The uplink and downlink

In all discussions it is important to remember that the signal path between a Node-B and a UE comprises two links with important differences in their characteristics:

- The **downlink** from the Node-B to the UE. This is characterised by a high power transmitter feeding a high gain antenna at the Node-B, and a low-gain antenna feeding a low-noise receiver at the UE.

- The **uplink** from the UE to the Node-B. This is characterised by a low power transmitter with a low gain antenna at the UE, and a high gain receiving antenna at the Node-B.

The gain of the antenna in a handset UE is typically very low and can be as little as -10dBi when the handset is held in the talk position close to the user’s head. The user is typically located close to ground level or inside a building, so the transmission path in the user’s vicinity is much cluttered. Base station antennas typically have gains around +18dBi and a low-noise amplifier is usually fitted close to the antenna to minimise the noise figure of the receiving system. The base station antenna is usually mounted in a high location where it has a clear field of view at least for some hundreds of metres.

Base stations typically transmit some tens of watts of RF power per channel (an effective radiated power (EIRP) of several hundred watts). For reasons of battery life and the need
to limit the exposure of the user to RF fields, handsets are generally restricted to no more than one or two watts of radiated power.

**Link balance** Current networks have a reasonable degree of balance between up- and downlinks, so the application of techniques which increase range or capacity on the uplink must in general be balanced by other measures which increase range or capacity of the downlink. This is evident in the standardisation of High-Speed Uplink Packet Access (HSUPA) protocol to accompany the preceding standardisation of the High-Speed Downlink Packet Access (HSDPA) protocol in 3GPP.

UMTS networks are engineered to support users with a wide variety of data services as well as speech channels. By nature, many data services are not symmetrical, data traffic on the uplink and downlink are unequal both in the short term and the long term. Web browsing is consistently characterised by large amounts of data (web pages, pictures and music) being passed on the downlink in response to simple prompts passed to the server on the uplink. A user sending a picture or an e-mail with a large attachment generates a short-term asymmetrical demand for uplink capacity, but users will correspondingly receive pictures and attachments, so in the long term this kind of traffic does little to improve the net excess of downlink traffic. As a further complication, the system will respond to a channel experiencing poor transmission characteristics (whether caused by low signal levels or interference) by adding more coding overhead, increasing the total data to be transmitted over the poor channel yet at the same time reducing the effective rate of user data transmission. The variability of traffic demands means that in a 3G system the concept of link balance is a statistical concept, relating the signal quality and capacity of the up- and downlinks with respect to the throughput demands stemming from some assumed mix of user traffic. In general we can expect that the capacity required on the downlink will be greater than that on the uplink, and this characteristic will increase as promised ‘richer content’ is made available by content providers.

### 2.8 Transmission standards

The close relationship between the operation of many types of smart antenna and the air interface (the transmission and signal protocol in use) is of great importance. In examining the potential application of smart antennas to mobile radios systems the aspects which are of most importance are:

- The relationship in terms of occupied time and frequency between up- and downlinks;
- The occupied frequency bandwidth.

#### 2.8.1 Frequency division duplex (FDD)

The uplinks and downlinks for both GSM and most UMTS channels operate simultaneously on different frequencies, a system known as frequency-division duplex (FDD). UMTS frequency allocations separate them by 190MHz.
Optimisation of the uplink  Multiple antennas can be provided at the base station to supply a number of different samples of the received signal, so it is possible to invoke powerful signal processing algorithms to optimise reception of multiple signals from many mobiles.

Optimisation of the downlink  In an FDD system, information obtained from the behaviour of the signal on the uplink is of limited effectiveness in making decisions about how to optimise the performance of the downlink. The only near-real-time information available about the actual performance of the downlink must be supplied by the mobile (via its uplink) which can provide a continuously updated (although slightly delayed) report of the signal level or error rate at the mobile receiver. The more frequent and accurate this report needs to be, the larger the loss of uplink data capacity will be, because capacity which would otherwise be available for user data is being consumed by ‘housekeeping’ (overhead) tasks. There is also a real problem if the signal on either uplink or downlink is lost, as the optimisation task is frustrated and it may be difficult to re-establish the link.

In proposals for smart antennas in TDD systems the most common tactic adopted at the base station is to estimate the direction from which the largest component of the received signal originates and then to form a transmit beam in that direction.

An FDD system has intrinsically similar capacity in the up- and downlinks, although this can be changed if burst lengths can be assigned different durations or alternative modulation formats are used for transmission in the two directions.

2.8.2  Time division duplex (TDD)

A time-division duplex system uses a single carrier frequency on which data frames are transmitted at different times in both directions. Providing the time occupied by each frame is short compared with the rate of change of the channel, information about the state of the channel (channel-state information CSI) obtained when a frame is received at the base station can be applied with confidence to the next transmitted frame. The optimum parameters for control of the antenna excitation (known as weights) can be recomputed when the next frame is received and the new weights are then applied to the following transmitted frame. Asymmetric data on the up- and downlinks is easily handled by allowing the length of the frames on the two links to change in response to traffic requirements or by adopting alternative modulation formats. This arrangement fails when the frame length becomes too long compared with the rate of change of the channel state. In general, the faster the user is moving, the more frequently the CSI must be updated, so the frame length must be reduced and the data transmission rate falls – a larger proportion of the available capacity is consumed by overhead.

A small amount of spectrum is currently allocated in the UK for UMTS TDD services. However, this 5MHz ‘unpaired’ spectrum is not extensively used by the operators at present though it may be in future for digital television or other services.

2.8.3  Multi-channel FDD-TDMA operation

In a TDMA system (typified by GSM) transmission and reception from the base station is divided into a stream of time slots organised in repeating sequences (frames). Transmission to and from a particular mobile occupies one slot in each frame. (Some
protocols can assign multiple slots, but these do not affect the following discussion.) A mobile can either transmit or receive in its assigned slot(s) and cannot do both at the same time.

2.8.4 Base station operation with duplex multi-user FDD-TDMA

In an TDMA-FDD system the up- and downlinks at the base station usually operate concurrently (the mobiles can only transmit OR receive in a given slot, so the base station transmission will generally serve different users in each time slot.) Each carrier frequency supports a relatively small number of concurrent users (8 in the case of GSM) and a base station will usually be equipped with transmitters and receivers operating concurrently on several frequencies to support additional users.

2.9 Physical and other constraints in deploying smart antennas

We now examine a number of physical and other constraints that will apply to any base station antenna with extended azimuth pattern-shaping characteristics.

2.9.1 Physical antenna dimensions

A UMTS base station is currently very compact, with a typical antenna complement of three directional dual-polar sector-coverage antennas, each approximately 1300mm (high) x 100mm (wide) x 60mm (deep).

At many base stations, UMTS antennas are co-located with GSM antennas. Alternatively GSM1800 and UMTS signals can be fed to the same broadband antenna, and either plane-polar or dual-polar radiating elements for GSM900, GSM1800 and UMTS can all be housed in a single radome. This practice is increasingly common in locations where planning restrictions or structural limitations dictate that minimum antennas must be used.

Current base station antennas are in columnar form; the extended vertical dimension allows the formation of a main beam with an elevation half-power beamwidth of $5^\circ$–$7^\circ$ and this beam is down-tilted to control the radial extent of coverage of each cell. As noted above, many new antennas are fitted with a set of electrically-driven phase shifters whose function is to vary the downtilt to allow remote adjustment of the elevation angle of the main beam maximum.

The control of the overlap between the coverage of adjacent base stations is very important in a UMTS system to ensure efficient hand-off of users between cells; excess overlap loses network capacity because mobiles operate in soft- and softer-handoff modes, consuming capacity in more than one cell and in the links connecting them together. A smart base station antenna is likely to maintain the same elevation beamwidth in the range of $5^\circ$–$7^\circ$ (and in consequence the same physical height) as typical current antennas because the control of the elevation beamwidth of antennas is already used as a means of increasing network capacity. An analysis of current proposals for smart antennas suggests that they will be substantially wider than current antennas by a factor of at least 3 and more if current Chinese practice is followed. Garg et al [12] concluded that the optimum
performance is obtained with 4 or 6 elements at an inter-element spacing of 0.5 wavelengths. This would result in UMTS antennas 300–450mm wide. This may be acceptable as long as only one antenna is needed for each sector; this in turn requires that antennas can be used in duplex mode, i.e. that separate antennas are not needed for transmission and reception. A 900MHz smart antenna would correspondingly be 2.4m high and 700–1050mm wide: the size of a door.

2.9.2 Weight and windload
Base station antennas currently weigh around 8kg (1800/2100MHz) or 20kg (900MHz). They are frequently installed without cranes or other power lifting equipment – the use of roof-mounted stub masts and towers for many sites makes it difficult to use heavy equipment such as power winches so manual lifting is normal, using ropes with block and tackle. Manual methods become increasingly unsafe as the antenna weight exceeds 25kg, so the potential weight of one-piece smart antennas must either remain below the existing limit or the complexity and cost of installation operations will increase.

The horizontal windload on a flat door-sized antenna in storm conditions is around 0.5 tonne. Supporting this windload would require many existing towers to be replaced with more heavily constructed structures.

2.9.3 Visual profile
The visual obtrusiveness of base stations has been an issue of public concern for some years. Although there is currently no evidence of any significant health effects from base stations, there is ongoing public unease on the matter and in the public mind there is almost certainly a strong connection between the size and number of antennas and the perceived threat that they may pose.

Antennas with the dimensions of a door are clearly visually unacceptable in many locations unless they can be hidden behind an electrically transparent screen, such as a fibreglass structure simulating a brick wall or rooftop feature. Another possibility might be that an antenna is mounted flat against a wall, but this method requires one or more walls facing in an appropriate direction and with access to possible mounting locations.

Another factor potentially increasing the visual profile of an adaptive antenna is the potentially large number of cables (6, 8 or even 10 cables) connected to it. To address this issue a larger part of the whole base station equipment needs to be incorporated in the antenna, so that only low frequency (or digital) signals are passed between the antenna and the remaining base station electronics.

2.9.4 Level of integration
The size of base station electronics has diminished substantially over the last decade and continuing progress with the design techniques will lead to further size reductions. This shrinkage cannot apply to antenna arrays, because the whole objective of a smart antenna array is to exploit spatial characteristics of the signal. The ability of an antenna array to resolve azimuth angles depends directly on its physical width (in wavelengths), so
increasing functionality inevitably means larger dimensions for any specified frequency band.

For some purposes it becomes attractive to re-distribute the functionality of the base station within the antenna system. Instead of using a 100W amplifier feeding a single antenna, ten separate 1W amplifiers each drive a separate antenna. This concept, used by the Chinese system described above, is attractive. It uses much less RF and DC power than the conventional system, an advantage magnified by the very low power efficiency of broadband multi-carrier power amplifiers. Implementation of this system for duplex multi-channel operation is not easy and the complete integration of electronics and antenna structure may increase problems of maintenance, access and the skill set of personnel.

2.9.5 Reliability

It is an inevitable fact that as equipment complexity increases it will become more prone to failure. Unfortunately the effects of larger size and weight will make a larger and heavier antenna slower to remove and replace. Both these effects will increase the time for which the base station may be unavailable (down-time), causing increased revenue loss to the operator. Current antenna systems are remarkably reliable and it is inevitable that reliability will be reduced by the integration of complex electronics; this will increase problems of access. Systems will certainly need to be carefully engineered to provide graceful degradation in the event of failure.

2.9.6 Skill set

Antenna installation work in the UK is generally carried out by riggers whose main skills are working at height and operation of the equipment necessary to handle and install large antennas even in adverse weather conditions. More highly trained technicians or engineers who have the necessary knowledge and skill to operate digital test gear and diagnose complex equipment faults are not usually willing to work outdoors and at height. The incorporation of complex electronics into heavy and relatively inaccessible antenna systems creates a significant difference in the skill set of those who would install, commission and maintain the equipment.

Some antennas are currently mounted on building walls where they are accessed by riggers abseiling down the wall using rope systems and techniques familiar to mountaineers. These locations avoid a large visual intrusion into the landscape but clearly pose challenges for the maintenance of complex electronics.

2.9.7 Cost issues

We have already noted that installation and supporting structure costs will be significantly higher for smart antennas.

Additional operational costs will arise on base station sites where the network operator is not the owner of the site. In this case the rental cost imposed by the landlord is frequently related to the windload of the antennas, and sometimes also relates to the number of cables attached to them.
2.9.8 Site sharing and co-location
Practical matters which will influence the uptake of smart antenna techniques include existing and future practice in the sharing of base station sites by mobile network operators, and the use of sites with a wide variety of other services including radio and television services.

At those base stations where antennas operated by different networks are erected at different heights on the same structure, the advent of adaptive beamforming or nulling will have relatively little impact on system planning.

Where base stations are situated alongside one another, the formation of narrow receive beams will increase the effective gain of the antenna and change levels of signals coupled from the adjacent transmitters. Filter and amplifier systems will need to have tighter specifications, with potential effect on their costs.

2.9.9 Cell range
One feature of the deployment of smart antennas which could be attractive is the potential ability of a large antenna system (needed to realise the increased spatial resolution) to create higher effective radiated power (EIRP) and provide an extended range of coverage. Reducing the number of base stations necessary to provide a given level of network service is obviously attractive, but it cannot be assumed that increased EIRP will increase coverage without creating other problems – for example in a cluttered urban environment the range of a base station is often determined by blocking by buildings, so increasing the EIRP may create only a small increase in coverage while potentially causing spectral contamination from the increased level of reflected signals that make no contribution to communication.

2.10 Business and cost issues
The discussion above has attempted to set the possible future adoption of smart antennas into the context of other available technologies. A dimension not discussed above is that networks do not comprise the commonly-assumed uniform network of hexagonal cells. The distribution of base stations is non-uniform, while that of users and traffic demand is both non-uniform and variable in time. Real networks are placed in real terrain, not on a smooth earth. Spectral resources are currently far from fully utilised in the 3G band, but as demand rises they are likely first to be under pressure in dense inner-city areas. These considerations mean that it is unlikely that a single smart antenna solution will be applicable to all the base stations in a network – perhaps only to a small minority. This means that prices will remain high and adoption will remain marginal because the measures listed above will remain more attractive, especially if adding an adaptive antenna requires re-engineering of substantial parts of the network.

Many advanced smart antenna techniques require cooperation between the base station and the mobiles to allow the downlink to be optimised. This requires industry-wide agreement about standards – a notoriously slow process. There is an additional barrier if
the system demands that a high proportion of mobiles can implement the standard before significant pay-back is gained in terms of capacity. Terminal replacement is slow and costly, and requires handset manufacturers to see benefits in terms of their market share before they become available.

The economics of the introduction of smart antennas into existing networks are very complex. In addition to the direct financial cost of the hardware – which is strongly dependent on the characteristics of the air interface – there are many other aspects which currently deter operators from introducing this technology.

Networks are currently introducing antennas providing remotely controlled electrical tilt (RET). These products were conceived almost 10 years ago and during the last year deliveries of RET-capable antennas for 3G networks have exceeded those of conventional antennas. This market was enabled by an initiative (by antenna manufacturers and network operators) to agree a common interface specification for controlling these antennas. The implementation of the necessary network software to enable the interactive control of this new facility is not yet complete and represents a large cost to the infrastructure vendors. In a discussion with one UK operator it was stated that the software cost of the apparently simple task of adding control for on-frequency repeaters (OFRs) was £300k and took 4–7 months to implement. There is currently a queue for priority for further system additions.

The size, environmental impact, physical complexity, maintenance and other very practical considerations are very real negative features which are likely to inhibit the adoption of smart antennas into the current generation of UK mobile networks. These constraints are much less significant at higher frequencies, or for systems operating with lower powers than are usual for the mobile radio services. The constraints are also different if a network is designed from the beginning on the basis that the entire system is optimised to make use of all the potential benefits of smart antennas. Such a system must exploit all the potential ways in which a smart antenna solution can save cost – for example by reducing the number of base stations needed to support a given capacity and by using multiple low-power amplifiers in place of a single high-power amplifier – but these possibilities are very protocol dependent.

The frequency separation between the up-link and down-link paths of an FDD system make it very difficult to achieve symmetrical increases in system performance without incurring a significant traffic overhead, reducing the benefit which is being sought. The smart antennas used in the Chinese SCDMA and TD-SCDMA systems (see Chapter 2) are seen as a means of reducing overall system cost.

Discussion with leading UK and European antenna manufacturers indicates that they do not envisage any practicable system within present networks more advanced than one using six-sector base stations (employing RET antennas with 45° azimuth beam width). This is for the reasons listed elsewhere in this report – visual profile, cost and the decreasing advantage of further reduction in azimuth beamwidth. The minimum useful azimuth beamwidth is determined by the angular spread of signals propagating through urban environments (which is where capacity problems are first experienced, so antennas with narrower beamwidths solve one problem while causing another).

The current trend to the adoption of transmit diversity and 4-branch diversity on receive will improve the coverage of 3G base stations. These techniques have already been standardised in 3GPP and their implementation will follow in about 2 years’ time.
One direction of current base-station equipment development is the integration of more of the RF functionality of a base station into a unit that can be located close to the antenna. This removes the requirement for large low-loss cables and reduces the RF power needed from the PA, half of which is typically lost in the coaxial cable. The cost of cables and their installation is high; they are unsightly and contribute to the need for heavy structures. The model for this direction of development is a masthead RF unit connected to the ground only by an optical fibre (for signals and control) and a DC feed. Although the RF equipment continues to benefit from improvements in solid state devices, the high operating power of typical base stations and the difficulty of building efficient multi-channel power amplifiers continue to make it difficult to achieve this.

The only scenario in which the adoption of smart antennas into base stations may prove attractive is in conjunction with a future radio interface based perhaps on TDD/OFDM and in which multiple networks share the infrastructure of a common base-station in a much more radical way than is the current practice in order to reduce total capital costs and environmental impact.

With present radio interfaces it may be a much more practicable path to exploit distributed systems in which a single base station is used to feed multiple RF heads and antennas. Such systems have been adopted in the past for special installations (in buildings, tunnels and other areas in which standard out-door coverage is not available) but they have been seen as too expensive and difficult to install for wider use. Improved products in this area are currently being developed and they may provide many of the sought-after benefits of improved spectral efficiency, lower power consumption (and consequent CO$_2$ generation), lower environmental impact and lower cost. Such systems allow the intelligent use of spectrum and other radio resources.

### 2.11 Regulatory issues

One of the sought-after benefits of smart antennas is increased range; this will require higher EIRPs than are usual with conventional antennas, potentially exceeding currently permitted limits. The margins of compliance of base stations with ICNIRP guidelines on public exposure to electromagnetic fields is usually very large, although some ‘keep-out’ zones, for example round rooftop antennas, may need to be increased. The public perception of larger antennas will certainly be that they are more dangerous.

The adoption of new standards for future radio systems is no longer seen as a regulatory matter, but the rate at which standards are developed is likely to determine what innovations can be put into practice.

As noted above, it seems possible that the greatest benefits are achieved by encouraging the use of common base station infrastructure by several operators. A full smart antenna system includes a complex signal processor which processes all incoming and outgoing signals on an equal basis. Once separated, the signals can be directed to the appropriate network of interest. Many current discussions of competition in mobile networks now see the real areas of competition as being in service offerings, added value services and content. This paradigm is similar to that in the broadcast business in the UK, where two large organisations transmit signals for a large and increasing number of programme makers and content assemblers.
However, it is unclear to the investigators how much the current 2G and 3G licence holders will be allowed to share such resources before it is deemed uncompetitive. Traditionally Ofcom (and its predecessor the RA) was quite prescriptive in its licence terms, however in its recent spectrum review; Ofcom is proposing to be much more market-driven in its future spectrum policy. This point is expanded upon in Chapter 6.

2.12 Summary

There is little doubt that the adoption of smart-antenna techniques can increase the utility of radio communications, providing enhanced data rates and improved coverage and spectral utilisation. It is argued that the administrative and financial environment of the industry and the current technical standards adopted in the mobile radio industry may not provide the most promising environment for the adoption of these techniques. It has been shown that a wide variety of techniques for the enhancement of the reliability of coverage and increase in network capacity have been applied and will continue to be developed in both GSM and W-CDMA systems. Reference has been made to the promising experience of smart antenna techniques in TDD systems in China, but these are currently only in service in small networks and have not yet been proved in large dense networks in urban environments.

It is also suggested that the financial and environmental constraints to the adoption of enhanced techniques could be resolved to the benefit of the community at large by the adoption of a different model for the ownership and operation of services for future networks. Combined with the specific choice of technical standards that can make best use of the techniques of multiple antennas, this could lead to a significant increase in spectrum efficiency of mobile cellular services in the UK.

Having addressed smart antenna technology in general, we devote the following chapters to the semi-smart antenna technology, which is the main body of the project.
The semi-smart antenna approach was first developed at Queen Mary, University of London, as a smart antenna approach for use with a novel load balancing scheme. This approach is of much lower complexity than conventional smart antennas, and has a minimal impact on the cellular system architecture and can address many of the issues highlighted in Chapter 2. The term semi-smart antenna has been coined to denote its inherent low complexity, compared to the fully smart systems with complex BFN requirements.

3.1 Basic concepts

The semi-smart concept is a response to the radio industries slow take-up of fully smart technologies which, as discussed in Chapter 2, are seen as being expensive to introduce, of limited value except in difficult locations and complex to manage and install. The basic concept is to introduce a much simpler scheme that meets the industry needs of accommodating traffic hotspots dynamically, but with minimum changes to the infrastructure. As will be seen, this approach can also give a lower requirement for base station (with corresponding decrease in costs) and a decrease in the network planning requirements for new network installations.

The basic idea behind the load balancing scheme is to shape cellular coverage according to the traffic needs. The traffic demand of the heavily loaded cell is decreased to match the available capacity by contracting the radiation pattern around the area of peak traffic, while adjacent cells expand their radiation patterns to compensate for coverage loss as shown in Figure 3-1 below.

Figure 3-1: semi-smart antenna system for geographic load balancing in a cellular network. Dashed cells representing the original uniform cellular network; solid cells representing the network employing the semi-smart antenna system and showing adaptation to the high traffic load present at the central cell.
In contrast to other approaches where smart antennas are employed, in the load balancing approach the only knowledge required is the location of clusters of mobile users and the traffic load and capacity of each cell. Invariably the movement of clusters is much slower than the movement of the individual mobiles, and the wide azimuth antenna beams used make the system relatively insensitive to the speed of movement of individual mobiles. Since only the location of mobile clusters must be determined – rather than the location of the individual mobiles – a much longer update period (of the order of 30 seconds) between demand pattern changes can be afforded than is needed to steer beams to individual mobiles. The significance of the longer update period is that it greatly reduces the requirements on the hardware implementation of the semi-smart antenna; there is not only less data to handle, but it can be processed more slowly with no loss in performance..

Another advantage of this concept is that the network will automatically compensate if a base station ceases operation. It therefore introduces a degree of system reliability as well as easing maintenance procedures.

It should be noted that the approach to cooperative coverage developed at Queen Mary for different kinds of semi-smart systems is equally applicable to fully smart antenna systems or, at the other end of the scale, to simple beam-tilting systems. It is equally applicable to different wireless technologies such as GSM, UMTS or WLAN.

3.2 Previous work at QMUL

The Networks Group and the Antennas & Electromagnetics Group at QMUL have investigated and developed this semi-smart antenna concept substantially over last five years, in connection with leading two EU-IST projects, SHUFFLE and ADAMANT, and recent work for the US Navy. The experience gained on these projects forms an important background to the present project, so these projects will now be described in outline.

3.2.1 EU-IST SHUFFLE Project

Based on original work on the use of agent technology for resource management in AMPS networks\(^1\)[14]-[16] Queen Mary initiated and managed the EU-IST project SHUFFLE\(^2\) (an agent-based approach to controlling resources in UMTS networks) to investigate the control and management of both the business interactions and the radio resources for 3G networks. Resource management is increasingly important as mobile networks become more complex – applications need more bandwidth, and customers demand better and more assured performance. The situation is further complicated by deregulation of mobile networks; an “any-to-any” marketplace is developing, where users may buy services from any service provider and where service providers in turn may buy capacity from any network operator. Management of resources is therefore inextricably linked to the business strategies of both service and network providers. SHUFFLE addressed both issues. It developed a hierarchical control structure where policy was passed down from cooperative

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\(^1\)Bodanese [14] showed that a distributed resource allocation scheme giving a degree of autonomy to the components offered an efficient approach to resource allocation of radio bandwidth to radio cells, reducing local congestion or degradation in QoS under moderate to heavy loads.

\(^2\)The full list of partners in SHUFFLE was: Emorphia Ltd (UK), Martel GmbH (CH), Queen Mary University of London (UK), Nortel Networks PLC (UK), National Technical University of Athens (GR), Portugal Telecom Inovação, S.A (P) and Swisscom AG (CH).
local planning to the faster-acting reactive layers. SHUFFLE also looked at how more flexible control, related to business policy, could be applied to interactions between service-providers and network-providers.

The part of this work which particularly relates to the present proposal was the way the cooperative layer in the control system should alter the environment of the mobile. This was achieved by shaping the antenna coverage.

The application of smart antennas in cellular networks has been widely investigated [17]-[19]. Unfortunately, most work on smart antennas only considers the radio propagation channels within one cell, while most work related to traffic load balancing focuses on different radio channel allocation schemes. These constraints limit the effectiveness of the solutions that have been proposed. Studies on dynamic sectorisation [20], the use of tilted antennas [21], and dynamic cell-size control [22] have shown that system performance can be improved for non-uniformly distributed users. However changing both cell size and shapes had not been studied and this was investigated in the SHUFFLE project by Queen Mary and in subsequent contracted work for the US Navy. This work looked at a method that can perform these changes in real time and evaluated the benefits and costs for simulated situations. Also, importantly for application in the field, a cooperative approach to real-time shaping of antenna patterns was first developed and evaluated in simulation experiments to allow assessment of the benefits at the network level. Parallel field experiments on a semi-smart antenna were conducted at Alan Dick and Co.

Since there are complex interactions over a physically distributed area, we use a multi-agent system approach [23]-[24] to realise such a system. Conceptually each base station agent and antenna agent has its own processing capability and each may be physically distributed. Optimisation methods are required to compute the best combination of cell size and shapes according to the current traffic distribution. A global optimisation technique, evolutionary computation, was first used to obtain a performance benchmark, and a distributed approach, cooperative negotiation, used to calculate the cell size and shapes in the real time.

A novel hardware implementation approach was developed and validated using measurements, shown as Figure 3-2. Artificial intelligence techniques are used in antenna pattern synthesis to aid the fast synthesis that must be performed in real time. Results of the investigation indicate that such use of artificial intelligence techniques offers significant advantages.
Figure 3-2: (a) linear antenna array prototype and (b) simulated measured pattern for the prototype antenna.

Computer-based Monte-Carlo simulations were performed to evaluate the system using semi-smart antennas with an intelligent control system. The test system is a mobile cellular network with 100 cells where four traffic hot-spots exist, shown as Figure 3-3.

Figure 3-3: A mobile cellular network with four traffic hot-spots (shadowed areas) building up over a period of 200 thirty second intervals.

The test results are presented in Figure 3-4. As hot spots form in a conventional network, the call-blocking rate increases. However, the scheme using intelligent geographic load balancing shows much lower blocking than the conventional one, especially when there are some hot-spots. This demonstrates that by the use of intelligent geographic load balancing, the system capacity can be improved significantly for non-uniformly distributed traffic.

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3 The heterogeneity increases to quite high levels and so the blocking rates can become higher than those acceptable in practice. However it can be seen that the performance is also very good at the lower blocking rates. Simulations starting with lower loads when demand is uniform produced similar results.
Figure 3-4: Simulation results for a geographic load balancing scheme using semi-smart antenna systems. The black line indicates the globally optimal solution and is used as a benchmark (note that the optimal global solution takes many hours to compute and is impractical). The green line shows results from using patterns obtained by fitting splines to the patterns computed by real time negotiation. The blue line shows results obtained using patterns that are generated from the real time negotiation results by a pattern synthesis algorithm that accommodates all the physical constraints. Traffic snapshots are taken every 30 seconds. Initially demand is entirely uniform and the hot spots build up progressively with time (x-axis).

Figure 3-5 shows the patterns generated around one of the hot spots. Notice that the base stations which lend capacity to the hotspot themselves receive added capacity from the surrounding cells – the helpers are themselves being helped.

Figure 3-5: The synthesised patterns generated from the negotiations

The angular shaped patterns are those that are generated by the negotiation. In this example very coarse azimuth granularity is used; recent developments are using finer...
granularity. The flow diagram of the intelligent control system in the QMUL smart antenna system is shown in Figure 3-6.

Under the SHUFFLE and US Navy projects a comprehensive 3G mobile network simulator was developed. Advanced features include uneven traffic distribution, admission control, power control, soft handover and controllable base station antenna patterns. Both uplink and downlink capacities are calculated based on the signal-to-interference and noise ratio (SINR) value of each mobile user and the SINR values are maintained at the threshold value by the power control. Better on-line optimisation methods for the load balancing scheme and better antenna pattern synthesis techniques are also under investigation.

The simulator has been considerably enhanced during this Ofcom project with respect to the management of prioritisation, terrain and multiple perspectives.

Figure 3-6: Flow of diagram of the intelligent control system model

3.2.2 EC – IST ADAMANT Project
The ADAMANT\(^4\) project proposed an agent-controlled sectored antenna for IEEE-802.11. In WLANs that cover large areas (such as those at an airport) the total area is divided into WLAN “cells”, and each cell uses an access point to provide coverage for wireless users. Clusters of users in a cell may experience poor bit rates, owing to that cell being heavily loaded. The challenge in WLANs is to increase network capacity without incurring excessive costs or complications in the process.

The concept of the agent-controlled antenna was extended in ADAMANT and a demonstration system was built. In conventional WLANs, access points use omni-directional antennas to provide coverage. In order to increase network capacity, a 4 x 90° sector semi-smart antenna approach was suggested. The four-sector antenna pattern

\(^{4}\) AirPort DecisiOn And MAinagement NeTwork, Queen Mary lead EU IST project. http://adamant.qmee.org
provides an overall coverage for each cell, with increased capacity. If a cell becomes heavily loaded owing to the number of simultaneously users, then the power drops to reduce the coverage and shed some of the potential users. A lightly loaded adjacent cell rotates its sectors and increases power for one of its sectors to serve the users shed by the heavily-loaded cell and balance the load. Users who would otherwise receive service at low bit rates are automatically transferred to the adjacent cell and are consequently served with a higher bit rate. This is referred to as a ‘handoff’. If the adjacent cell drops users from one of its sectors, a neighbouring cell rotates its sectors and increases power to pick up those users. The result is a well balanced network, offering users uniform bit rates and an overall maximum bit rate for all users (Figure 3-7).

Figure 3-7: Proposed four-sector antennas for WLAN Access Points. a) Four sector ceiling mounted WLAN antennas and its radiation patterns. b) Concept of changing power and rotation to solve WLAN traffic “hot-spot” problem.
3.3 Development of Semi-Smart techniques in this Project

This study has extended the previous work on semi-smart antennas considerably and has demonstrated the advantages and feasibility by taking into account many scenarios in a realistic wireless network environment. The project was carried out at two levels simultaneously.

At the system level, we developed an advanced simulator to support network analysis of the performance of semi-smart antenna systems for load balancing in cellular base stations and specifically an evaluation of semi-smart systems in the context of:

- Heterogeneous demand – users are physically unevenly distributed,
- Differentiated services and
- Non-uniform topography and topology.

In addition a comparison has been conducted with the use of RET antennas with fixed azimuth radiation patterns.

At the level of the physical layer, we have successively developed:

- **The design** of a practical semi-smart antenna
- **Use of downtilt** to control antenna pattern to avoid the use of attenuators
- **Phase Control** and examined different methods of achieving the required phase control
- **Hardware**: Built hardware to demonstrate the concept in reality
- **Software**: Developed beam-forming controlling software for the demonstrator

Each of these developments will now be reported on in detail. The results of these developments have led to conclusions on a route map that will allow the benefits of semi-smart antennas to be realised and these conclusions are presented at the end of this report.
4 SEMI-SMART ANTENNA SYSTEM SIMULATION STUDY

4.1 Background

In this work, simulation software was developed to evaluate the performance of a network of semi-smart antenna systems as proposed in this project. This software was designed to conform to common W-CDMA standards, both for uplink and downlink, including uplink and downlink call admission control (CAC) and power control. A key feature of the simulator is that it does NOT assume that the ratio of the inter-cell interference to intra-cell interference is constant, as this is not valid when demand is heterogeneous.

It should be noted that while the simulator emulates a W-CDMA network, the results obtained are almost certainly not specific to W-CDMA and the specific form of semi-smart antennas modelled, but reflect the potential of the cooperative coverage in general.

Following the development and validation of the simulator, evaluation of the performance of the semi-smart approach progressed in four areas.

Firstly, the effect of cooperative shaping in terms of increased capacity and reduced blocking and dropping rates were assessed for heterogeneous demand. This core analysis used simple path loss models so as not to confound the evaluation with other effects, such as topography, which were analysed independently. Results indicate significant capability to increase capacity and decrease blocking and dropping rates both in uplink and downlink. For example, at 70% loading using exponential arrivals and holding times, scenarios show a substantial improvement which increases with the amount of heterogeneity. For the uplink, figures such as a 50% reduction in the blocking rate (downlink) and 80% reduction (uplink) have been found when averaged over all the cells for 40 hotspots in 100 cells. Simulations where there is, for example, a 5% blocking rate using a conventional network, has a 0% blocking rate using the cooperative approach. Average capacity improvements of around 9% were found. Given that these are averaged over many cells of the network where capacity was easily available (over 50% of the cells were remote from the hotspot and no improvement was possible – in fact they become emptier as time passes) this indicates that where capacity is needed, it is being found. Enhancements to the algorithm to support antenna pattern coverage sectorisation were then added in the base station capability so that the comparisons would match closely what is done in real base stations.

Secondly, extensions have been made to the cooperative algorithms to support differentiation between customers and experiments have been conducted in which users were assigned defined service priorities. Again these have been performed using simple path loss models so as not to confound different issues. Comparisons have been performed for different ratios of traffic classes drawn from the 3GPP specifications and for different ratios of Gold, Silver and Bronze customers. The results have shown that differentiation is achieved between all three classes while still achieving increased capacity and lower blocking rates for all three priority levels. Unlike some techniques for prioritisation found in the literature, the results are achieved without using forecasting techniques or buffering of capacity. The ability to cooperatively change cell shape means that Gold customers can be tracked and the generated shapes reflect the relative priorities of the observed traffic.
Thirdly, the basic algorithm was modified to accommodate real topographical data. Data for Guernsey (Channel Islands) was obtained and a data base of the pilot signal strengths in Guernsey was constructed. Significant enhancements to the base algorithm were made to incorporate queries regarding signal strength in the database and mapping onto a perceived location. Other changes were made to allow for multiple perceptions (seen Para 4-6) from neighbouring base stations. Development of the enhancements to the algorithm and modifications to the simulator to represent real terrain and restricted movement required a significant effort. Results from different scenarios revealed the significant advantages of the semi-smart approach in real terrain. Similar and even greater performance improvements were found for the non-topographic simple path loss model, but improvements were apparent even when the demand was uniformly distributed over an area. The topography effectively clusters uniform traffic in the radio space and because of the shaping the semi-smart system can handle it better.

Research was carried out to quantify the benefits of cooperative shaping in terms of the reduction of the complexity of network planning. It is clear that cooperative shaping considerably simplifies the requirements for network planning, so there is scope for the use of such systems for networks requiring rapid deployment.

Fourthly, the cooperative algorithm was modified to support cooperative down-tilting and experiments performed to assess the relative benefits of using cooperative tilting alone and in conjunction with cell shaping. This used the same core algorithm, but modifications were needed to the way that sectoring is managed. These results clearly show that cooperative tilting has some benefit. Improvements of around 20% of that obtained by full shaping have been obtained but this depends considerably on the scenario. It is noticeable that benefits do not necessarily increase with the number of hotspots and for a large number of hotspots the performance is little or no better than with the conventional approach. This indicates that the degree of control is not enough for high load heterogeneity, but further experiments will be conducted with a richer model for tilting, outside the scope of this study, to see if these conclusions are general.

### 4.2 Algorithms and Implementation

A typical coverage output from the semi-smart system in Figure 4-1 shows that each cell is shaped and that the load is better balanced. In outline, splines are fitted to the ideal shape computed by the cooperative control algorithm and then an antenna pattern synthesis program is applied to best fit the ideal pattern. Performance results are then collected based on the synthesised pattern.
Mathematically the cooperative load balancing problem can be formulated as an optimisation problem of increasing the system capacity while keeping the transmission power at the minimum under a set of constraints. These are:

- The total served demand at any base station should be less than its capacity;
- The total transmission power at any base station should be less than its maximum transmission power;
- At most three base stations can serve one traffic unit (for soft and softer handover);
- The distance from a base station to any served traffic unit should be shorter than the maximum range of the base station.

The problem is similar to the Multidimensional Knapsack Problem (MKP), which is an NP-hard problem and does not yet have a universal algorithm. The dual objective and the complicated constraints make this problem even harder than MKP. Our initial work made use of intelligent agents at each BS to provide the cooperative control via negotiation of optimal antenna pattern overages between adjacent BS. Here a single BS coverage area is segmented into a polar grid which is quantised in both angle and radial distance. The degree of angular quantisation is chosen to reflect the level of azimuthal resolution that the antenna array can offer. While the negotiation approach was effective at finding solutions for very fine quantisation, its speed was not within the bounds that would support real time control. We therefore explored new methods that can utilise the special characteristics of geographical load balancing to obtain better results with shorter computation time. An

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5 In computational complexity theory, NP ("Non-deterministic Polynomial time") is the set of decision problems solvable in polynomial time on a non-deterministic Turing machine. NP-hard is the complexity class of decision problems that are intrinsically harder than those that can be solved by a nondeterministic.
algorithm, based on an analogy with bubbles, which we call the Bubble Oscillation Algorithm (BOA), was developed. A fuller description of the BOA can be found in the paper appended to this report. The algorithm computes the utility of covering areas called Quantisation Cells (QCs). To do this it measures how much it ‘wants’ to cover a QC on its own behalf (R), which is inversely related to the distance from the base station⁶. Locations not covered by the base station or other neighbouring base stations are treated as vacuums, with utility of coverage proportional to the demand at the uncovered QC and inversely to the distance from the vacuum. The total utility of serving a QC is found as a sum of the individual utility R and the sum of the projections of the attractions on to the radial direction. Based on the computed utilities, a new coverage is created for the base station. Knowledge of the new state of coverage is now used by the neighbouring base stations to (re-)compute their coverage patterns. In this way the system progressively iterates to a better pattern of coverage. The algorithm is designed to re-compute shapes in real time. Note that although it is convenient to talk about a base station re-computing its coverage pattern, in practice this is performed by the RNC (Radio Network Controller) using 3G terminology. Even if a QC contains no active mobiles it will create a weak vacuum, as it is important that there are no holes in the network.

Figure 4-2 shows a typical pattern generated to better balance the load in a particular scenario using the BOA. For each base station, splines are fitted to the ideal coverage shape (which is a made up of sectors each with an appropriate radial distance) that is computed by the BOA according to the granularity chosen. Typically the coordinate system has 72.5° sectors and a radial quantisation of 20 levels. Then an antenna pattern synthesis program is applied to create an achievable pattern that approximates to the ideal pattern as closely as possible. Performance results are based on the synthesised pattern.

Figure 4-2: How the BOA works. V5 is an un-served mobile acting as a vacuum

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⁶ Notice: not the squared distance. Other factors such as power control make the linear relationship work better. This is later modified to signal strength.
Assuming perfect power control, all comparisons of call blocking rates, call dropping rates and system capacities show significant but scenario-dependent improvements in all the criteria. These results are not presented here separately, as there is clear evidence of these effects in other results quoted, such as those on differentiation of service provision. Typically, a demand corresponding to 70% of capacity, when spread uniformly over the network, results in no blocked or dropped calls. When the same number of mobiles cluster they can cause blocking of new calls and dropping of existing calls. However with cooperative load balancing these problems were eliminated.

Additionally, dynamic real-time cell sectorisation has been included (Figure 4-3). To achieve this, a real-time search algorithm has been superimposed on the BOA that solves the following sectorisation optimisation problem.

$$\text{Minimise } \sum_{i=1}^{m} \Delta_i, \Delta_i = |I_i - I_{i-1}|, I_0 = L_0$$

subject to:

1. $B_i \in [B_{i,\text{min}}, B_{i,\text{max}}]$  
2. $S_i \in [S_{i,\text{min}}, S_{i,\text{max}}]$, $S_i = |B_i - B_{i-1}|$  
3. $\text{Minimise } \sum_{i=1}^{m} \Gamma_i, \Gamma_i = \left| \frac{B_i + B_{i-1}}{2} - D_i \right|, B_m = B_0$

Here $m$ is the number of sectors for a single cell,

$Li$ represents the total demand of all the traffic in the sector $Ci$,

$Bi$ is the sector upper boundary of the sector $Ci$,

$Si$ is the angular size of the sector $Ci$, and

$Di$ is the central directions of the standard antenna pattern.

$Bi;\text{min}$ and $Bi;\text{max}$ are the lower and upper limits of the sector $Ci$, which indicate the physical limits of the sector that the antenna pattern can ever reach.

$S\text{min}$ and $S\text{max}$ are the minimum and maximum sector sizes, which are also limited by sector antennas.
Si is the angular size of the sector $S_i$. $S_1$ has reached $S_{\text{max}}$ and $S_2$ has reached $S_{\text{min}}$, but neither of $B_1$ or $B_2$ has reached its limit.

As can be seen from the mathematical specification, the aim is to equalise the load in each sector by a blend of dilation, contraction and rotation, all subject to constraints. The sector angle must be larger than a lower bound and smaller than an upper bound; the edges of a sector must lie within a certain range corresponding to the physical orientation of the antenna serving the cell; and the central axis of the sectors should be not far from the geometric central axis when all the sectors are of equal size. The latter constraint performs a secondary objective function in that once the load is equalised the solution which involves minimal rotation is chosen. This pragmatic approach solves the optimisation problem through a fast search that uses a lexicographic optimisation approach and exploits the granularity appropriate for the semi-smart system, as distinct from the slow but more refined solutions reported in the literature.

### 4.3 Features of the Simulator

A static simulator was built to support the evaluation in the context of W-CDMA. Figure 4-4 illustrates the key steps of control in the simulator. A key feature of the simulator is that it does NOT assume that the ratio of the inter-cell to intra-cell interference is a constant. This assumption is often made, but it is certainly not true for heterogeneous traffic.

The simulator uses traffic snapshots. The granularity of the snapshots can be defined at simulation set up. Some experiments have been run at fine granularities and some at coarser. The granularity chosen for the results is a trade-off between speed and management of what is in reality a continual stream of events.

Admission control is performed for both uplink and downlink at each traffic snapshot. The soft and softer handover in the uplink is taken into consideration, while it is ignored in the downlink as the Site Selection Diversity Transmit (SSDT) soft-handover strategy is assumed there. Power control is realised iteratively for each traffic snapshot.
Results using the simulator employing the BOA were obtained based on the following assumptions:

- Each traffic snapshot contains 50,000 users in the whole area, and all the users are uniformly distributed at the first snapshot;
- One or more traffic hot-spots form during the period between the first and last snapshot;
- Each fully-developed hot-spot contains 1000 users, and the other users are always uniformly distributed in the whole area;
- The locations of the users in hot spots follow normal distributions around the hot-spot centre. The mean values representing the location of the central points of each traffic hot-spot, are uniformly distributed with the minimum central distance between any two hot-spots greater than $3r$, where $r$ is the cell radius, and the standard deviation $0.5r$ represents the size of each traffic hot-spot;
- The active and idle times for each user have a negative exponential distribution. The mean values are 120 sec and 720 sec respectively.
• One base station with 6 sectors is installed in the centre of each cell and no dynamic sectorisation was employed.

In Figure 4-5 and similar later figures, the horizontal axis shows the sequence number of the snapshot at which the blocking was computed. It effectively represents time, as the traffic progressively becomes more and lumpy in distribution. On the left (Snapshot 0) traffic is completely uniform, while at the last (usually 100th) snapshot on the right the traffic is completely formed into hotspots.

It will be noted that many of the simulations eventually create high call blocking and dropping rates, beyond those that are tolerable in a real system, even when the semi-smart system is used. It should be remembered however that each simulation experiment is progressive, gradually increasing the heterogeneity with time, until it is in some cases substantial. This depends on the number of hot spots chosen in the experiment. Most simulations use a 70% load factor, and when demand is uniform and the terrain is uniform there is initially a very low blocking and dropping rate. Simulations have been conducted with lower load factors and in all cases the same effects are seen. The high load factor chosen allows us to rapidly explore a wide range of heterogeneity and to put stress on the system.

Figure 4-5 shows the observed system capacity in the uplink and downlink for 10 and 40 hotspots. There is a considerable improvement, this being more pronounced (as would be expected) in the uplink. Notice that the results are for a hundred cells and the efficiency of the approach is masked by the large number of cells where the demand is still uniform.

Figure 4-5: System capacity for the uplink and downlink for system shown in Figure 4-3.
4.4 Increase in Handover Rate

Although coverage is changes gradually as the traffic changes, extra user handovers are still the main side effect of concern when adopting such a scheme (Figure 4-6). With shaping there is bound to be an increase in handovers because a user will pass through a small cell more quickly than through a large cell. To assess this, experiments using traffic travelling at a constant speed were used, as clearly accelerating and decelerating traffic could mask the effect of the shaping. Some results are shown below:

- Some simulations for the handoff rate were performed using the same configurations those used for simulation of capacity and call-blocking rate. The increment of handoff rate is small and nearly fixed.

- The handoff performance in the downlink is better than in the uplink, as soft-handoff is not considered in the downlink

![Figure 4-6: The graphs show the increase in handover rate incurred when shaping coverage rather than using fixed (conventional) coverage pattern. It can be seen that shaping does increase the rate. This is however not necessarily always bad as it has to be remembered that the alternative can often be rejecting the handover request](image)

The fact that the handoff rates remain constant as the heterogeneity increases reflects the fact that the traffic moves at a constant speed throughout the simulations.

The results obtained also testify to the stability of the bubble oscillation algorithm. It appears that it can almost always reach the optimum cell size and shape according to the current traffic distribution, thus reducing the increase in handoff rate.

4.5 Uniformisation Effect

Perhaps one of the more significant results is related to the ‘uniformisation’ effect of the approach. Under a uniform distribution the expected value of the ratio of other-cell to
current-cell interference is 0.5. This is assumed by many network planners and their tools. As can be seen from Figure 4-7 this does not hold when the demand is heterogeneous. However, it remains much closer to the ideal ratio of 0.5 when cooperative shaping is adopted. It seems that the effect of the shaping is to distort the world so that demand in the distorted world is uniform.

Figure 4-7: The PDF of the Ratio $I_{other}/I_{own}$ for conventional and optimised networks with (a) uniform traffic, (b) 1 traffic hot-spot, (c) 10 traffic hot-spots and (d) 40 traffic hot-spots.

### 4.6 Handling propagation effects in a semi-smart antenna system

Apart from difficulties associated with the design of antenna systems and the design of efficient algorithms for cooperative load balancing, a major concern is whether dynamic load balancing is applicable and feasible in a complex propagation environment.

There are two important problems that have to be resolved, namely the multiple-perception problem and the multi-path problem.

**Multiple-Perception Problem:** This is caused by terrain and reflections. While an MS can only be in one physical location the real world, as far as wireless coverage is concerned it can appear to be in different places from different base stations, because the path loss and the relevant reflections seen by each base station are different. Because of terrain, for example, an MS can be perceived to be farther away (or sometimes closer) in terms of...
signal strength than would be expected if there were uniform path losses. Because of this, when there are multiple base stations (BSs), an MS may appear to be in a different location to each BS – see Figure 4-8. The multi-path problem also creates multiple perceptions at different base stations.

The multiple perception problem complicates the work of the cooperation algorithm as it has to recognise that when an MS is satisfactorily served by one BS it is removed from consideration by other close BSs.

**Multiple-Path Problem:** This is caused by reflections. It is worth noting that in the semi-smart approach a small 4-element array is used to generate coverage shapes for each sector. This is a compromise explicitly chosen so as to mitigate (but not eliminate) the multi-path problem while still allowing a good degree of shaping. If the shaping were too fine then the danger is that directing energy only exactly towards the known direction of the mobile station would be inappropriate as the signal is actually being received by a reflection. In the semi-smart approach, if a mobile station is far away then the angular spread of the direct and reflected signals is usually less than about 10 degrees and if the mobile station is close there is lots of energy anyway. In the following simulations the reflection problem has not been explicitly addressed, though future work will address this through reinforcement learning. We feel this is feasible as the capability to change the shape in a controlled manner allows exploration of the interplay between the geographic locations, terrain and the perceived wireless world.

The main problem addressed is the multiple perception problem. Modifications were made to the BOA to resolve the multiple perception problem and so allow a real-time approach to managing terrain data and its resultant problems. The BOA was made to work on the ‘perceived’ distance instead of geographic distance. For each physical location, the mobile station is mapped to the location it would occupy if the chosen simple underlying path loss model were to apply. This location is called the perceived location. In this transformed world, i.e., the world where mobiles are at their perceived locations, the chosen path loss model applies – by definition. The iterations for optimal coverage are performed in this transformed world. At each iteration, mobile stations that are covered by a base station are
removed from consideration by other base stations, hence avoiding reconsideration because of the multiple perceived locations.

4.7 System level simulation on real terrains

4.7.1 Cell’s view – Perceived grids

Figure 4-9 shows the circular polar cell-grid model used for the representation of quantisation cells (QCs). The frontier of this circle is where the pilot signal falls to the minimum acceptable pilot channel level. The green circle is representative of the coverage if a conventional system is used.

With the revised BOA, MSs are mapped to their perceived locations and the cell intelligence works on the virtual spider-web, i.e. it assumes the MSs are at their perceived locations (according to where they would be if a simple path loss model applied). The basic idea in this design is that the closer an MS is perceived to be, the higher the chance it should have to be served. After this decision has been made, based on the computed optimum coverage pattern, sector antennas receive instructions on how much gain is to be achieved in each angular direction and the antenna adjusted accordingly.

4.7.2 Incorporating signal strength into the model

Aircom International Ltd kindly made available their network planning tool (NPT) ASSET 3G and data on pilot signal strengths for the island of Jersey were used to create predictions on propagation effects, based on simple assumptions of proportionality. This data was then made available to the simulator by porting it into a database for use in the BOA. During the iterations to find the best coverage, the model of the world in the simulator queries the database to look up perceived distance of an MS of concern.
Figure 4-10 is an example of propagation prediction output from ASSET 3G that is made available to the simulator. BS nodes can be seen from the signal level contour lines. From the signal strength, a perceived distance can be readily worked out and used in simulation. It should be noted that this does not assume that signal strength decreases monotonically. Points with the same signal strength are at the same perceived location irrespective of their physical location.

4.7.3 Simulation scenario
Jersey was selected as the test case and a digital map was used. For the simulation, BSs are deployed in their real locations (Figure 4-11). The network planning activity itself is not central to this work. The aim here is to establish whether there is a significant difference between an adaptive system and a conventional system in a more complex path loss situation, and the feasibility of creating a real-time load-balancing scheme in such a context. No modification has been made to the prediction data provided, and the accuracy of the data used depends on the NPT's settings. They were set to use the highest precision in most of the propagation models created. The path loss constant decay exponent is set to be -4, but this is only used in creating the perceived distances.

In the experiment 100 snapshots of the network are used. Each snapshot represents the situations after an interval of 60 seconds. (Smaller time intervals have been used in other simulations and the results are similar.) Initially the MSs are more or less uniformly distributed and move randomly. To emulate the forming of unbalanced traffic, some of the mobiles gradually coalesce into hot-spots consistent with the topography of the island. There are totally 10,000 MSs within the network and all the traffic is always moving.
A number of hotspots are in the process of forming during the simulation and each has a population of at least 1,000 subscribers, so all the subscribers are within hotspots at the end of the simulation. The relative location of each MS within a hotspot follows a normal distribution with a standard deviation of half the cell radius.

A negative exponential call model is used for all the MSs. The average call time is 120 seconds and call inter-arrival time is 720 seconds.

The maximum capacity of a cell is 120, approximately calculated according to the capacity in an interference-based approach for W-CDMA network. During simulation it is only a reference and the maximum allowance for a cell is the average load of its neighbouring cells.

Plots of the blocked calls at snapshot 24 (they all show similar effects) for a conventional network and for a cooperative network are shown in Figure 4-11. They clearly show a marked difference, and this difference is apparent from the first snapshot.

The performance is in fact very consistent with the performance found previously for scenarios with simple path loss models and arguably in several cases it is much better. They convincingly show that the semi-smart cooperative approach has the potential to work on non-uniform terrain and that the benefits are NOT only achieved when the mobile stations are physically clustered in hotspots. The terrain has the effect of making uniform data appear to be clustered to the wireless network. The consistent improvement from the outset in call blocking is shown in Figure 4-12.

A simple explanation of this result is that even when traffic is uniform over a terrain, the non uniform path loss effectively clusters the mobiles in the perceived world and so shaping is effective.
Figure 4-11: Dropped calls during snapshot 24 are shown in red. MS connected are green and MS in soft handover in purple. MS not wanting connection are not shown. Top conventional structure, bottom shaping.
4.8 Providing enhanced QoS differentiation using semi-smart antenna

Geographic load balancing has the potential of providing enhanced QoS to realistic 3G service traffic classes and also to provide user prioritisation, even in situations where non-uniform demand occurs over the network. A general scheme to provide QoS differentiation in W-CDMA networks with geographic load balancing was developed to check that prioritisation could be achieved in the presence of different traffic mixes. The major objective of this scheme is to reduce the blocking rate for the high priority users. We have adopted a user priority scheme for the admission control and soft handover functions. It ensures that the high priority user is preferentially admitted to the network. A retry method for Gold users is also introduced as a further example of a measure that can be employed. A Gold user is given another chance to be admitted to the network. Seen from the simulator results, this can further decrease the blocking rate of Gold users. To add the capabilities of service differentiation and user priority to the bubble oscillation algorithm, a modified utility function was created to represent the different traffic and user priorities.

In previous work all calls were notionally voice calls. They were identical in their resource requirements and had equal priority. The 3GPP QoS architecture is designed to provide differentiation and allows user negotiation of bearer service characteristics, such as throughput, error rate, and delay. To give different users (using different services) a differentiated service, a traffic utility is defined for each traffic unit depending on the user grade (classified here simply as Gold, Silver and Bronze) and traffic class (from 32 bps to 384 bps as defined previously). The differentiated QoS utility of a single traffic unit is formulated as:

$$U^T_i = W_e \cdot G_i + W_r \cdot R_i$$  (Equation 4.1a)

$U^T_i$: the traffic utility of traffic unit $I$. 

\[ \text{Figure 4-12: Call blocking at snapshot 1-50} \]
$G_i$: the user grade of the traffic unit,

$W_g$: a constant user weight that is same for all user grades,

$R_i$: the rate grade of the traffic unit $i$; numerically $R_i = \text{maximum bit rate of traffic class}/16\ \text{kbps}$, e.g. $144/16 = 9$,

$W_r$: a constant rate weight, it is the same for all rate grades.

Clearly many business models could be used in place of this simple model. The utility could also depend on the location.

There are two kinds of ‘force’ at work in the bubble oscillation algorithm. The radial repulsion force represents how interested the base station is in having the specific traffic unit assigned to it.

The repulsion force $R_y$ is expressed as (Equation 4.1b) local polar coordinates.

$$R_y = (d_{i,\text{max}} - d_{i,j}, \theta_y) \quad \text{(Equation 4.1b)}$$

Where $d_y$ and $\theta_y$ are the distance and angle from the $i$-th base station to the $j$-th traffic unit, and $d_{i,\text{max}}$ is the distance to the frontier for the $i$-th base station. The attraction forces are generated from the unserved traffic units in order to adjust the initial repulsion force of the traffic units nearby. The attraction force from the $k$-th unserved traffic unit $V_k$ to the $j$-th traffic unit $T_j$ at the $i$-th base station $B_S_i$ during the $\lambda$-th iteration is defined as $A_{ij}^\lambda$ in the local polar coordinates,

$$A_{ij}^\lambda = \begin{cases} (w_0, \theta_y) & k = j \\ (w_0, \theta_0 - \theta_k), k \neq j \end{cases} \quad \text{(Equation 4.1c)}$$

where $\theta_0$ and $\theta_k$ are the angles from the $i$-th base station $B_S_i$ to $V_k$ and $T_j$ respectively, and $W_0$ is a constant for controlling the ratio of the attraction force to the repulsion force. If there is more than one unserved traffic unit within the frontier, the resultant attraction force $A_j$ for the traffic units $T_j$ is calculated by vector sum of the attraction forces from all the unserved traffic units $V_k$, expressed as (Equation 4.1d):

$$A_j = \sum_{k=0}^{U_i} A_{ij} \quad \text{(Equation 4.1d)}$$

Where $U_i$ is the number of unserved traffic units near the $i$-th base station.

The utility value of a single Quantisation Cell $i$ is expressed as the sum of the absolute value of the repulsion force and the projection of the resultant attraction forces on the radial direction:
$U_i = |R_i| + \sum_{j=0}^{N} |A_j| \cdot \cos(\theta_j - \theta_y)$  

(Equation 4.1e)

$|R_i|$ is the absolute value of the repulsion force,

$|A_j|$ is the attraction force at the QC $i$ generated from un-served QC $j$,

$\theta_j$ is the angle of the resultant attraction force,

$\theta_y$ is the angle from the base station to the QC $I$,

$N$ is the number of un-served QCs near base station.

The modified utility value of a single QC is obtained by multiplying two factors, the original utility value of QC (Equation 4.1e) and the traffic utility of traffic units within the frontier (Equation 4.1a), formulated as (Equation 4.1f)

$U_i = |R_i| + \sum_{j=0}^{N} |A_j| \cdot \cos(\theta_j - \theta_y) \cdot (\sum_{m \in M} U_m + 1)$  

(Equation 4.1f)

where $M$ is the set of all the traffic units in QC $i$.

The basic algorithm, without differentiation and for uniform path loss models is given in the appendix.

### 4.8.1 Prioritisation Results

In the following experiments the mixtures of traffic used are:

- **Mix I** all requests are 32 kb/sec
- **Mix II** 32 kb/sec 64 kb/sec 144 kb/sec ratio 1:1:1,
- **Mix III** 32 kb/sec 64 kb/sec 144 kb/sec ratio 6:3:1,
- **Mix IV** 32 kb/sec 64 kb/sec 144 kb/sec 384 kb/sec ratio 1:1:1:1,
- **Mix V** 32 kb/sec 64 kb/sec 144 kb/sec 384 kb/sec proportion 80% 10% 9% 1%.

#### A. The Impact of User Grade

In this experiment 10 hotspots form, and each hot-spot has 2000 users. The traffic mixture V was used. The weights in the utility function were $W_g = 1$ and $W_r = 0.04$. 

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Semi-Smart Antenna Project

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The results of using the bubble oscillation algorithm in a W-CDMA network are compared with the results from a conventional W-CDMA network, where the combined antenna patterns provide near circular cell shapes.

The simulation results of the last traffic snapshot for different user priority distributions are shown in Table 4-1. We can see the system blocking rates for different user distributions with semi-smart antennas follows a similar pattern to that when geographic load balancing is used, but are nearly halved. As the network leans to service the high-priority users, it must block some low-priority users and the total system blocking rate increases. The differentiation provided is clearly shown in Figure 4-13.

<table>
<thead>
<tr>
<th>G:S:B</th>
<th>G-BR</th>
<th>S-BR</th>
<th>B-BR</th>
<th>Sy-Cap</th>
<th>Sy-BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1:3</td>
<td>C</td>
<td>0.10</td>
<td>0.15</td>
<td>0.24</td>
<td>2380</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>0.05</td>
<td>0.07</td>
<td>0.14</td>
<td>2660</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.11</td>
<td>0.15</td>
<td>0.23</td>
<td>2315</td>
</tr>
<tr>
<td>1:2:3</td>
<td>G</td>
<td>0.04</td>
<td>0.06</td>
<td>0.14</td>
<td>2570</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.05</td>
<td>0.10</td>
<td>0.21</td>
<td>2398</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>0.02</td>
<td>0.07</td>
<td>0.10</td>
<td>2632</td>
</tr>
</tbody>
</table>

Table 4-1: Simulation results at the 100th traffic snapshot for different user priority combinations

The following abbreviations are used in the column headings in Table 4-1 and following tables.

- **G**: The ratio of gold user to silver user to bronze user
- **G-BR**: Gold User Block Rate
- **S-BR**: Silver User Block Rate
- **B-BR**: Bronze User Block Rate
- **Sy-Cap**: System Capacity
- **Sy-BR**: System Blocking Rate
- **C**: Conventional Network
- **G**: Network using Geographic Load Balancing

When considering the system blocking rates it should be remembered that these include all the UEs and all cells, even those that are lightly loaded and where not much difference between the conventional and load balancing approaches would be expected.
Figure 4-13: Blocking rates for Gold, Silver and Bronze customers over 100 snapshots as the hotspots evolve.

Figure 4-14 shows the number of blocked users on the 100th snapshot. Note the fixed sectors in (a) and the dynamic sector in (b). The larger dark dots represent blocked calls. In the scenario shown 10 hotspots were gradually created. The one at the top right hand side ended up with almost all Gold customers. The two next to this ended up being predominately Silver and the others predominately Bronze. The G:S:B ratio was 1:2:7 uniformly spread initially.

Figure 4-14: Blocked calls (a) using a conventional structure; (b) using geographic load balancing at the 100th snapshot.
B. The Impact of Load and Traffic Mix

Impacts of load and traffic mix are shown in Table 4-2 below.

<table>
<thead>
<tr>
<th>Traffic type</th>
<th>G-GR</th>
<th>S-GR</th>
<th>B-GR</th>
<th>G</th>
<th>S-GR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix I</td>
<td>C</td>
<td>0.04</td>
<td>0.12</td>
<td>0.18</td>
<td>2755</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>0.02</td>
<td>0.04</td>
<td>0.93</td>
<td>2996</td>
</tr>
<tr>
<td>Mix II</td>
<td>C</td>
<td>0.07</td>
<td>0.12</td>
<td>0.25</td>
<td>865</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>0.03</td>
<td>0.04</td>
<td>0.12</td>
<td>944</td>
</tr>
<tr>
<td>Mix III</td>
<td>C</td>
<td>0.07</td>
<td>0.14</td>
<td>0.19</td>
<td>2137</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>0.02</td>
<td>0.05</td>
<td>0.10</td>
<td>2406</td>
</tr>
<tr>
<td>Mix IV</td>
<td>C</td>
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<td>0.19</td>
<td>0.26</td>
<td>1258</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>0.06</td>
<td>0.12</td>
<td>0.16</td>
<td>1389</td>
</tr>
<tr>
<td>Mix V</td>
<td>C</td>
<td>0.05</td>
<td>0.10</td>
<td>0.21</td>
<td>2398</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>0.03</td>
<td>0.07</td>
<td>0.10</td>
<td>2632</td>
</tr>
</tbody>
</table>

Table 4-2: Simulation results for different traffic mixtures at 100th traffic snapshot

The ratio of each grade of user is 1:2:7.

From Mix I to Mix IV, we can see the blocking rate of Gold users is always lower than Silver users, which are in turn lower than for Bronze users.

C. The Impact of the Number of Hotspots

To test the impact of the hot-spot number with the same total population, the total number of users over all the hot-spots was set to 40,000. Similar scenarios but with 40 hot-spots each with 1000 users and then 10 hot-spots each with 4000 were tested. The simulation results are shown in Figure 4-15 (a), (b) and (c). Notice that the scales on the graphs are different. The tests are based on the traffic mixture V and the ratio of each grade users is 1:2:7.
Considering the case of the 10 hot-spots each with 4,000 users, it is clear that the network has a very high blocking rate, as there are simply far too many users to serve in one hot-spot. However, even in this extreme case, it can be seen that the blocking rate of Gold users is very similar for the two scenarios nearly 3% - 6%, and the blocking rates of low priority users are very different – for Silver users about 15% and for Bronze users about 30%. So, for example in temporary emergency situations, when the hot-spots are heavily occupied, the Gold user still can have a considerably lower blocking rate than other users with the load balancing scheme.
D. The Impact of number of users in hotspots

This system was tested with different numbers of users in the hot-spots – the simulation results for scenarios with 2,000, 3,000, and 4,000 users in each hot-spot are shown in Figure 4-16. The tests are based on traffic mixture V and the ratio of each grade of users is 1:2:7. When the hot-spots are relatively lightly occupied, the high priority users have lower blocking rate than the low priority users, and the difference is very small compared with the geographic load balancing system. When the hot-spots are very heavily occupied, the geographic load balancing system reaches its optimisation limit; the difference of user blocking rates become large, and the higher priority users have much lower blocking rate than the low priority users.

Some comparisons with the different hot-spot population for the same priority user were also performed in the tests. As seen from the results, the difference between user blocking rates increases for lower user grades. In the three user grades, the Gold users achieve the lowest blocking rate and have smallest difference. The high priority users will have a low blocking rate or good service in a densely-occupied part of the network with the scheme. So this scheme performs well even in very high hot-spot population.

Figure 4-16: Blocking rate for different hot-spot number
4.9 Antenna tilting

Adaptive tilting in W-CDMA is challenging because of the complexity of managing the system interference. The duplicate use of the same frequency by adjacent cells makes the capacity model complicated. Traditional techniques of tilt-angle selection are based on empirical studies of performance with different tilt angles on the basis of coverage, throughput and service probability [26]. In [25] an adaptive tilt scheme is suggested. The model aims to find the optimal tilt angle when load factors of two adjacent sectors are just balanced through a tilt-down and tilt-up search process. Capacity enhancement is reported for different hotspot positions. Although there is no direct indication that a tilt angle is optimal when two sectors are balanced, analysis through simulation shows that given a fixed traffic distribution, the service probability curve of a sector (percentage of served subscriber) is an almost cap-shaped when the tilt angle increases from 0. This suggests that a search process could be an effective method to help adaptive tilting when a mathematical solution is not available, as there are unlikely to be multiple extrema. However, the search process needs to be carefully managed, as a minimum load factor difference between neighbouring sectors is not the goal of the search. The method should be capacity driven.

The study here uses a downlink-based search method for adaptive tilting. There are several reasons for the focus on downlink. Firstly, in an urban environment the downlink throughput is statistically lower than that of uplink, due to decreased orthogonal code efficiency caused by multi-path propagation. Secondly, the capacity of a W-CDMA network is restricted by sector antenna transmission power, which means generally the downlink determines the highest possible capacity. So the uplink is arguably not obviously affecting the capacity-driven search. Thirdly, the speed of the search method is vital in practical application for real-time adaptive down-tilt. The chosen method is designed to reach maximum downlink capacity through tilt angle adjustment. The adjustment of tilt angle aims to balance the downlink power-based load factor, and is regulated by a capacity enhancement criterion.

The downlink load factor can be expressed in either total transmission power or as the sum of the connection load:

\[
\eta_{DL} = \frac{P_{\text{trans}}}{P_{\text{max}}}
\]

\[
\eta_{DL} = \sum_{i=1}^{N} v_j \left(\frac{E_b/N_0}{W/R_j}\right)_i \left[1 - \alpha_j \right]^{-1}
\]

where \(N\) is the number of mobiles, 

\(E_b/N_0\) is signal to noise ratio,

\(v_j\) is voice activity factor,

\(W/R_j\) is processing gain and

\(\alpha\) is orthogonality factor.
In the second load factor $ij$ is the other-cell to own-cell interference ratio which eats up the load headroom when it increases. Tilting an antenna down can reduce $ij$; the interference from the neighbour decreases because the EIRP decreases above the maximum of the elevation pattern, so capacity enhancement is possible. An over-tilt will decrease the coverage and lead to the decrease of capacity, as the number of mobiles within range is reduced. The search method is then designed as this: in a hexagonal cellular network, a sector tilts cooperatively with its neighbouring sector, aiming to maximise the service probability in both sectors when traffic distribution is unbalanced. Here only interference from the opposite neighbouring sector is considered, as interference from that direction is most prominent. The two sectors are firstly set at a tilt angle 0º which means the main beams of both are horizontal. The transmission power of the two sectors marks the load of each sector. The service probability of mobiles within the two sectors’ coverage is used as a tilt indicator. If the service probability is not above a set threshold (e.g. 90%), the sector with the bigger power load factor will try tilting down a step (e.g. 0.1 degree), and the transmission power and service probability re-evaluated. The down-tilt process goes on as long as the service probability improves, and a maximum tilt angle should be defined to prevent coverage holes based on site spacing and antenna height. The tilt search process goes to another sector which now has the largest load factor; the process stops when down-tilting either will not improve the load factor, a service probability target has been met, or both sectors have reached the maximum tilt angle available. There is no obvious need of up-tilting during the process, because the angle starts from 0º and down-tilting is likely to improve the service probability before the extreme is found. Elevation side-lobes of antennas can pose a problem when an antenna is down-tilted too far, but since the search process starts from a 0º, the impact can be ignored.

Two simulations are reported for a W-CDMA FDD network, one applying adaptive tilting and another for a network where semi-smart antennas are used. Both results are compared with the performance of a conventional network, where adaptive optimisation is not applied to maximise system capacity and tilt angle is fixed. The major uplink and down link configuration parameters are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site spacing</td>
<td>$d$</td>
</tr>
<tr>
<td>Cell radius</td>
<td>$r$</td>
</tr>
<tr>
<td>Antenna altitude</td>
<td>$h_B$</td>
</tr>
<tr>
<td>Mobile altitude</td>
<td>$h_m$</td>
</tr>
<tr>
<td>WCDMA chip rate</td>
<td>$W$</td>
</tr>
<tr>
<td>Bit rate</td>
<td>$R$</td>
</tr>
<tr>
<td>DL SNR (ITU Pedestrian A)</td>
<td>$E_b/N_0$</td>
</tr>
<tr>
<td>UL SNR (ITU Pedestrian A)</td>
<td>$E_b/N_0$</td>
</tr>
<tr>
<td>Voice Activity</td>
<td>$\nu$</td>
</tr>
<tr>
<td>Max sector transmission power</td>
<td>$P_{MAX-DL}$</td>
</tr>
<tr>
<td>Max UE transmission power</td>
<td>$P_{MAX-UL}$</td>
</tr>
<tr>
<td>Max downlink load</td>
<td>$\eta_{DL}$</td>
</tr>
<tr>
<td>Max uplink load</td>
<td>$\eta_{UL}$</td>
</tr>
<tr>
<td>Pilot threshold</td>
<td>$P_{MON}$</td>
</tr>
<tr>
<td>Soft-handover threshold</td>
<td>$P_{SHO}$</td>
</tr>
</tbody>
</table>

In a simulated scenario as before, User Equipments (UEs) move to form hotspots traffic. 100 snapshots of the network are taken during simulation. Each snapshot represents the positions after an interval of 60 seconds. Initially the UEs are uniformly distributed and
move randomly and the BS is at the centre of the hexagons in the assumed hexagonal
tessellation. To emulate the forming of unbalanced traffic, some of the mobiles gradually
coalesce into hot-spots. More precisely, the network configuration is:

- 100 Node-B within the network each has 6 sector antennas.
- There are totally 50,000 UEs within the network and most of UEs are always moving.
- 10 hotspots form during the simulation and each has a population of 2,000 subscribers so 40% of the subscribers are within hotspots at the end. The relative location of each UE within a hotspot follows a normal distribution with a standard deviation of half the cell radius.
- A negative exponential call model is used for all the UEs with an average call time of 120 seconds and call inter-arrival time of 720 seconds.

Figure 4-17 compares the call blocking rate of three networks:

- the conventional network with a fixed tilt angle of 1.5 degrees;
- the network where traffic is geographically balanced using semi-smart antennas and
- the network where adaptive EDT is applied.

The results show the semi-smart system has the best performance throughout 100 snapshots. Adaptive tilting also gives performance enhancement, but does not perform as well.

The results given in this report try to show the benefit of these adaptive approaches on a time-varying unbalanced traffic distribution and to compare the general performance difference, rather than quantifying the enhancement percentage. The improvement rate strongly depends on the specification of the scenario: parameters such as hotspot locations, traffic distribution, network scale, site configuration, antenna main lobe half-power beamwidth, etc. Relationships between these factors can be found in details in7.
As can be seen, cooperative tilting for this scenario has an approximately 25% reduction in blocking rate at the 100th snapshot, but it is still significantly out-performed by adaptive shaping where the relative improvement is over 60%. Again, it is useful to consider the growth of blocking as the heterogeneity increases. Shaping copes much better than tilting or conventional base stations. At the 50th snapshot there is a 40% improvement with tilting and with shaping it is around 100%.

Figure 4-19 is the last (100th) snapshot of the simulation. This figure illustrates the patterns generated using tilting when there are 6 sectors in each cell. Notice that the patterns form arcs of circles and that the central axes of each sector are not equally spaced. The many contours in the figure are horizontal beam shapes for each sector of the antennas. Some of the areas of coverage near the hotspots can be seen to be much smaller than in areas where the demand is lighter. (The apparent very narrow beams are overlap regions and are not separate antenna beams.)
4.10 Summary

A fully functional UMTS simulator has been developed that has enabled a semi-smart antenna to be evaluated in a number of scenarios. In particular, in the context of:

- Heterogeneous demand,
- Differentiated services and
- Non-uniform topography.

In addition a comparison has been conducted with the use of antennas having only adjustable tilt.

The results have demonstrated that a reduction in call blocking rate of up to 80% could be achieved using semi-smart antennas with adaptive pattern shaping with an overall effective network control. Of particular interest is that whereas with uniform topography, the improvement is seen only when the users are collected in hot spots, with non-uniform topography, the improvement is seen even when users are distributed uniformly. This is thought to be because the network optimisation process overcomes holes in the coverage due to topography in its search for the optimum network configuration.

As the review of current practice suggests that adaptive antenna pattern tilting is currently being installed in UMTS networks, the results have been compared with simple cooperative pattern tilting. The results suggest that, although this would be cheaper to install, the benefits of a full semi-smart system are not realised, with only a 20% reduction in call blocking rate.

The next chapter examines how the semi-smart antenna could be realised in practice to achieve this increase in performance.
5 SEMI-SMART ANTENNA DESIGN ISSUES

The choice of base station antenna design has a significant influence on the performance of the semi-smart antenna. Several potential designs have been considered. The fundamental requirement is the capability of control of the azimuth radiation pattern around the base station. The method employed here is to synthesise the pattern from an antenna array consisting of a number of separate radiating elements whose individual excitations are controlled to achieve the desired coverage.

To demonstrate the practicality of the proposed semi-smart antenna, a simplified prototype base station antenna sector has been designed, constructed, measured and validated. A comparison between phase shifters, the key component in smart antennas has also been undertaken.

5.1 Design considerations

5.1.1 Antenna arrays

In order to achieve controllable beam or variable pattern coverage, it is typical to use an antenna system (array) composed of several identical antennas elements. In any array, the control of the total radiation pattern can be achieved by a suitable choice of the excitations in amplitude and phase of the individual elements and of their spatial distributions. There are other controls that can be used to shape the overall pattern of the antenna, such as the geometrical configuration of the array (linear, circular, etc.), and the relative pattern of the individual elements.

The choice of design was restricted by various criteria, most of which are imposed by the required performance and other requirements by network operators and service providers. Our target design in this project aimed to achieve the following:

- Low complexity and robustness
- Low cost
- Compact size and light weight
- Minimal maintenance skill
- Low profile
- Resistance to wind load, temperature variations, etc.

5.1.2 Linear arrays

Initially, the simple geometry of a linear array was considered where elements are placed along a line consisting of $N$ identical elements spaced equidistantly with distance $d$.
between consecutive elements. Assuming that the reference and the first antenna coincide, the geometry can be represented as shown in Figure 5-1.

The field at a point \( P \), from the array, will be the sum of the contributions from each element of the array,

\[
E = \sum_{n=0}^{N-1} a_n \frac{e^{-jk_n}}{4\pi r_n}
\]

Where \( a_n \) represents the complex excitation (amplitude and phase) of the \( n \text{th} \) element and \( r_n \) represents the distance of the \( n \text{th} \) element from point \( P \), \( k = \frac{2\pi}{\lambda} \) is the wave number. If point \( P \) is in the far-field, then the assumption that \( r_0 = r_1 = r_2 = \ldots = r_n = r \) can be made for amplitude variations, this assumption however does not hold for phase variations, hence we have:

\[
E = \frac{e^{-jkr}}{4\pi r} \sum_{n=0}^{N-1} a_n e^{i\psi_n}
\]

\[
r_n = r - \psi_n
\]

\[
\psi_n = n \cdot d \cdot \cos \theta
\]

The first element of the array has been chosen here as the reference point, i.e. \( r = r_0 \), phase variations \( \psi_n \) due to the geometry of the array shown in Figure 5-1.
It is apparent that the total field of a linear array of equally-spaced identical elements is equal to the product of the field of a single element (here, the field from the isotropic point source is proportional to $e^{-jkr}/4\pi r$), at a selected reference point, and a factor (known as the array factor) given by:

$$AF = \sum_{n=0}^{N-1} a_n e^{j\gamma n}$$

where $\gamma = k \cdot d \cdot \cos \theta$

This is the array factor for a linear array with complex element excitations. The product shown here derives from the pattern multiplication principle for arrays of identical elements. Much more important is the fact that this principle applies to arrays of similar non-isotropic elements, which are used in practice, leading to simplifications in the calculation of the array radiation pattern.

$$E(\text{total}) = [\text{element pattern}] \times [\text{array factor}]$$

The element pattern is a function of the individual elements from which the array is constructed; it depends on their geometry and can be chosen within reasonable bounds by the construction used. The array factor is a function of geometry of the arrangement of the elements within the array and their excitation. The product of the element pattern and the array factor is a complex (vector) function, the magnitude of which is usually referred to as the array pattern. Once chosen, the geometry and mechanical structure of the array usually remain fixed (mechanical steering excluded): it is the element excitations which are used to control the characteristics of the array pattern.

**Uniform Arrays**

Important deductions about the characteristics of arrays can be drawn by considering an array where all the elements are excited with unit amplitude and the same phase $\alpha$. An array of identical elements with identical current magnitude and progressive phase is referred to as a uniform array. The array factor for the uniform array becomes,

$$AF = \sum_{n=0}^{N-1} e^{i\gamma n}$$

where $\gamma = k \cdot d \cdot \cos \theta + \alpha$

Through some simple mathematical manipulation, the array factor of a uniform array can be expressed in an alternative, compact and closed form expression, the properties of which are more recognisable:

$$AF = \frac{\sin \left( \frac{N\gamma}{2} \right)}{N \cdot \sin \left( \frac{\gamma}{2} \right)}$$

The above equation represents the array factor of a uniform array in a normalised form. This is a periodic function, often termed the quasi-sinc function. It passes through a
maximum ±1 each time the denominator and numerator are simultaneously equal to zero, that is to say:

\[ \gamma = k \cdot d \cdot \cos \theta + \alpha = 2\pi p \]

\( p = \text{integer} \)

According to the above equation, two consecutive maxima are separated by an interval \( \Delta \tau \) (where \( \tau = \cos \theta \)) such that,

\[ \frac{d}{\lambda} \Delta \tau = 1 \]
\[ \Delta \tau = \frac{\lambda}{d} \]

This shows an important property of uniformly spaced arrays, namely the existence of several grating lobes periodically located at a distance inversely proportional to the element spacing. These lobes are in general undesirable because they are a source of directional ambiguity. To avoid them or separate them sufficiently, small inter-element spacing should be used, e.g. for \( d = \lambda / 2 \), \( \Delta \tau = 2 \), with the result that the grating lobes lie outside the domain \((-1, +1)\) or the visible region (real space). Appearance of grating lobes in the visible region is illustrated in Figure 5-2.

![Appearance of grating lobes in the visible region, for a five-element uniform array](image)

Figure 5-2: Appearance of grating lobes in the visible region, for a five-element uniform array

**Phase scanning in one dimension** Linear arrays allow for scanning in one dimension. A maximum of the array factor is obtained for direction \( \theta_0 \) such that,

\[ k \cdot d \cdot \cos \theta_0 + \alpha = 0 \]
Thus a pointing direction $\theta_0$ is obtained with a phase gradient, $\alpha = -k \cdot d \cdot \cos \theta_0$

This is achieved by choosing weights $a_n$ to be,

$$a_n = |a_n| e^{-jkd \cos \theta_0}$$

$$AF = \sum_{n=0}^{N-1} |a_n| e^{jkd \cos (\theta - \cos \theta_0)}$$

Figure 5-3: Scanned patterns of a uniformly excited equally spaced ($d=0.4\lambda$), five-element phased array, (a) Broadside array $\theta_0 = 90^\circ$; (b) Scan angle $\theta_0 = 75^\circ$; (c) Scan angle $\theta_0 = 30^\circ$; (d) End-fire array $\theta_0 = 0^\circ$. 
The above expressions imply the use of phase shifters to set the complex weights $a_n$. In a scanning array the phase of each element is changed with time, so the main beam pointing direction changes with time. Figure 5-3 shows the patterns of a linear array with different linear phase shifts. As the beam direction is scanned from broadside ($\theta = 90^\circ$) the main beam broadens. The main beam broadening is almost compensated by the reduced volume contained in the total pattern (formed by rotation about the array axis). For equally spaced arrays with spacing less than a half-wavelength, as the beam approaches end-fire ($\theta = 0^\circ$) it does not broaden as rapidly as the pattern volume decreases. Therefore the directivity remains nearly constant for wide scan angles about broadside but increases near end-fire. In order to avoid grating lobes, the condition for scanned beam is,

$$\frac{d}{\lambda} \leq \frac{1}{1 + |\cos \theta_0|}$$

For an array with all elements located in a plane, the pattern is symmetric about that plane, and the array factor forms a second, mirror image-beam below the plane. Most arrays are required to have only one single main beam, and this is achieved using elements with a ground screen to make the element patterns nearly zero for the region behind the array.

### 5.1.3 Cylindrical Conformal Arrays

In comparison to the limited scan angle of planar arrays, **cylindrically conformal array antennas** offer an efficient means of providing omni-directional coverage with dynamic pattern control. They are also more efficiently packed around a standard antenna mast and have much lower visual profile and wind loading. Consequently, this form of array is a much more practical semi-smart implementation.

The overall radiation pattern of a conformal array is generated by the spatial superposition of all the individual element radiation patterns. Although planar arrays are capable of providing highly directional beams, they are not particularly preferred in semi-smart antenna base stations. Because of the local curvature of the cylindrical array, their antenna weight modules offer sufficient flexibility to provide high-performance $360^\circ$ radiation patterns. Therefore, cylindrically conformal base station antenna arrays may provide better performance than a linear array for the semi-smart antenna system.

The cylindrical array approach results in low cost, low weight and compact design with high-performance radiation and impedance characteristics. However, the utilisation of a conformal antenna array introduces complexities where the excitation weights of elements differ from those of the linear array. To address this, a simplified approach is used in which the existing linear array algorithms are modified to control conformal array geometries.

Figure 5-4 illustrates an analytical approach for simplifying the problem by projecting the cylindrically array onto a plane perpendicular to the beam pointing direction. The resulting array can be considered as an equivalent linear array, with unequally spaced elements with each element pointing in different direction.
It is worth noting that these algorithm modifications have been accounted for in our newly developed program. They have been modelled to test the spatial constraints on the behaviour of the array radiation pattern and to test the feasibility of achieving desired patterns. The modified algorithms are used here to prove the concept of operation, but full conformal array algorithms must be used in later studies to achieve better accuracy.

5.2 Synthesis issues

The aim of the synthesis process is to find a set of excitations which minimise the error between the desired and synthesised pattern, i.e. to find the set of excitations which gives the best approximation to the desired pattern. In this study we are interested in the pattern synthesis of antenna arrays which involve few antenna elements, and highly shaped beams with low angular accuracy and gain. In general, power pattern synthesis methods give a good approximation to the desired pattern. This is due to the larger number of degrees of freedom that are inherently available for beam shaping once the far-field phase constraint is removed.

Several synthesis techniques are available for linear array designs in various applications. However, cylindrical conformal arrays are more complex and adequate synthesis techniques are needed for calculating the field radiated by the cylindrical element.
excitations. Typical linear or planar array analysis is concerned with identical elements in pattern, polarisation and gain. In conformal arrays, the axes of the elements point in different directions, so the antenna element cannot be factored out of the array pattern. The formulations of the array factor must take into account the conformal surface of the array. Due to the time limitations in this project, the usual synthesis techniques for planar arrays are altered to approximate the array.

5.3 Experimental semi-smart base station antenna design

The design is based on a cylindrical array consisting of twelve radiating elements whose individual excitations are controlled in order to achieve the desired radiation pattern. The elements are mounted around a cylindrical metallic surface. The four elements comprise the antenna for one base station sector; three sectors, each comprising four elements are used to provide 360° azimuth coverage (Figure 5-5-a).

In our prototype design, a single power amplifier has been assigned to each sector followed by full-power phase and amplitude controllers that are mounted at the top of the tower. However, in order to achieve better coverage capabilities, a stack of the cylindrical arrays would be used in practice to provide sufficient gain and achieve the required elevation half-power beamwidth and facilitate the adjustment of beam tilt by altering the vertical element phase (Figure 5-5-b).

The implementation of the conformal array is based on the following considerations:

- Cylinder radius = 245 mm
- Desired frequency = 2GHz

Figure 5-5: (a) A 12-element cylindrically-conformal array. (b) The structure of the proposed base station – stacks of cylindrical arrays
5.4 Design of the base station prototype

The design of the base station antenna can be divided into the following areas:

- Modelling and analysis of the antenna element radiation pattern.
- Synthesis and analysis of the array pattern to obtain the element excitations.
- Design of the feed network to obtain the desired excitations.
- Fabrication and testing of an array prototype.

A one-sector prototype consisting of four dipole antenna elements has been fabricated and tested for demonstrating the array operation (Figure 5-6-a). The elements are separated by a half-wavelength and angled at 30° from each another, forming a 120° arc. With such arrangement, the overall base station diameter can be contained within a total radius of 0.5m (Figure 5-6-b).

Figure 5-6: A 120° sector antenna consisting of four elements
The sector feed-network has been designed as a 4-way power splitter. Each of the output signals is connected to an independent variable phase-shifter, dynamically adjusted to satisfy the necessary coverage requirements. With this arrangement, amplitude control is regulated by introducing attenuators along each transmission line.

The excitation weight of each element is computed by synthesising the overall array pattern that is required to be produced by the elements positioned around the cylinder. The contribution of each element to the total radiation is considered individually as the antenna elements do not point in the same azimuth direction. This means that a common element factor is considered individually for elements around the cylindrical array. An adequate synthesis technique is needed for calculating the fields radiated by the cylindrical distribution of element excitations.

In our analysis, the scenario is simplified to an equivalent linear array of unequally spaced elements with each element pattern pointing to various directions. This is achieved by projecting the contribution of each element on a plane perpendicular to the beam pointing direction. This approach has been applied here for simplicity but can be significantly improved by formulating the conformal array directly.

In order to obtain in-phase addition of the signals for the columns of elements, a feed network with appropriate phasing has been designed using phase shifters driven by computer-controlled stepper-motors.

Figure 5-7 shows the components used in building the prototype system which comprises four elements – one element of each column of a full system. The phase shifters used here are based on mechanical movement of a conducting arm around an arc to alter transmission line lengths, a design developed by Jaybeam Ltd [27]. The amplitude control was implemented using four attenuators. The amplitudes and phases of each element are computed by a software code which was developed for this purpose.

Testing is performed by inputting a desired pattern into the developed software. The program performs numerical synthesis and the best element excitation weight is determined in terms of amplitude and phase. The program then automatically adjusts the phase shifters using the attached stepper motors and prompts the user to adjust the amplitude for each element (which is manually operated in the prototype). The process of altering the amplitude can become much simpler: If a stack of the cylindrical arrays is used it is possible to alter the vertical phases to control the amplitude of the signal radiated at any azimuth angle by the means of elevation pattern tilting.
Many factors influence the design and architecture of a cylindrical array antenna. In order to minimise complexity, it is important to minimise the number of controls necessary to satisfy the radiation coverage requirements.

5.5 Design verification

The initial step in the study has involved simulating the antenna element using an electromagnetic simulation code (CST Microwave Studio®)[28]. The modelled single element antenna setup was identical to that of the physical model which was measured independently (Figure 5-8). Figure 5-9 suggests a good agreement between the measured and simulated radiation patterns and the return loss of a single element.

The dipole antennas used in this project, are simple, compact and capable of satisfying the radiation and impedance requirements across a wide frequency band. They can be arranged around the surface of a metallic cylinder (See Figure 5-5-b).
Figure 5-8: (a) A single antenna element consisting of a cross-dipole printed on a substrate and located within a metallic cavity; and (b) the printed dipole configuration.

Figure 5-9: A comparison between the simulated and measured radiation patterns and the return loss of a single element.

Further electromagnetic modelling was conducted to test the performance of the 4-element conformal array sector. Figure 5-10 shows the computed radiation patterns which result from commutating the input power among each of the array elements. It can be seen that switching the radiation source from one element to another results in a main beam pointing at directions corresponding to the element azimuth angle (which is 30° in this particular case). Therefore, we can conclude that a full cylindrical array can generate a 360° azimuth scan by switching the input power around the elements pointing in each direction.

Figure 5-11 illustrates the radiation pattern produced when exciting an identical signal source at all of four elements of one sector simultaneously. In this scenario, the resulting main beam points in a direction perpendicular to the centre of the array. It is worth highlighting the fact that arranging the (square) elements around the cylindrical array has resulted in separating the element cavity edges by triangular gaps. These gaps can act as
secondary sources which interfere with the overall radiation pattern. To avoid this possibility the gaps have been filled with a conducting material to minimise this effect.

Figure 5-10: Computation of the conformal array sector; (a) illustrates the 4-element sector, and (b, c, d & e) illustrate the radiation pattern generated when switching the entire power into ports 1, 2, 3 or 4 respectively.
Figure 5-11: Computation of the conformal array sector; (a) a three-dimensional representation of the radiation pattern resulting from exciting all of the four-elements with identical signals, simultaneously, (b) illustrates the radiation pattern in the theta-plane.

The performance of the prototype sector antenna has been further investigated by applying different excitation weights at each element. Figure 5-12 shows the radiation patterns produced when exciting the array elements with the following weights:

Element 1:  
Amplitude = 1.06  
Phase = 32.8°

Element 2:  
Amplitude = 1.06  
Phase = 39.6°

Element 3:  
Amplitude = 0.97  
Phase = 0.0°

Element 4:  
Amplitude = 1.01  
Phase = 56.1°
Figure 5-12: Computation of the conformal array sector; (a) a three-dimensional representation of the radiation pattern resulting from using different excitation weights at each of the four-elements, (b) illustrates the radiation pattern in the theta-plane.

The above suggests that this design provides a good means for producing various arbitrary radiation patterns if the appropriate excitation amplitude and phase weights are computed for each of the antenna elements.

In our proposed full-sized design comprising four columns of elements in each 120º sector, we have incorporated phase shifters to control the phase of the signal reaching each element but have controlled the amplitude of the appropriate azimuth element by the means of down tilting the vertical column of elements.

5.6 Experimental verification of the antenna prototype

Experimental verification of the prototype antenna array has been carried out by performing measurements of the azimuth radiation pattern and comparing the results with electromagnetic simulations.

Several excitation scenarios have been considered, where the excitation amplitudes of each antenna was kept constant and their relative phases were altered.

Initially, all of four elements of one sector were fed with identical amplitudes and phases and the azimuth radiation patterns were compared with predictions (See Figure 5-13).

Element 1: Amplitude = 1.0
Phase = 0°

Element 2: Amplitude = 1.0
Phase = 0°
Figure 5-13: A comparison between the measured and computed radiation pattern of the prototype antenna array. In this configuration, the centre of the antenna array points in the 0 degree direction; the excitation amplitudes and phases for all elements were equal.

Figure 5-14 illustrates the radiation patterns of the antenna array when feeding all elements with similar amplitudes and phases shifted by 8 degrees respectively.

Element 1: Amplitude = 1.0
Phase = 0°

Element 2: Amplitude = 1.0
Phase = 8°

Element 3: Amplitude = 1.0
Phase = 16°
Figure 5-14: A comparison between the measured and computed radiation pattern of the prototype antenna array. In this configuration, the centre of the antenna array pointing in the 0 degree direction; the excitation amplitudes for all elements were equal, and the phases were 0, 8, 16 and 24 degrees for the elements 1, 2, 3 and 4 respectively.

Figure 5-15 illustrates the radiation pattern produced when feeding the array elements with identical amplitudes and shifted phases by 34, 29, 0, and 22 degrees respectively.

Element 1: Amplitude = 1.0
Phase = 34°

Element 2: Amplitude = 1.0
Phase = 29°

Element 3: Amplitude = 1.0
Phase = 0°

Element 4: Amplitude = 1.0
Phase = 22°
Figure 5-15: A comparison between the measured and computed radiation pattern of the prototype antenna array. In this configuration, the centre of the antenna array pointing in the 0 degree direction; the excitation amplitudes for all elements were equal, and the phases were 34, 29, 0 and 22 degrees for the elements 1, 2, 3 and 4 respectively.

It is worth noting that the front to back ratio is much less than theory suggests. This is due to the one-third construction of the prototype system which allows the elements at each edge of the sector to radiate freely into the space behind the array. This degradation in performance would be improved significantly when the overall 360° system is designed and built.

5.7 Down-tilt as means of amplitude control

In a practical implementation of the system described, a sector would comprise 4 columns of between 8 and 14 elements. The elevation pattern of such an array would have the same beamwidth as that of a conventional base station antenna and would provide enhanced gain and control of radial coverage in the conventional manner.

Controlling the down-tilt is one of the most frequently used techniques for producing small cells and achieving good frequency reuse. Electrical down-tilting is achieved by phasing the feeds to the elements that make up the vertical array.
Varying the down-tilt can be viewed as varying the amplitude on bore-sight as illustrated in Figure 5-16.

Figure 5-16 provides good evidence of the fact that good range of amplitude control is achievable. To avoid the power loss of attenuators or the complexity of using multiple PAs to feed each column, down-tilt can be used to provide the amplitude control.

The difference between down-tilting the columns of the proposed cylindrical array and down-tilting a single RET antenna serving each sector is that with the cylindrical array each sector is served by four array columns which can be independently downtilted to create the required azimuth pattern shape. The patterns can be adjusted independently for each sector. With a conventional RET solution the azimuth pattern of each sector remains constant as the sector is down-tilted.

This concept has been verified by simulating a base station antenna array in CST Microwave Studio® and examining the patterns produced with different column downtilts. The possibility of using downtilt control to adjust effective amplitude is dependent on the techniques used in base station antennas to affect variable downtilt and is known to be valid for some available antennas. Further investigation will be needed to establish the wider applicability of this technique.

Figure 5-17 illustrates a numerical model of a linear array which replicates a base station array consisting of four radiating elements. The radiation pattern produced corresponds to the modelled scenario where all elements are excited by currents of identical amplitude and phase.
Figure 5-17: The concept of down-tilting; (a) a linear array consisting of four elements, (b) a three-dimensional representation of the radiation pattern resulting from using identical excitation weights at each of the four-elements, (c) illustrates the radiation pattern in the theta-plane.

In order to verify the characteristics of the produced down-tilt, the phase of consecutive elements have been varied to achieve different elevation tilt angles. Figure 5-18 illustrates the changes of elevation angle as a function of the phase variation along the linear array.

Figure 5-18: The variation of radiation elevation angle as a result of altering the phase shift along a linear array. Each figure corresponds to the resulting radiation pattern when using a phase shift $\phi$ of (a) 10°, (b) 20° and (c) 30°.

The results have shown linear variation of the field intensity when changing the phase difference along the vertical linear array (Figure 5-19).
Figure 5-19: The recorded variation of field power density when altering the phase difference among the vertical array of elements (down-tilting). The observation point is located in the far-field region.

Further to the above, three vertical arrays have been stacked alongside each another to form a two-dimensional planar array (Figure 5-20). The new configuration can be considered to consist of three horizontal elements, each consisting of a vertical array. The new configuration allows full control of the complex excitation weights using phase shifters only. Here, as proposed, the ‘amplitude’ of element currents is controlled by altering the phase shifts along the elements in the vertical plane (down-tilting), and the phase is achieved by varying the signal phase arriving to each vertical array.

Figure 5-20: Illustration of the radiation pattern produced when introducing identical element excitations to all elements (a) three-dimensional view of, (b) gain plot (theta plane).

Figure 5-20 illustrates the resulting radiation pattern with identical excitation of all elements.
Figure 5-21 illustrates a comparison which has been conducted between azimuth radiation patterns produced using direct amplitude control or down-tilting (by controlling the phase shift in the vertical element arrays). Good agreement has been observed in both cases, so subject to some simple assumptions about the way in which down-tilt is achieved and which is valid for at least some commercially available antennas, it can be confidently considered as means of controlling the amplitudes of the horizontal elements.

![Figure 5-21](image)

Figure 5-21: A comparison between the radiation pattern produced when using either direct control of the amplitudes and their equivalent down-tilted counterparts. In all cases, all array elements are excited with amplitude of 1.0 and phase of 0°, except in (a) elements in the third vertical array are assigned with ‘amplitude’ of 0.5, and (b) central vertical array is assigned with ‘amplitude’ of 0.7.

### 5.8 Non-mechanical phase shifting

In the previous sections, a novel design of a low-loss antenna array has been developed, based on using phase shifters for controlling the horizontal phase shift and vertical down-tilt. The design of the phase shifters creates some problems. By far the most suitable linear phase shifting solution which avoids intermodulation products and is capable of handling full transmission power is a device based on mechanical movement. However to offer a more reliable and less bulky solution, alternative linear non-mechanical phase shifters are desirable.

The phase shifters used in the prototype are based on mechanical actuators causing changes in physical transmission line lengths. These are very reliable, with an expected lifetime of 1-2 million operations. The semi-smart concept only requires the network to adapt to changes in user density and these will occur only slowly. Assuming a change in network parameters every five minutes, the expected lifetime of the mechanical phase shifters is more than adequate for this application.

Despite this, a brief study has been conducted to find a full-power non-mechanical phase shifting solution. In this aspect, optically-controlled phase shifting methods and ferroelectric techniques have been investigated.
Figure 5-22 illustrates a novel design which has been proposed in this study and has been tested in electromagnetic simulations. The design consists of a microstrip transmission line whose ground plane is made of a thin metallic sheet. The thin metallic sheet consists of split ring resonators (SRRs) which have been designed to operate at 2GHz. A thin layer of a ferroelectric material is then sandwiched between the thin SRR sheet and a metallic ground plane (Figure 5-22).

The design enables altering the phase shift of the signal transmitted along the microstrip line by applying a potential difference across the thin SRR sheet and the ground plane. This effectively alters the dielectric properties of the ferroelectric material. Figure 5-23 shows the modelled transmission line characteristics (reflection coefficient and phase shift) and the result of altering the ferroelectric material properties by applying a voltage of 400kV/cm across the material. The result suggests that at 2GHz, a phase shift of 30° is achievable when the relative permittivity ($\varepsilon_r$) of the ferroelectric material alters between 200 and 300.

Figure 5-22: A design of a ferroelectric material phase shifter. The phase of the signal travelling along the microstrip transmission line can be altered by applying a potential difference between the SRR sheet (1) and the ground plane (2).
5.9 Summary

The design of a semi-smart antenna for cellular base station applications needs to satisfy several essential requirements. An extensive review has been given of the principles, advantages and disadvantages of linear and cylindrical conformal arrays. The outcome of this review suggests the utilisation of conformal arrays as they can provide better performance in the application we have considered.

A novel cylindrical antenna array with an appropriate feed network has been designed and tested. The new design is simple, robust, light and small in size (low profile). Most importantly, it provides dynamic radiation pattern coverage in the azimuth plane. This approach offers substantial improvements in cellular system capacity.

The design of the base station antenna has been verified and optimised by measurements and by using electromagnetic modelling and analysis.

Pattern synthesis and hardware control codes have been developed to operate with the semi-smart antenna prototype. They have been demonstrated to provide a significant degree of real-time radiation pattern control.

Figure 5-23: The phase shift produced when applying 400kV/cm across the ferroelectric material phase. (a) The reflection coefficient is maintained well below 20dB, and (b) a useful change in phase shift is achieved at 2GHz.
The study has been further extended to verify the concept of down-tilting as means of amplitude control. In this part of the study, extensive electromagnetic modelling has been carried out on linear arrays. The outcome of this study has proved the validity of this concept, and it can be recommended for a full system implementation.

Finally, a brief review has been given on non-mechanical phase shifting solutions and the potential technologies which might be used in future to replace the current mechanical methods. However, it appears the current commercially available mechanical phase shifters should have adequate reliability and response time to allow semi-smart systems to be deployed. More research is needed in this area, to consider a wider range of concepts that could offer a linear phase shift solution, perhaps in conjunction with distributed amplifiers for each azimuth array column.

6 COMPARISON OF DIFFERENT SMART ANTENNA TECHNOLOGIES AND THE WAY AHEAD

In Chapter 2, the current status of smart antennas was reviewed and it was concluded that there has been very limited implementation of the technology despite its potential benefits in spectral efficiency. In this chapter we compare various forms of smart antenna technology available to the wireless communication network designer. We seek to obtain a clear view of the advantages offered by them by examining the claims in the literature and by responses obtained from interviewing key players in the industry. We also suggest a possible way for wireless networks to advance and discuss briefly how the semi-smart antenna technology can bring the desired gain in spectrum efficiency.

Finally, we examine some regulatory hurdles that Ofcom may wish to consider when licensing future spectrum and allow rapid deployment of the technology in the UK with its associated spectrum advantages.

6.1 Comparing different approaches to smart antennas

6.1.1 Comparing the technical performance of smart antenna designs

An objective of the work in this project has been to provide clear statements about the increase in capacity and spectrum utilisation that can be provided by the adoption of smart antenna techniques. However, in attempting to assess the benefits of different algorithms and physical systems and to compare the work of different authors, it is apparent that the wide range of claims made by them are based on comparisons between different parameters of antennas operating in scenarios which cannot be easily related to one another. There are unfortunately no accepted standards of comparison and no standard system models that provide any common context for the making of clear and direct comparisons. This dilutes the value of results and makes it difficult to see the value of potentially useful advances. The variables which make comparison difficult include:
- Work in systems using different signal formats – GSM (TDMA-FDD), W-CDMA (FDD), TD-SCDMA (TDD). Wireless LAN and other TDD systems;

- Studies using signals with different modulation schemes (G-MSK, CDMA, OFDM and high-order QAM systems;

- The adoption of a wide range of signal scenarios, numbers of multipath components, their angular and delay spread, the number and disposition of interferers;

- Studies comparing capacity, but with insufficient clarity about what is being measured;

- Studies making no consideration of the effect of deploying smart antennas at adjoining base stations;

- Studies comparing C/I ratios, but making different starting assumptions and in the case of CDMA making different assumptions about own-cell and adjacent-cell interferers;

- Studies assuming perfect power control and those with either no power control or no description of the assumptions made by the author;

- Comparison of smart antennas with a variety of conventional antennas which do not reflect current real practice, and with no clear factors by which the different comparisons can be related. Examples include comparisons with single omnidirectional base station antennas and with sector antennas of undefined azimuth beamwidth;

- Studies making no reference to the sensitivity of the conclusions to the angular, delay and Doppler spreads of the signals, or to the effects of noise or interference.

Many studies only describe a few of the parameters of the scenario that is modelled, leaving the reader to assume the state of others. A study such as the present one, in which a wide variety of real parameters have been included, and which may represent the real environment quite closely, cannot be properly compared with other models in simple idealised scenarios.

The effectiveness of a smart antenna depends critically on the assumed signal format, modulation scheme, physical environment (which gives rise to the spreads in angle, time and frequency) and the noise and interference present. When these variables are taken in conjunction with the wide range of control algorithms and arrangements of physical hardware (as well as the many conventional or hypothetical systems with which they are compared) the result is that out of many hundred papers consulted there are very few which come to conclusions that can be assembled into any coherent picture.
6.1.2 Common scenarios for comparative studies and experiments

A set of clearly defined standard core scenarios would benefit researchers by making it much easier to see which proposed systems can provide the most useful benefits. There is little to be gained from a system which provides real benefit in only a small range of signal conditions and performs badly in most practical conditions. Agreement on a relatively small number of cases which would form the core of any simulations or experiments could make the results much easier to compare. This would allow potential users – the mobile networks and infrastructure equipment manufacturers – to understand reported results more easily and to relate results to real network operations. This is very important, as no new solutions will be adopted if future users cannot understand their potential benefits. At the same time researchers must focus on the real-world problem and must understand the basic economic fact that no one is interested in adopting an expensive solution which delivers only marginal benefits.

The nature of the core scenarios needs careful consideration. Too complex a scenario makes meaningful work too difficult, while as an over-simplification makes it easy to produce results but renders them of doubtful value. A small range of scenarios, perhaps of increasing complexity, could allow a scoring system to be created that could help rank various potential solutions. This would allow comparisons between solutions and create some benchmarks by which progress can be measured.

In this context it is regrettable that the work on smart antennas in 3GPP was discontinued some years ago without even agreeing some framework within which future results could be evaluated on a common basis.

It is suggested that technical comparison between the wide ranges of available techniques could be facilitated by the adoption of some standard method of comparison. Table 6-1 compares four antenna technologies, i.e. dumb antenna, antennas with RET only, semi-smart antenna and conventional smart antenna.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Dumb</th>
<th>RET only</th>
<th>Semi-smart</th>
<th>Conventional smart</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>18dBi</td>
<td>18dBi</td>
<td>18dBi</td>
<td>21dBi</td>
</tr>
<tr>
<td>Polarisation</td>
<td>Dual</td>
<td>Dual</td>
<td>Dual</td>
<td>Single</td>
</tr>
<tr>
<td>Speed of response</td>
<td>Months</td>
<td>Minutes</td>
<td>Minutes</td>
<td>Milliseconds</td>
</tr>
<tr>
<td>Protocol dependence</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Very dependent</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sub-optimal for</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FDD downlink</td>
</tr>
<tr>
<td>Azimuth pattern flexibility</td>
<td>None</td>
<td>None</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Origin of control information</td>
<td>n/a</td>
<td>n/a</td>
<td>RNC</td>
<td>BTS/Node-B</td>
</tr>
<tr>
<td>Physical size</td>
<td>Baseline</td>
<td>1</td>
<td>4 – 8</td>
<td>4 – 8</td>
</tr>
<tr>
<td>Hardware</td>
<td>Familiar</td>
<td>Becoming</td>
<td>Similar to RET</td>
<td>New skills needed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>familiar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>High unless protocol is chosen to suit</td>
</tr>
</tbody>
</table>
6.2 Advantages of the semi-smart antenna

All smart antennas are intrinsically devices which operate in a closed-loop mode of control: the parameters of the antenna are changed in order to maximise some external measure of performance. The control signal can be derived from various layers in the protocol stack – signal levels, BER, FER and other parameters. The problem with many of these forms of feedback is that they require the antenna system to be closely integrated with the design and software architecture of the associated base station. The cost of integrated implementations is high and unless very large numbers will be sold there is little incentive to develop them. Systems that are seen only to provide a last-resort solution for problem coverage areas will remain expensive and cannot contribute to overall network improvements.

The semi-smart antenna solution investigated during the present project sets out with comparatively limited objectives, but its control input is at a very high level – it reacts to current patterns of network traffic demand. This is the same level as that required for the control of the RET antennas currently being installed. This high level of control and absence of any requirement for communication with the Node-B / BTS means that the system has many significant advantages compared with more ambitious ‘smart’ systems. Its comparative extreme simplicity and low requirement for to the adaptation of existing cellular networks has led to the use of the term ‘semi-smart’. While its use has been shown to increase available network capacity within the existing spectral resources and the established number of base stations, it has many important advantages over more complex techniques:

- Complete indifference to the air interface protocol in use
- No requirement for any feedback from the base station – control is from the radio resource management system.
- No system overhead in the radio access network
- Full multi-channel duplex operation with no degradation of PIM performance
- Symmetrical uplink and downlink improvement
- Maintains polarisation diversity on receive
- Maintains the current number of transmit antenna ports
- Compatible with 3GPP transmit diversity
- Can be controlled using the existing industry-standard AISG interface
- Advantage is obtained even when only some base stations are equipped with the solution
- Neighbour lists are not significantly affected by the application of the technique
• No new untried hardware designs are needed – the required phase shifters are already applied in RET antennas

• No additional feeders are needed to the antennas; each of the proposed arrays is fed by a single cable with a single TMA – large cables are not needed between columns.

• The complexity of the antenna system is not dependent on the number of connected transceivers or the number of users to be serviced.

6.3 Future wireless networks

Many discussions of possible future technologies for wireless networks assume the adoption of multiple antenna techniques, both at the UE and the base station. The advantages of such a system are indisputable. They include:

• Increased capacity and spectral efficiency through the use of SDMA and/or STBC / MIMO techniques;

• Increased reliability of communication in poor channel conditions through the use of multiple-branch diversity;

• Reduced power requirements – because the same effective radiated power requires less RF input power when multiple antennas are used. This advantage is multiplied by a large factor, because multi-channel power amplifiers are notoriously inefficient, so the required mains power and power used for air conditioning are all reduced by a large factor compared with the reduction in RF power allowed by the improved system.

One problem with MIMO technology is getting sufficient decoupling between the antennas at the UE so each antenna provides uncorrelated signal samples. At present the technique is better suited to larger devices (laptops) than for small hand-held devices (mobiles). (This limitation can be overcome by cooperative transmission between base stations or the use of remote RF heads.)

6.3.1 Existing mobile radio network practice

As has been indicated in previous chapters there are many significant – and perhaps insuperable – problems in adopting these powerful multiple antenna techniques into the existing structure of mobile radio networks. At the frequencies in use for mobile radio systems, multiple antennas are physically large, and a single antenna configuration cannot easily support multiple transmitters and receivers. The question which will now be addressed is whether the existing organisational structure of mobile radio networks could be changed in such a way as to allow the advantages of these potentially beneficial techniques to be achieved more rapidly.

One characteristic of current practice is that each mobile network operator currently rolls out a complete network of base stations. At some locations these occupy common supporting structures (masts, towers or building roofs) while in other locations each
network builds a separate structure. The antenna installations are almost always independent, with each group of physical antenna arrays serving one operator. At many locations each of the network operators installs radio equipment and antennas operating on several different frequency bands. Four UK network operators have spectrum in three different frequency bands (GSM900, GSM1800 and 3G-2100); they provide GSM service and a 3G service and in some high-traffic locations they use all three bands at the same base station. The antennas for each frequency band are sometimes physically combined in a single physical device, but they are often separate – an arrangement which allows more operational flexibility in allowing the physical networks at each band to be optimised and upgraded independently. The complete ensemble of current networks is characterised by base stations grouped together with large and complex antenna installations, but each physical network having comparatively simple antennas with basic functionality that does not embody ‘smart’ techniques.

6.3.2 Broadcasting practice

It is interesting to contrast the situation described in the mobile radio industry with that applying to radio stations in the broadcast service where it is entirely normal that single physical antenna is shared by different broadcast operators. This approach reduces the amount of visible antenna hardware needed to support a given number of service providers and reduces the often very large cost of antenna hardware (including antenna feeder cables). The broadcast model in the UK is based on the total number of stations being divided between the two physical providers (Arqiva and National Grid Wireless, formerly NTL and BBC, but now operating as independent commercial companies). At each transmitting station one company is the landlord and owns the land and the antenna structure; transmitters are specified to meet individual needs and are purchased separately by each company. The transmission equipment is housed in areas equipped and maintained separately by the two organisations. Filter networks housed in a common area combine the transmissions of both organisations into common antenna feed cables and antennas. Coverage and interference planning is carried out jointly with the result that the same antenna performance provides for the requirements of both operators. This approach was mandated for the UHF TV network in the 1960s; it is adopted at many VHF radio stations and has become common practice even for radio stations operating in the MF band. The use of a similar model for television and sound radio is interesting; the transmission companies are responsible for broadly similar TV broadcast capacities, while for historical reasons radio services are much less equally divided – Crown Castle inherited the high-power national transmission network facilities of BBC radio, while only smaller local services were previously provided by NTL.

Broadcast content providers (including BBC, ITV, Channel 4, Virgin Radio, Classic FM and a host of smaller companies) can obtain competitive quotations for the supply of transmission services by two commercially independent companies using common antenna infrastructure. For the television service there is no competition on the basis of coverage; requirements for coverage are contained in the public service remit of the transmitting companies. The transmission network is highly reliable; this factor owes much to the public service ethos of earlier times, but the loss of advertising revenue in the event of loss of service creates a financial incentive to maintain a high-grade infrastructure.
6.3.3 A possible model for future mobile services

It is interesting to examine the potential result of adopting a model more like that of the broadcasters to the provision of mobile radio services. We will envisage a possible future shared network scenario, examine various implications and see how these might be addressed.

A large majority of proposed future radio systems using multiple antenna techniques assume the use of multi-carrier bearers for each transmission. In such a system, a data stream with a high data rate is transmitted on a large number of separate radio carriers closely spaced in frequency each with a narrow bandwidth and carrying only a small fraction of the total data – typical examples are orthogonal frequency-division multiplex (OFDM) and multi-carrier code-division multiple access (MC-CDMA). OFDM is currently used or proposed for most wireless LAN schemes and for wider area schemes such as WiMax, as well as for several broadcast service applications including Digital Audio Broadcast (DAB) and Digital Radio Mondiale (DRM). Multi-carrier signal formats are robust in channels with frequency-selective fading, and also have the characteristic that multiple signals can be multiplexed onto a common output without any effective increase in the peak-to-mean power ratio. This is a very important property if we are to combine a potentially large number of transmissions into a single antenna – especially if it contains power amplifiers. It derives from the fact that although the effective peak-to-mean power ratio of a single transmission is relatively large, further carrier clusters add together in amplitude only very occasionally, and the composite signal can be limited in amplitude with only a very small resultant decrease in the data rate supported by each channel.

As we have seen above, smart antenna techniques are easier to apply and are more effective in a system using time-division duplex (TDD), in which the channel with a particular frequency is alternately used for transmitting and receiving (in mobile radio terms for the up-and down-link). TDD systems are also easily adapted to systems where the amount of data to be transmitted in the up-and down-links are unequal – typical of activities like Web browsing.

With a suitable multiple antenna system we can now apply a variety of techniques including space division multiple access (SDMA), space-time block coding (STBC), and a variety of methods aimed at optimising the signal-to-noise and signal-to-interference ratio, and using MIMO to enhance the data rate in the available RF bandwidth (if UEs also have more than one antenna). In the upper frequency bands (1800/2100MHz) such a base station antenna might comprise 16 columns of elements forming a cylindrical antenna cluster typically 1.3 – 1.8m high and around 0.5m in diameter. Larger arrays, perhaps up to 1m in diameter might be appropriate at locations with a high density of users, because the spatial resolution of the array will increase with its diameter. In rural areas there would be a choice between installing large numbers of small antennas, or a smaller number of base stations with large antennas. The real advantage comes from the fact that the same antenna cluster serves all users and content providers.

It is likely that all antennas would provide polarisation diversity, which would be available both on the uplink and downlink. Providing beamforming with multiple antennas reduces not only the required transmitter power at each antenna, but greatly reduces the total power required, both by the radio equipment and the air-conditioning equipment currently needed to cool it.
It was noted earlier that current practice is to share a single antenna between the up-and-
downlinks, and that it is difficult to share multi-carrier power amplifiers because of the
appearance of intermodulation products (created by the outgoing transmitter carriers) in
the receiver frequency band. Not only does OFDM have the characteristic that the peak-to-
mean ratio can be constrained to that of a single signal, but the digital processing of the
received signals can provide filtering of unwanted spurious signals. We may also note that
the result of using TDD is that the entire assigned frequency band is available for
transmission, so we can choose groups of frequencies for each base station which allow
the most effective combinations of combining methods, including baseband combining
and RF filtering.

In Figure 6-1 we have assumed that only one frequency band is used, although for this
purpose it may be possible that the 1800MHz and 2100MHz bands are served by a
common antenna; this is an antenna design matter, as the radiating elements must be
placed around one half-wavelength apart at 2170MHz, while maintaining their radiation
characteristics down to 1700MHz – difficult in practice, but not impossible in principal.
Physically separate antenna could be used for the 900MHz band, but there are existing
combined antennas providing operation at 900 + 1800/2100MHz, and some of the antenna
design methods already in use could be adapted to the new scenario.

It can be argued that the adoption of a common infrastructure of the kind described
reduces the areas for competition between the network operators. However if the result is
smaller total infrastructure cost, less environmental impact and reduced carbon dioxide
emissions, it should be possible to develop a regulatory incentive to maximise coverage
and optimise capacity. Competition in the area of mobile communications is increasingly
driven by specialisation in the services and content offered by the networks, much of it
deriving from ‘content providers’ a new layer of specialisation in the value chain.
The ‘virtual network operator’ is already a familiar model, and in the limit where the whole infrastructure is operated by another party all the operators become operators of ‘virtual networks’, competing with marketing, bundled packages, value-added services and content. The increase in network capacity which flows from the proposed system, as well as its reduced costs would allow mobile operators to compete more effectively with fixed line services. A recent paper by Beckman and Smith [13] comments on the relative maturity of the network infrastructure market in comparison to the substantial level of innovation and specialisation currently occurring in the services offered by the mobile networks. They comment on the potential economic benefits of the physical structure of the networks being run by ‘neutral hosts’, especially when applying the kind of technologies (for example distributed antenna systems) used in closed physical environments such as tunnels and airports, but as we have seen, very similar arguments can be applied to much wider parts of the physical network. This present report, beginning from a discussion of smart antennas, has shown that a ‘neutral host’ model could create significant innovation in network architecture and operation, stimulating new technologies which can bring additional benefits to society as a whole.

The role of the regulator in the scenario which has been described is a significant one. It is clearly necessary to ensure fair and equal access to the network by all operators, to establish a stable and comprehensible economic model which provides incentives for the neutral network host to develop and maintain the capacity and quality of the shared network to the benefit of the service providers and users.

6.4 Achieving the Gains in Spectral efficiency

It is clear from much of the published work that increases in spectral efficiency can be realised by the use of smart antennas, and the results of practical trials generally confirm this. For the reason explained above exact comparisons are not possible, but the order of increase in capacity for a given spectral occupancy is of the order of n, where n is the number of antennas in the array.

All these techniques require more complex antennas, coding or network alterations and so therefore involve additional cost to the operators. Whether this is compensated by increased revenue depends on the service. Generally both 2G and 3G networks are now in an advanced state of deployment and have been planned to match the expected traffic levels (which in some cases, have grown slower than first thought). Consequently, the scope for saving costs in existing deployments by using smart antennas in the immediate future is small.

New services are likely to be a much better candidate for smart antenna technology. In particular, bands at 3.5GHz and 5GHz could be the first to widely use smart techniques in a cellular application. There are several advantages:

- Antenna size is smaller and physical constraints are no longer an issue
- Phase shifters are smaller and cheaper to implement
- Cost of deployment is determined by the large number of base stations required due to larger propagation loss. Hence increase coverage afforded by smart is more important
• Wall and building losses are higher and so there is much more variation in signals observed at higher frequencies at a constant distance from the base station.

There is however, one drawback to smart antenna systems that require a rich multipath to achieve a spectrum gain (such as STC or MIMO). That is, at higher frequencies, multipath is a much lower component in the signal with increased line of sight propagation. However, the techniques that rely on beam-forming (including semi-smart) will be much simpler to achieve and provide genuine financial advantage.

The final hurdle to implementation is the provision of the technologies into the standards for the radio systems that may be deployed. These are likely to be OFDM based (as opposed to current CDMA systems) and it is noted that the main standard organisations (IEEE) are looking at putting smart antenna techniques into their latest standards (including 802.16). Further work will however be required to standardise the semi-smart concept into these systems.

6.5 Summary

This chapter has examined the prospects for installing smart antenna technology in order to provide improved spectral efficiency at economic cost. The conclusions are:

• Significant spectrum efficiency can be achieved using smart antenna systems.

• There are no agreed standards that can be used to compare cost and benefit of the various schemes that have been proposed. Existing cellular operators are unlikely to install smart antenna technology unless they can identify the best technology to install.

• The cost and effectiveness of installing smart antenna networks is strongly dependent on the selected network protocol, but one of the advantages can be that the network can be shared amongst many operators. This also has other benefits in that it is less physically obtrusive, requires less planning consent and uses lower materials and energy. If Ofcom wishes to promote this technology, it should take into account the economic analysis of Beckman & Smith of the use of neutral networks in developing future licences. In particular, the use of the broadcast model seems appropriate for this technology.

• Existing networks have been planned to have sufficient capacity without smart antennas.

• There is great potential for smart antennas for cellular networks operated in the 3.5GHz and 5GHz bands.

For the main technical focus of this study, the semi-smart approach, there may well be other factors that will be more significant than the spectrum efficiency gain. This includes the ability to handle peak traffic loads without expensive microcells, the lower network planning requirements and the greater network reliability in event of failure.
CONCLUSIONS

Over the course of this project, a variety of studies have been conducted on developing and evaluating a semi-smart antenna technique, in the context of assessing the current smart-antenna technology and the associated spectrum efficiency gains, and addressing some of key technical and regulatory issues. Having accomplished the project, we can draw the following conclusions.

We have studied the current state-of-the-art of smart antenna technology in general. The information is derived from published technical papers and reports, discussions with mobile radio operators worldwide and experience of the design of antenna systems for mobile radio base stations. All of this was with the aim of understanding where the technology is and where we think it may be heading. There is little doubt that the adoption of smart-antenna techniques can increase the utility of radio communications, providing enhanced data rates and improved coverage and spectral utilisation. However, it is argued that the administrative and financial environment of the industry and the current technical standards adopted in the mobile radio industry may not provide the most promising environment for the adoption of these techniques. It has been shown that a wide variety of techniques for the enhancement of the reliability of coverage and increase in network capacity have been applied and will continue to be developed in both GSM and W-CDMA systems. Nevertheless, it is promising to learn that the smart antenna techniques in SCDMA systems are currently in service in small scale networks in China (mostly rural and suburban environments). The Chinese 3G standard TD-SCDMA has been engineered to enable the use of smart antennas in the network, although the implementation of the networks using this air interface continues to be delayed.

It is also suggested that the financial and environmental constraints to the adoption of enhanced techniques could be resolved to the benefit of the community at large by the adoption of a different model for the ownership and operation of services for future networks. Combined with the specific choice of technical standards that can make best use of the techniques of multiple antennas, this could lead to a significant advance in network engineering.

Extensive simulation studies have been conducted of network level performance of semi-smart antenna systems. A novel optimisation technique has been developed in parallel with extending the system level of simulation into the aspects of heterogeneous demand, differentiated services, non-uniform topography and comparisons with the antenna down tilting. The performance simulation of the semi-smart antenna system for heterogeneous demands has indicated a significant decrease of blocking and dropping rates, i.e. an increase of the capacity, both in the uplink and downlink. The analysis on the support of different classes of customers and services has given encouraging results showing that the differentiation is achieved between all three classes while still achieving increased capacity and lower blocking rates. Results obtained from simulating different scenarios in a real topographic environment have revealed that very similar and even better performance can be achieved. The cooperative down tilting technique has been shown to achieve only a fraction of the improvement of network performance (around 20% as opposed to 80% for a full semi-smart network). Preliminary simulation work has indicated that the semi-smart antenna technique has true potential to support efficient networks where there can be little conventional network planning.
A novel cylindrically-conformal antenna array has been designed and tested. The new design is simple, robust, light and small in size (low profile), and most importantly, operates efficiently in providing dynamic radiation coverage in the azimuth plane. Synthesis and hardware control codes have been developed to operate with the semi-smart antenna prototype for real-time control pattern control. The study has been further extended to verify the concept of down-tilting as means of amplitude control. In this part of the study, extensive electromagnetic modelling has been carried out on linear arrays. Also, a brief review has been given of non-mechanical phase shifting solutions – a key component in smart antennas – and the potential technologies which might be used in the future to replace the current mechanical methods.

In comparison with conventional smart antenna or other antenna approaches, the semi-smart antenna technology has proven to be of much lower complexity and has minimal impact on the cellular system architecture. The work has not found any reasons why the semi-smart approach should not offer major benefits in spectrum efficiency over other methods and possibly at lower cost as detailed in Chapter 6. Assessments conducted on some important technical, business, standard and regulatory issues when employing the smart antenna technology in general have also shown in favour of the semi-smart antenna technology.

In summary, the work has further proven that the semi-smart antenna approach has enormous advantages and potential for civilian cellular radio systems and could offer a viable migration path from the current network deployments to the full smart antenna scenario. Further work will therefore be directed to exploiting this potential by working with the industry to standardise the semi-smart concept and system interfaces further.
8 REFERENCES


[27] Jaybeam wireless company, url: http://www.jaybeamwireless.com

APPENDICES:
9.1 Appendix A: The Bubble Oscillation Algorithm (BOA)
9.2 Appendix B: Extended bibliography