Mobile Network Design:

Orange UK 2G to 3G Mobile Backhaul Evolution

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Definition of terms

Term	Definition
1GE	1 Gigabit per second Ethernet
2G	2nd Generation mobile system - GSM
3G	3rd Generation mobile system - UMTS
4G	4th Generation mobile system - LTE
3GPP	3rd Generation Partnership Project
A	Interface between GSM TRAU and MSC
AAL1	ATM Adaptation Layer 1
AAL2	ATM Adaptation Layer 2
AAL5	ATM Adaptation Layer 5
Abis	Interface between GSM BTS and BSC
ADM	Add Drop Multiplexer
AIA	Association for Industrial Archaeology
AMPS	Advanced Mobile Phone System
Ater	Interface between GSM BSC and TRAU
ATM	Asynchronous Transfer Mode
AXC	ATM Cross-Connect
BSC	Base Station Controller
BSS	Base Station Sub-system
BTS	Base Transceiver Station (GSM radio base station)
CAPEX	Capital Expenditure
CBR	Constant Bit Rate
CDC	Control and DC Power card (Tellabs 8660)
CE	Customer Edge (IP end device)
CES	Circuit Emulation Service
CHAT	Contemporary and Historical Archaeological Theory
C-NBAP	Common-NodeB Application Part
C-RNC	Controlling Radio Network Controller
CSD	Circuit Switched Data
CSG	Cell Site Gateway
dB	decibel
DC	Direct Current
DCH	Dedicated Channel
DCS	Digital Cellular Service
DDF	Digital Distribution Frame
D-NBAP	Dedicated-NodeB Application Part
DTI	Department of Trade and Industry
E1	2.048 Mbps
EDGE	Enhanced Data-rates for GSM Evolution
eNB	Evolved Node B (LTE radio base station)
ETSI	European Telecommunications Standards Institute
EU	European Union
FDD	Frequency Division Duplex

FR	Frame Relay
FSK	Frequency Shift Keying
Gb	GPRS interface between PCU and SGSN
Gbps	Giga-bits per second
GERAN	GSM/EDGE Radio Access Network
GFP	Generic Framing Protocol
GHz	Giga Hertz
GGSN	Gateway GPRS Support Node
GNSS	Global Navigation Satellite system
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global Systems for Mobile communications
HDB3	High Density Bipolar 3
HDSL	High-Speed Digital Subscriber Line
HEC	Header Error Checksum
HSCSD	High Speed Circuit Switched Data
HSDPA	High Speed Downlink Packet Access
HS-DSCH	High Speed - Downlink Shared Channel
HSUPA	High Speed Uplink Packet Access
IDU	Indoor Unit
IEEE	Institute of Electrical and Electronic Engineers
IETF	Internet Engineering Task Force
IFUD	Interface Unit D
IMA	Inverse Multiplexing for ATM
IP	Internet Protocol
Iub	Interface between UMTS NodeB and RNC
Iu-cs	Interface between UMTS RNC and Circuit Switched network
Iu-ps	Interface between UMTS RNC and Packet Switched network
Iur	Interface between UMTS RNCs
ITU	International Telecommunication Union
kbps	kilo-bits per second
kHz	kilo Hertz
ksps	kilo symbols per second
LAG	Link Aggregation Group
L2 VPN	Layer 2 Virtual Private Network
LAN	Local Area Network
LNA	Low Noise Amplifier
LSP	Label Switched Path
LSTI	LTE/SAE Trials Initiative
LTE	Long Term Evolution (3GPP standard)
MAC	Media Access Control
Mbps	Mega-bits per second
MEF	Metro Ethernet Forum
MDC	Macro Diversity Combining
MHA	Mast Head Amplifier
MHz	Mega Hertz

MNO	Mobile Network Operator
MPLS	Multi-Protocol Label Switching
MPLS-TE	Multi-Protocol Label Switching - Traffic Engineering
MS	Mobile Station
MSC	Mobile Switching Centre
MSP	Multiplex Section protection
MSPP	Multi-Service Provisioning Platform
MSSR	Multi-Service Switched Router
NG-SDH	Next Generation Synchronous Digital Hierarchy
NMS	Network Management System
MSSR	Multi-Service Switch/Router
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
NodeB	Node B (UMTS radio base station)
O&M	Operation and Maintenance
OAM	Operations Administration and Maintenance
ODU	Outdoor Unit
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
OSS	Operational Support System
P	Provider (core MPLS router)
PCM	Pulse Code Modulation
PCMCIA	Personal Computer Memory Card International Association
PCU	Packet Control Unit
PDCP	Packet Data Convergence Protocol
PDSCH	Physical Downlink Shared Channel
PDU	Power Distribution Unit
PDV	Packet Delay Variation
PE	Provider Edge (MPLS router)
PELR	Packer Error Loss Rate
PDH	Plesiochronous Digital Hierarchy
PDN-GW	Packet Data Network Gateway
PoS	Packet over SDH
ppb	Parts per billion
PSK	Phase Shift keying
PSN	Packet Switched Network
PSTN	Public Switched Telephone Network
PWE3	Pseudo-Wire Emulation End to End
QAM	Quadrature Amplitude Modulation
ODF	Optical Distribution Frame
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RFC	Request for Comment
RLC	Radio Link Control

RNC	Radio Network Controller
ROADM	Reconfigurable Optical Add Drop Multiplexer
rt-VBR	real-time Variable Bit Rate
S1	Interface between eNB and S-GW
SAE	Systems Architecture Evolution
SAR	Segmentation and Reassembly
SC-FDMA	Single carrier - Frequency Division Multiple Access
SDH	Synchronous Digital Hierarchy
SGSN	Serving GPRS Support Node
S-GW	Serving Gate-Way
SLA	Service Level Agreement
SMG5	Special Mobile Group number 5
SMS	Short Message Service
SONET	Synchronous Optical Network
SPMA	Society for Post-Medieval Archaeology
SRNC	Serving Radio Network Controller
TACS	Total Access Communications System
TCO	Total Cost of Ownership
TCP	Transmission Control Protocols
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TN	Transport Node
TNL	Transport Network Layer
TRX	Transceiver
UBR	Unspecified Bit Rate
UDP	User Datagram Protocol
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UNI	User to Network Interface
UTRAN	UMTS Terrestrial Radio Access Network
WAN	Wide Area Network
VC	Virtual Circuit (ATM term)
VC	Virtual Container (SDH term)
VCI	Virtual Circuit Identifier
VLR	Visitor Location Register
VP	Virtual Path
VPI	Virtual Path Identifier
WCDMA	Wideband Code Division Multiplexing
WDM	Wavelength Division Multiplexing
WTN	Wideband Transmission Network
VoLTE	Voice over LTE
VPN	Virtual Private Network
X2	Interface between LTE eNBs

Abstract

The research presented in this thesis is focused on the evolution of a GSM/GPRS (2G) cellular mobile network to UMTS (3G) and then subsequently, HSDPA. The particular technical area of research relates to the mobile backhaul network which provides the connectivity between radio cell sites which support the wide area radio coverage, and the mobile network operator's core network. Due to the evolution of UMTS with HSDPA, the research covers the initial UMTS network rollout and then addresses the evolution of this infrastructure to support mobile broadband communications, through the introduction of HSDPA as a network upgrade. The two research questions being addressed are therefore:

- How is it possible to evolve a GSM/GPRS mobile backhaul network to support a converged GSM/GPRS and UMTS cellular mobile service?
- How is it possible to ensure scalability of the converged backhaul network given the introduction of HSDPA and associated mobile broadband data growth?

The starting point of the research is an established GSM and GPRS commercial network in the UK and the study is based on the design of the Orange network and focused on the period 2000 to 2010. During this period the author was working as Principal Network Designer within Orange and had overall responsibility for the strategy, architecture and design of the UK mobile backhaul network. The thesis provides a detailed explanation of the novel network design that was adopted and how it was evolved throughout the ten year period covered by the research.

The research proves that the original static TDM approach was not suitable for UMTS and therefore the outcome was the introduction of an ATM network with optimisation based on traffic class rt-VBR over protected STM-1 transmission links. HSDPA drove further traffic growth and resulted in an evolution of the solution to ensure massive scalability was supported through the migration to Carrier Ethernet and implementation of pseudo-wires.

In addition, to providing a technical description of the network design, the thesis also aims to provide a historical record of the technologies and equipment used during this period of rapid change within the UKs mobile networks.

1. Introduction

Since the launch of commercial cellular mobile communications services in the UK by Vodafone on 1st January 1985, swiftly followed by Cellnet on the 7th January 1985, there has been a rapid adoption of mobile phones and evolution of associated networking technologies. From the original analogue mobile phone networks the industry eco-system has migrated to digital systems, the mobile phone has become a mass market product while the introduction of mobile broadband data communications has truly revolutionised how people access information, communicate, navigate and consume entertainment.

This thesis presents research which in part enabled this revolution for the Orange UK cellular mobile network. The mass adoption of digital cellular based on the GSM standard, known more commonly as 2G, resulted in a very large mobile phone subscriber base, the introduction of GPRS enabled basic data communications services on mobile phones and a range of alternative mobile equipment; such as PCMCIA data cards and telemetry devices. The growth in cellular data communications resulted in the need to evolve the GSM/GPRS standards to enable much higher peak and average user data rates and greater overall system capacity, to support a greater density of users. This evolution resulted in changes to the GPRS standard with the introduction of EDGE technology along with a new, parallel cellular mobile technology, known as UMTS or more commonly, 3G.

Whilst the prime focus of the research presented in this thesis is on the technical development and evolution of a mobile network from 2G to 3G, a secondary consideration of the work is to examine the impact of technological change on recording and maintaining historical records. The rapid pace of technological evolution in this field presents a particular challenge for the fields of industrial heritage, industrial archaeology and history of technology. The mobile industry is forward looking, focused on the next new device and next new network capability, recently 4th generation LTE technology has further enhanced the user experience since EE launched the UKs first 4G network on the 30th October 2012. Whilst LTE continues to evolve there is already significant focus on 5G, the 5th generation of mobile communications technology, which is likely to deliver commercials services around the year 2020. There will have been five generations of mobile communications technologies in a period of 35 years; each has also evolved in life so the technological roadmaps are extremely complex.

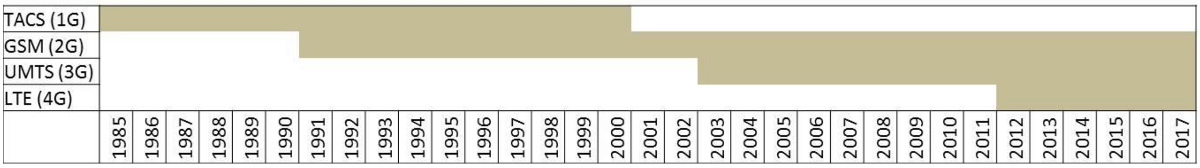


Figure 1: Timeline of UK mobile network technologies

Given the forwards looking focus of the mobile industry, there is little historical record maintained to explain the various phases of network evolution, records are often company confidential and then simply destroyed once no longer relevant. Mobile phone towers and rooftop sites are an increasingly common sight on the urban, sub-urban and rural landscapes, yet with each evolution of technology or introduction of a new radio frequency band, these installations change as form follows function. There is very little documented evidence of the previous state of these installations and therefore the historical record is lost. It is likely that the most common artefact to survive into the future will be examples of mobile phones from the various periods of cellular mobile communications. Artefacts relating to the actual networks which enable the increasingly ubiquitous connectivity that exists today will be in very short supply. Thankfully the science museum in London has managed to acquire one of the last remaining analogue cellular base stations for the Information Age gallery and had they not done so there would be no artefact remaining to support the limited historical record of the first ten years of this revolutionary period in the history of radio communications.

The research presented in this thesis is therefore deliberately aiming to address multiple requirements, firstly; it will provide some context and technological background as the basis for the primary research question, secondly; it will address the following research questions:

- How is it possible to evolve a GSM/GPRS mobile backhaul network to support a converged GSM/GPRS and UMTS cellular mobile service?
- How is it possible to ensure scalability of the converged backhaul network given the introduction of HSDPA and associated mobile broadband data growth?

Thirdly, this thesis aims to provide a detailed record of the state of the art in GSM, GPRS and UMTS mobile backhaul technologies and an example of a live commercial network, based on Orange UK during the years 1994 until 2010, when the company merged with T-Mobile UK to form Everything Everywhere (later, simply EE). The detailed research, mobile backhaul network engineering and conclusions refer to the period post 3G spectrum auctions in 2000 until 2010. The period between 1994 and 2000 is discussed in chapter 3 as this provides the background and baseline to the research presented in chapters 4 and 5. Appendix 5 provides details of the cell sites and installations in the photographs used in this thesis, this includes network operator and location, if known.

This work is original in as much as it isn't just a theoretical model of what could be done on a mobile network, it is the actual mobile backhaul network architecture and technical design which was implemented on the Orange UK network and enabled the launch of the Orange 3G network service in 2004 and then ensured this network evolved to support HSDPA which marked the start of the mobile broadband era. The author, working for Orange as Principal Network Designer, was instrumental in designing this network and defining the strategy for its future evolution. This included analysing the 3GPP UMTS specifications, understanding the vendors UTRAN products, modelling the backhaul network capacity requirements, developing the target architecture and producing the high-level design.

Reviewing literature related to the primary research field alongside industry heritage, industrial archaeology and history of technology literature helps to provide context and position this thesis to be of use to a wider community of interest, from those wanting an understanding of mobile communications technologies to those studying the historical evolution of mobile communications and its place within industrial archaeology.

The literature review is deliberately broader than the scope of the research questions because it aims to provide a comprehensive summary of the evolution of the mobile industry to date, therefore framing the period relating to the specific research while providing a view of how the principles developed have influenced more recent network strategies, architectures and designs.

The approach to the research is important as this is ultimately network specific, albeit many generic principles are explored throughout. The application of the target architecture and network designs developed in this research is based on a well-defined starting point. The background to UK mobile networks is covered in chapter 3, this section goes on to present a detailed overview of GSM network architecture and design along with a review of the various mobile backhaul technologies. The introduction of GPRS is analysed and then the focus shifts to provide a detailed understanding of the Orange network prior to the introduction of UMTS. This network is the basis on which the research questions must be answered and any solutions must ensure the existing services continued to operate in parallel with the introduction of new UMTS services.

Chapter 4 addresses the first research question by presenting an overview of the key subject matters to be considered, these include; the background to 3G, the UK 3G spectrum auction, an overview of UMTS technology and a review of UMTS network equipment, in the case of Orange UK this equipment was purchased from Nokia Networks. Once the requirements are fully understood the development of the target architecture can commence, the output of this drives vendor selection activities for new equipment and transmission connectivity. The detailed design phase then follows; this provides the technical solution which is implemented on the national network to enable 3G rollout and the launch of commercial service.

The ever growing demand for mobile data leads to the development of HSDPA technology which truly enables the era of mobile broadband data communications. Chapter 5 addresses the challenge of scaling the UMTS network to support the growth in traffic while ensuring costs are managed within acceptable bounds. The introduction of advanced technologies such as IP/MPLS, pseudo-wires and Carrier Ethernet is explored and their application to the mobile backhaul network is defined. This results in further vendor selection for new high-capacity transport network elements which must integrate with the existing converged GSM/GPRS and UMTS mobile backhaul solution.

The thesis concludes with a review of what has been achieved, how the network has evolved as a result of the research that is presented in this thesis and how much 3G capability was deployed and enabled as direct consequence of the network architectures and technical designs developed by the author.

2. Literature review

The deliberate adoption of a cross-disciplinary approach to this work has resulted in a broad review of literature relating to the fields of telecommunications network engineering, in particular cellular radio site planning and design, transmission and mobile backhaul, along with the history of technology, industrial archaeology and industrial heritage.

2.1 The early days of cellular

Whilst the history of electrical telecommunications in various guises can be traced back to the 19th century, this research is focused on cellular communications and as such the first key paper to consider is that of DH Ring. In December 1947 DH Ring published a Bell Technical Laboratories technical memoranda. This paper introduced the cellular concepts, including frequency reuse and explained the concept of low-power radio base stations known as cells. Primary and secondary areas are defined and how amplitude discrimination due to attenuation with distance enables the reallocation of a given frequency in a non-adjacent cell (Ring, 1947). At the time of writing his theory it wasn't possible with the technology of the day to build such a cellular system. The cellular concept lay fallow until the 1960s, when Richard Frenkiel and Joel Engel of Bell Labs applied computers and electronics to make it work (Huurdeman, 2003). Work continued in this field and by 1978 the FCC invited the US telecommunications industry to propose solutions for a more effective land mobile telephony network. AT&T responded with a proposal which originated from the 1947 paper along with the later work of Frenkiel and Engel (AT&T, 2016). The solution AT&T proposed was accepted, this was the cellular Advanced Mobile Phone System which was to have a significant influence in the UK during the 1980s. The story of cellular communications in the UK started in 1982 when the government awarded operating licenses for cellular mobile communications in the 900 MHz band; these licenses went to Cellnet and Vodafone. After some debate the two newly appointed UK mobile network operators agreed on a common specification for their respective networks, this was based on AMPS however with one key difference, individual radio channels would be of 25 kHz bandwidth rather than 30 kHz as deployed in the USA (Barnes, 1985). The period between 1982 and network launch in 1985 was extremely busy; little is written about this period but the story is documented through research and a series of interviews by Francis Spufford. Spufford offers a fascinating account of the development of cellular network planning, there were lots of theories and system specifications however no real propagation models for this use of 900 MHz spectrum (Spufford, 2004). Cellnet and Vodafone had to develop solutions from scratch to enable successful radio network planning, this involved deploying test transmitters and driving around different geographical areas; dense urban, urban, sub-urban, rural and sparse rural, to understand the different behaviours that could be expected. Eventually computer models were built, in the first instance a modified version of the Okumura model, substituting the Japanese landscape for that of the UK (Okumara, Ohmori, Kawano, & Fukuda, 1968). Early cellular propagation modelling was focused on outdoor coverage. Over time a range of models evolved to help plan radio coverage through an understanding of the propagation channel and channel characterisation, therefore enabling an understanding of both the transmitter power levels and receiver behaviour (Sarkar, Ji, Kim, Medouri, & Salazar-Palma, 2003). In parallel with the development of propagation models, drive and later walk surveys taking measurements from test transmitters and actual base stations continued for many years to provide data to optimise the prediction algorithms and enable new tools to be built for additional cellular frequency bands. It’s often stated in archaeological parlance that form follows function and often this is demonstrated through an examination of building design (Palmer, Nevell, & Sissons, 2012). To produce a historical archaeology of cellular radio base stations it’s important to understand not only the radio propagation environment discussed above but also factors which influence the physical appearance of a radio cell site, why one type of structure is deployed rather than something different at a given location, why are the antennas of different shapes and sizes, and what does the different size of building or cabinet mean for the function of the cell site, etc.

2.2 Cell site design

Early cell sites were typically deployed on rooftops where available and towers or masts where necessary, some of these towers and masts would have been existing infrastructure or, in many cases, new builds. The antenna systems of the original analogue cellular networks which were known as Total Access Communications System differed considerably from the state of the art today. Vodafone used three directional antennas on many of their TACS sites, multiples of these three antennas (typically 3 x 3), could provide 360 degrees of coverage where one antenna would be in transmit mode only while the other two would be receive only (White, 1998). Cellnet chose an alternative approach at the time, using an omni directional antenna or number of them to transmit and separate directional antennas to receive. A typical omni-directional cell will provide 360 degrees of coverage while a typical sectored cell would cover 120 degrees, hence 3 cells to provide 360 degrees of coverage. Sectored sites will have greater coverage potential and more capacity than omni-directional cells (Webb, 1988). TACS base station antenna systems operated with a technique known as space diversity, a system in which two receive antennas are deployed at the base station to improve the uplink (connection from mobile phone to base station), these antennas are separated in space such that the relative phase of the signals arriving at the antennas are different and therefore the probability of both antennas receiving a fade simultaneously is minimised, therefore reducing call drops (Saunders & Argon-Zavala, 2007). The use of space diversity antennas is a key consideration in determining the size of structure and mounting frame required for the antennas, typically a base station would require ten wavelengths of separation between the two receive antennas. A radio frequency wave can be completely described by either its frequency or its wavelength which are inversely proportional to each other and related to the speed of light through a given medium. At 900 MHz the physical separation distance between the two receive antennas would be in the region of 3.3 metres. However an alternative approach was developed and brought to market during the late 1990s. At this time there was much discussion about this new design of antenna which uses polarisation diversity rather than space diversity. All radio wave transmissions operate at a particular polarisation, most common designs are either vertical or horizontal. A vertically polarised signal has an electric field which is perpendicular to the Earth's surface; a horizontally polarised signal has an electric field which is parallel to the Earth's surface. Polarisation diversity replaced vertically polarised spaced antennas with one antenna being orientated 45 degrees clockwise of vertical (0 degrees) and the other being offset 45 degrees anti-clockwise. By removing the need for spatial separation, a new range of narrower towers and even slim columns and lampposts could be used to support cellular antenna systems; this reduced the visual impact of cellular radio antenna structures and enabled many new and innovative site designs. It has been concluded (Joyce, Barker, McCarthy, & Feeney, 1999) that spatial diversity performed better than polarisation diversity however only by 1dB to 2dB, therefore an operator had to consider the advantages of not needing to build the spatial diversity requirements into site and structure designs, over time antenna polarisation diversity became the solution of choice.

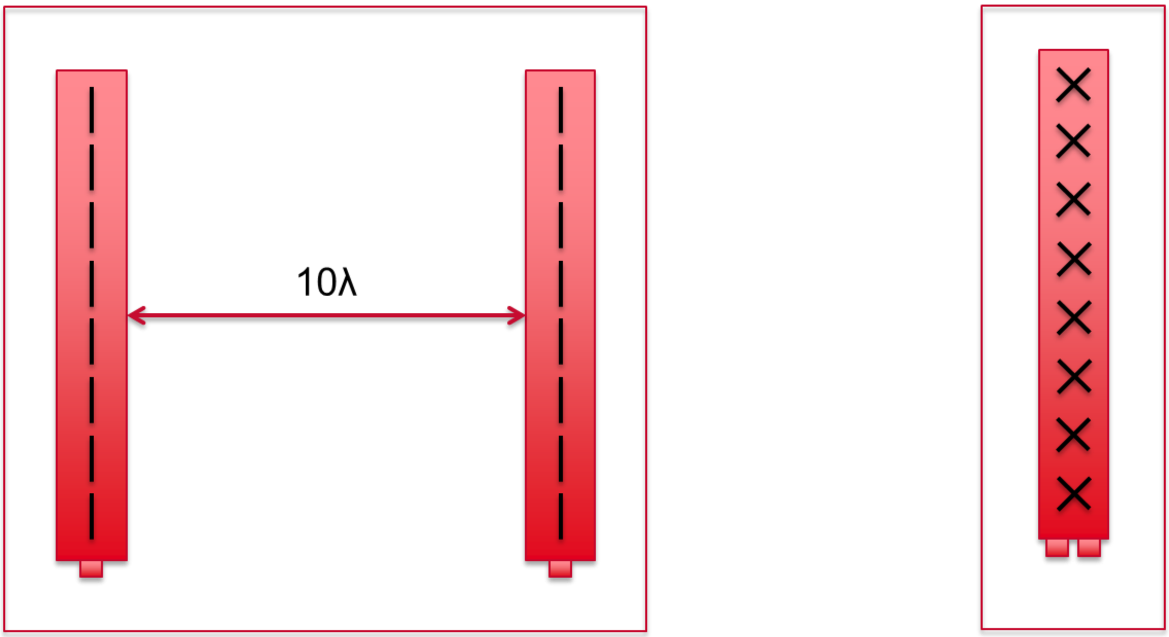


Figure 2: Vertically polarised space diversity antennas (left) compared with a polarisation diversity antenna with +/-45 degrees slant polarisation (right)

Additionally, as sites became ever closer in distance to support higher area capacity density in urban and suburban areas it became less of an issue, the greater flexibility with site design was the main advantage of polarisation diversity antennas. Likewise in rural areas once the new antenna system performance figures were built into the propagation modelling tool they were automatically taken into consideration when selecting new site locations and parameters. As with all aspects of cellular radio engineering, base station antenna design is a constantly evolving field, dual band, dual polarisation antennas became the norm after the introduction of 3G UMTS systems and before long remote electrical tilts started to simplify the process of network optimisation (Beckman & Lindmark, 2007). Today's cell sites support 2G GSM, 3G UMTS and 4G LTE technologies across a wide range of frequency bands which range from 800 MHz to 2600 MHz (Song & Barker, 2017). New cellular bands at even lower and higher frequencies will appear over the coming years. In addition to the cellular antennas it's common to find tower top low noise amplifies on sites, these work to boost the receive signal from the mobile device and help balance the radio path between base station transmit and base station receive, both independent radio link budget calculations.

2.3 Mobile backhaul

Mobile backhaul provides the connectivity between a cellular radio base station site and the mobile network operator’s core switching equipment (Sutton, Building Better Backhaul, 2011). Backhaul connectivity may be provided via copper lines, fibre optic cables or microwave radio systems, albeit copper is not used frequently nowadays due to the high capacity demands of modern mobile broadband networks. Backhaul connectivity may also affect the appearance of a radio cell site; the microwave antenna will be more visible than cable connectivity which is generally buried under-ground. Mobile backhaul refers to more than just the physical connectivity between a cell site and core network, it also refers to the transmission and transport network technologies used to communicate operations and maintenance information along with signalling and user data. This topic is an essential component of the research presented within the thesis. The transmission layer has evolved over time from time division multiplexing based on the plesiochronous digital hierarchy to TDM based on the synchronous digital hierarchy and more recently, to a completely new concept based on Carrier Ethernet (Metsala & Salmelin, 2012). 3GPP introduced the concept of a transport network layer for UMTS; this was specified to use Asynchronous Transfer Mode technology however over time evolved to the Internet Protocol. IP is particularly well suited to transmission over Carrier Ethernet (Korhonen, 2003).

2.4 Mobile technology evolution

Technologies have evolved significantly since the UK deployed analogue TACS technology, GSM introduced digital speech quality and evolved to support packet data services offering initially some tens of kbps and evolving through EDGE technology to support data rates greater than 100kbps (Mouly & Pautet, 1992) (Sanders, Thornes, Reisky, Rulik, & Deylitz, 2003) (Halonen, Romero, & Melero, 2003). GSM didn’t only operate in the established cellular band of 900 MHz though. Following on from a paper written by the UK DTI in which it proposed the concept of Personal Communications Networks, GSM also become available in the 1800 MHz band, this was originally known as DCS 1800 however quickly became known as GSM 1800 (Department of Trade and Industry, 1989). As adoption of mobile communications took off in the UK there was a need for a new technology which would add more capacity and in particular support the need for ever higher data rates and volume (Mobile Operators Association, 2017). The Mobile Operators Association has monitored the significant growth in UK mobile subscribers as shown in figure 3. Towards the end of the 1990s the number of mobile phone users increased considerably and by mid-2000s there were more mobile phone subscriptions than people in the UK.

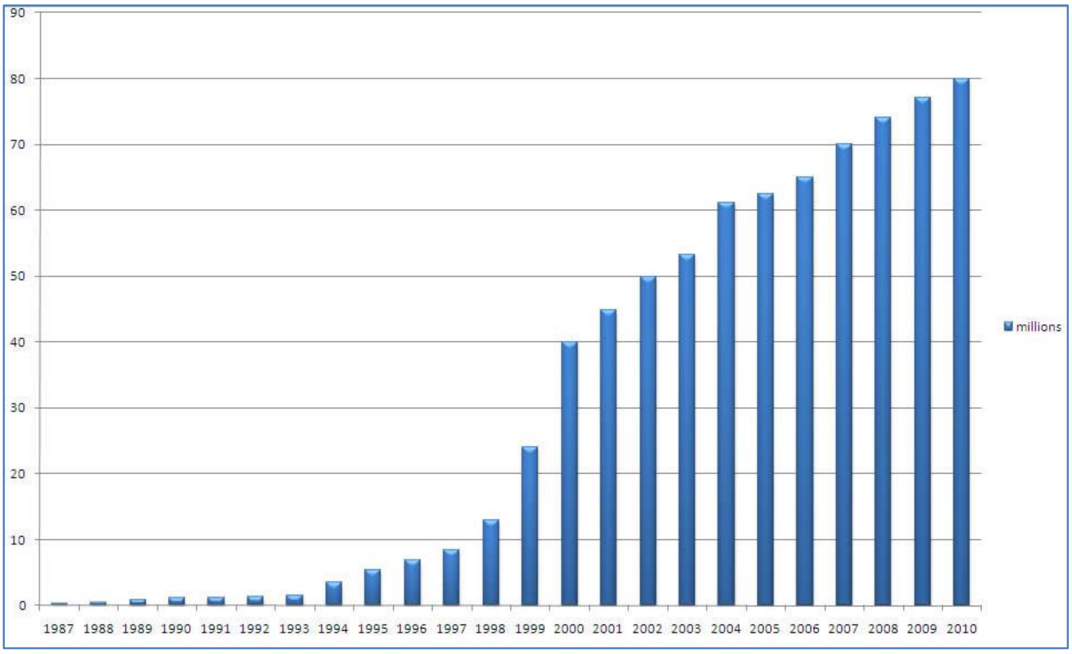


Figure 3 : Growth in mobile connections in the UK (Mobile Operators Association, 2017)

As witnessed with GSM it is not uncommon for work on a future generation of mobile communications technology to start prior to the implementation of the system it will replace (or in reality compliment as currently 2G, 3G and 4G systems co-exist) given a typical research and development cycle of ten years. The objectives for a third-generation mobile system were discussed during the 5th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications which took place in The Hague, Netherlands, during 1994. Of particular note from that conference is an output from a project of the second phase of the Research and Development in Advanced Communications for Europe programme (Konidaris, 91) (Oudelaar, 1994). Work arising from the MObile NETwork MONET) project offers a number of implementation options which range from integration with existing fixed and mobile networks to designing and building a completely new system.

It concluded that UMTS will be a Broadband-Integrated Services Digital Network solution for broadband mobile applications, albeit at this stage there was still much work to be done before the final standards could be defined.

3G was looking for a so called killer application to differentiate itself from 2G, early prototype and even production mobile devices focused on video telephone which whilst novel, did not prove to be a great success with consumers (Holma & Toskala, WCDMA for UMTS, 2000).

Initial 3GPP release 99 3G networks could support maximum data rates in the downlink, from the network to the mobile phone, of 384 kbps at launch. The data rates would increase with new high speed packet access technologies to some tens of Mbps (Dahlman, Parkvall, Skold, & Beming, 2008). 3G was initially licensed in the 2100 MHz frequency band and therefore required not just new base station radio equipment but also new antennas, therefore changing the physical appearance of the cellular radio base station site. As the cycle of research and development continued this lead to the next major evolution in mobile communications technology; Long Term Evolution (LTE) or 4G as it is commonly known. Once the initial LTE standards had been frozen in December 2008 (3GPP, 2017) it was agreed between major network operators and equipment vendors to form The LTE/SAE Trials Initiative (LSTI) (Robson, 2009). LSTI was tasked with taking LTE/SAE from specification to technology rollout. 4G technology is a true all IP packet based multi-media technology which can support data rates in excess of 100 Mbps and operate across a wide range of radio frequency bands; once again requiring new equipment and antennas and as such the form of the cellular radio base station had to change yet again (Holma & Toskala, LTE for UMTS: Evolution to LTE-Advanced, 2011) (Agilent Technologies, 2013).

The network operator influences the way a cellular radio base station site appears however there are also certain external influences, mainly relating to planning permission from local authorities. Over the years local authorities have taken very different views to cellular radio installations, some have welcomed the infrastructure while others resisted it. It’s fair to say nowadays that a combination of central government policy and the need for modern high-speed digital connectivity has led to a general acceptance that the mobile communications industry and local authorities need to work together to deliver suitable digital infrastructure for the UK. Local authorities publish guidelines often in the form of supplementary planning guidance (SPG) (Department of Environmental Planning Services, 2004, p. 1) (Salford City Council, 2013) (Bristol City Council, 2002). In the case of Guildford Borough the SPG is explained as follows:

“This Supplementary Planning Guidance (SPG) provides advice to all those with an interest in the siting of telecommunication masts in Guildford Borough. Whilst we have issued this guidance primarily for use by telecommunications operators, it will be an important source of information for the general public interested in the issues involved”.

Such guidance enables site designs to be sympathetic with their surroundings. For example, fake trees and other structures are often used in rural locations where a traditional lattice tower or column would be inappropriate; however such structures can present some technical challenges for the operator.

2.5 Historical archaeology

The value of contemporary industrial archaeology is explored by Nevell (Nevell, 2014) which is particularly relevant because the work presented in this thesis covers the late 20th and early 21st centuries. Historical archaeology established itself as a specialist field of archaeology during the 1960s and in many cases, will study contemporary sites for which there is an amount of documentary evidence in the form of documents, photographs, drawing and oral histories available. Organisations such as: The Society for Post-Medieval Archaeology (SPMA) and Contemporary and Historical Archaeological Theory (CHAT) have been looking at 20th century archaeology for a decade. However, within the work undertaken by SPMA and CHAT, limited reference exists to telecommunications. Nevertheless CHAT did successfully campaign to get George Gilbert Scott telephone boxes listed which in itself was a most worthwhile contribution to preserving telecommunications heritage. In particular no specific studies of cellular radio base stations in the UK have been undertaken and consequently, existing literature does not deal directly with this subject from a historical archaeology perspective but it can be used to inform the manner in which this research is conducted and advise on methodology for studying the typology of cellular radio base stations and presenting the specific mobile backhaul research. The only formal academic work to address the topic of mobile communications from a historical archaeology perspective is that of Cassie Newland (Newland, 2004) which explores the historical background to the development of the mobile phone, tracing wireless technology back to the latter part of the 19th century and then exploring the rollout of cellular radio networks in the UK, reviewing the typology of cell sites and detailing the level of protests which occurred due to proposed siting of cellular radio base stations during the period of major networks rollout. Interestingly nowadays there are probably as many protests about the lack of mobile phone coverage and active campaigns for new cellular radio base stations in areas without sufficient coverage than there are protests about new site builds. This highlights the growing dependency individuals and businesses have on mobile communications. Cellular mobile communications became available to the general public within the UK on the 1st January 1985 when Vodafone launched the first network (Linge & Sutton, 30 years of mobile phones in the UK, 2015). Work on the design and deployment of this network and the competing Cellnet network which launched a week later, commenced early in the early 1980s and as such many of the senior technical staff, if still alive, are in their 70s now and few oral histories exist. Additionally, very little documentary evidence exists from these early network designs as such documents are often kept confidential within the network operator's business and as they become legacy and therefore redundant, are simply deleted from document libraries. As a result of this there is very little evidence of this period of rapid technological development, this trend has continued to the present day and therefore puts mobile communications history and heritage at risk. The aspects of this challenge has been considered by Hilary Orange who noted that "there comes a point in time when it is no longer possible to obtain first-hand accounts of change and event" (Orange, Reanimating Industrial Spaces: Conducting Memory Work in Post-industrial Societies, 2014, p. 13) . She particularly notes the temporary nature of many businesses and technologies, a trend which has certainly been witnessed during the last 30 years of cellular mobile communications in the UK. Mass market mobile communications has become the accepted norm nowadays, not just in the UK but also globally. Consequently, globalisation of cellular communications has enabled a mass market economy which in turn means that technology can now be offered at a price-point that's accessible to the vast majority of people living in the UK, a point that is further elaborated by Lachohee (Lacohée, Wakeford, & Pearson, 2003),. The review of the birth of the mobile phone in the USA has been examined by Agar, (Agar, 2004), Whereas, Temple, provides an in-depth analysis of how GSM was created (Temple, Inside the Mobile Revolution A POLITICAL HISTORY of GSM, 2010) , Meurling considered the evolution of mobile communications from an Ericsson perspective (Meurling & Meurling, 1994) but includes significant insights because they were able to interview key decision makers from Vodafone, Cellnet and Mercury one2one, all of which were UK mobile network operators at the time. Given the extraordinary pace of change which is being experienced within the field of telecommunications in general and cellular mobile communications in particular, there is now recognised a need for active engagement from the heritage and historical archaeology communities to identify and conduct appropriate research (English Heritage, 2010, p. 25). English Heritage, in their Research Strategy for the Historic Industrial Environment make reference to telecommunications, stating that:

“Communication over distances has evolved from the visual - beacons and telegraph towers through electric telegraph and telephone to the present day digital systems and each stage has left evidence of these advances. Projects which study the evidence for these stages, their technology and survival are to be supported to anticipate protection issues”.

There is little evidence of any real action or progress being made. Indeed it can be argued that the current pace of developments in the digital era alone poses as much of a risk of lost knowledge, history and heritage as anything earlier in the history of telecommunications. Liffen (Liffen, 2014) discusses the invisible network and how microwave radio antennas are disappearing as the UKs trunk networks migrate to buried fibre-optic cables. Microwave radio systems are still in use for cellular radio base station site connectivity, along with fibre optic cables, both of which will be discussed later in this thesis (Sutton, Radio Systems, Microwave and Millimetre Wave, 2015). Liffen also explores a wide range of telecommunications technologies and observes that little is being done to preserve buildings or specialist installations for future generations. It is clear that the history of telecommunications is not a mature discipline within UK academic programmes and in fact relies on a small yet enthusiastic number of amateurs to maintain the level of records which currently exist, the notable exception being BT Archives. Much more needs to be done and formal academic led research is essential to ensure suitable historical data is captured, analysed and recorded. Given the rapid evolution from 1G to 2G to 3G to 4G and onwards to 5G, all within 30 years or so, there is clearly a huge risk that society will suddenly realise that the early technologies are old stuff which is no longer trendy is in fact an important part of the history of technology and many of the corresponding underlying technical principles remain the key foundations on which the future connected society will be built. Linge (Linge, The archaeology of communications' digital age, 2014) reviewed the evolution of digital communications from the perspective of the telephone network and computer communications, both of which would eventually merge to form today's digital access networks, Intranets and the public Internet. He goes on to discuss the development of digital cellular communications and raises the important topic of digital obsolesce. Papers such as this are vital to building a portfolio of literature which addresses our digital heritage, highlights the pace of change and inspires others to play their part in the preservation of artefacts and to actively document the technology which plays a vital role in the evolution of our increasingly connected planet. The linkage between the research presented in this thesis and future historical and industrial archaeological interest is best summarised by Hilary Orange (Orange, Changing Technology, Practice and Values: What is the Future of Industrial Archaeology, 2014, p. 68) who said: "Where engineers go, industrial archaeologists tend to follow".

This chapter has reviewed technical and historical literature relating to cellular mobile communications systems and their deployments in the UK. The scope of the technical review is broad as the literature review has covered four generations of mobile communications technologies. Aspects of industrial archaeology, industrial heritage and the history of technology have been introduced in the context of mobile communications to highlight the need for a sustained programme of recording the rapid pace of technological evolution within this sector.

Chapter 3 explores the development of GSM and its deployment in the UK. The chapter starts with a general overview of GSM and then explores the UK market before going on to focus specifically on the Orange UK network rollout. This provides the context for positioning the research questions and is the baseline against which the research was conducted.

3. Background and 2G developments

This chapter provides the technological context to the research and design requirements. The aim is to set the scene by exploring the development of the GSM digital cellular communications standards and the implementation of GSM networks in the UK. It is essential to review GSM radio site design and mobile backhaul implementation as this is the foundation on which the research is based. The successful outcome of the research will be measured against the target architecture and network designs ability to support the existing GSM and GPRS service as much as it will be measured against enabling a UMTS network service. The chapter will also provide a historical overview of the introduction of digital cellular in the UK and as such aims to support the broader aims of the thesis in providing a record of events and technologies.

Cellular radio sites provide the radio signal which connects the mobile phone (or other cellular enabled user equipment) to the mobile network. To date, mobile phone networks in the UK have operated in Frequency Division Duplex Mode. In FDD mode the base station transmits a signal from the network to the user on the downlink channel and receives a signal from the user on the uplink channel. The separation between a downlink and uplink frequency is known as the duplex spacing. First generation Analogue TACS networks operated in the 900 MHz band in frequency division duplex mode.

3.1 GSM standards

GSM was developed by the Confederation of European Posts and Telecommunications Administration as a result of a project which was initiated in 1982; to design a pan-European mobile communications technology. By February 1987 the basic parameters of the standard were agreed and the GSM Memorandum of Understanding (MoU) was signed by 15 network operators from 13 different countries; all of whom had committed to deploying GSM networks (Temple, RARE GSM DOCUMENTS, 2017). The European Telecommunications Standards Institute was formed in 1988 and took over the responsibility for existing and future GSM standards. Initial GSM specifications focused on providing a digital mobile voice service which would work throughout the EU through the establishment of roaming agreements between MNOs. In addition to voice, GSM supports the short message service and circuit switched data services.

The introduction of GSM and associated mass-market economics realised through the near global adoption of this standard, resulted in low cost handsets and significant innovation between competing manufacturers. The low-cost handsets drove ever greater adoption of digital cellular which resulted in greater demands on networks. These demands included both wider geographical coverage and ever greater capacity to manage large numbers of subscribers in urban centres.

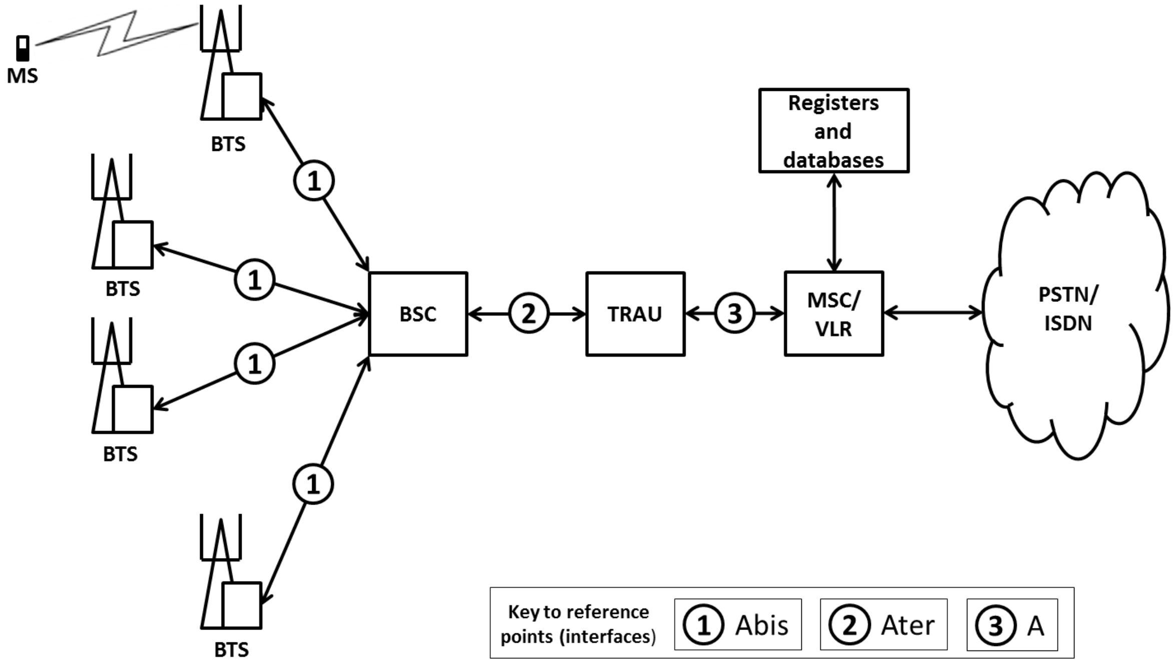


Figure 4: GSM network architecture

Figure 4 illustrates the GSM network architecture and reference points; these are commonly known as interfaces with those identified as 1, 2 and 3 being interfaces to or within the Base Station Sub-system (BSS). A GSM Base Transceiver Station (BTS) connects to a Base Station Controller (BSC) via the Abis interface. The BSC may include the Transcoder and Rate Adaptation Unit (TRAU), in which case interface no. 2 is internal or the TRAU may be implemented as a standalone platform in which case interface no. 2 is exposed, this is known as the Ater interface. The interface between the TRAU and Mobile Switching Centre (MSC), which contains the Visitor Location Register (VLR) is a standard 64kbps A-law PCM interface, defined as the A interface.

The evolution of the mobile backhaul network is the technical focus of this research and therefore the primary GSM nodes of interest are the BTS and BSC, along with its associated Abis interface. In certain deployment scenarios the BSC was distributed and located away from the mobile network operator's core MSC sites. Hence, this node was often deployed within the access network and therefore the Ater interface also falls within the scope of this research. The decision to centralise or distribute the BSC node was based on a number of considerations which included; the capacity of the BSC, this was influenced by the choice of preferred equipment vendor, and the cost of TDM transmission between the cell sites and core network site, this is important because the Ater interface carries voice traffic at 16kbps whereas the A interface, carries voice at 64kbps (after transcoding within the TRAU). The use of Ater interface rather than A interface over the wide area results in a significantly lower capacity transmission solution and therefore lower total cost of ownership (TCO).

3.2 GSM in the UK

Vodafone and Cellnet weren't allocated any new spectrum for GSM and therefore had to use channels within their existing 900 MHz allocations; this reallocation of radio spectrum from one technology to another is commonly known as spectrum 'refarming', a common practice nowadays however this was the first implementation. The refarming of spectrum from their analogue network to GSM required significant planning as existing subscribers continued to use, and new subscribers sign up for, the analogue service while the GSM network was developed in parallel. For quite some time the geographical coverage of the analogue network was superior to that of GSM, which was dependent on investment in new digital base stations and associated network infrastructure.

The UK Government was keen to encourage further competition within the mobile market and to expand capacity. Therefore it commissioned the Department of Trade and Industry to produce a consultative document called 'Phones on the Move'. Published in January 1989 this document set forward plans to licence new operators who could provide GSM networks operating in the 1800 MHz frequency band which would be known as Personal Communication Networks. Lord Young, Secretary of State for Trade and Industry announced that one licence would be offered to Cable and Wireless who owned and operated the Mercury Communications Limited fixed network, in competition to British Telecom, whilst a second and third licence would be opened up to bidders. This competition was subsequently won by Unitel which was owned by a consortium including US West and Microtel that was owned by a consortium which included British Aerospace. In 1992 Cable and Wireless and US West merged to form Mercury Personal Communications through which they launched Mercury one2one while British Aerospace sold Microtel to Hong Kong based Hutchison Telecom. As a consequence the original three PCN licences became two meaning that the total number of UK mobile network operators had grown from two to four.

Vodafone was the first UK Mobile Network Operator (MNO) to launch a commercial GSM consumer service when their network went live in July 1992. The Mercury one2one network became the world’s first 1800 MHz GSM network when it was launched on 7th September 1993. Initially this network was restricted to the London area but offered a unique proposition to customers of free calls during the weekday evenings (7pm - 7am) and throughout the weekends.

The UKs third GSM network to launch was Cellnet which opened in December 1993 and this was followed by the fourth, launched by Hutchison Telecom on 28th April 1994; the second of the two new entrants at 1800 MHz. Hutchison's approach was to focus on providing national coverage with products targeted at the general consumer for which they launched the Orange brand and renamed the company to align with that brand.

As Vodafone and Cellnet were deploying GSM in their existing frequency band, they could reuse antennas in the first instance however as technology evolved, they replaced their older antennas with more advanced antenna systems. Figure 5 illustrates an early cellular antenna system as deployed by Vodafone.

Figure 5: Early cellular antennas, as deployed for the analogue network, being reused to support GSM signals (2014).

A GSM base station contained duplex filters which allowed for transmit and receive paths to share an antenna and therefore the initial 900 MHz configuration consisted of two antennas on each 120^{o} sector. Sectors were typically designated A, B and C with antennas being identified as A1, A2, B1, B2, C1 and C2. Antenna 1 would typically be transmit and receive while antenna 2 would be receive only, providing the receive diversity to improve the uplink path budget.

3.3 Cell site design

Cellular radio site design is generally based on one of two cell site antenna configuration at initial deployment, the omni and 3 cell sectored site. An omni configuration is a site with a single RF path (a cell) which connects to a set of omni-directional antennas, one for Tx/Rx and one for Rx only. The antennas offer 360^o horizontal (also known as azimuth) coverage albeit the interaction between the two antennas does flatten the radiation pattern slightly. A typical vertical (also known as elevation) antenna radiation pattern beamwidth is 7^o. Figure 6 is an example of an omni-directional site. A three cell sectored site consists of three 3 separate RF paths, each providing coverage to 120^o. The three cell sectored site offers higher area capacity as each RF path and its associated number of transceivers (TRX) only has to service 120^o rather than the full 360^o. Another advantage of the sectored site configuration is coverage, the use of directional antennas means that higher gain can be achieved in the direction of transmission/reception and therefore the overall radio path budget allows the coverage to extend further than the lower RF gain of the omni site configuration.

Figure 6: 900 MHz GSM omni-directional cell site (2014)

The concept of omni and sectored sites is illustrated in Figure 7; this shows the full 360° horizontal coverage pattern of an omni site compared with the 3 x 120° coverage patterns of a three sectored site.

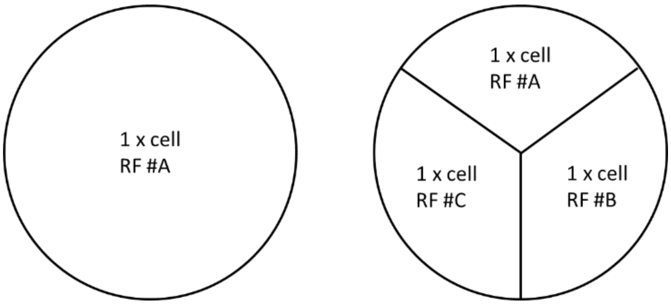


Figure 7: Representation of coverage in the horizontal (azimuth) plane of omni (left) and sectored (right) antenna configurations, including number of RF paths.

The RF path consists of a number of transmitters and receivers for the primary path and a number of receivers on the secondary (or diversity) path. For an omni or 1st sector of a sectored site, these are designated A1 and A2. The number of GSM transceivers was determined by the capacity forecast for the coverage area, in the early days of GSM rollout this would typically be 1 x TRX per cell, an omni site consists of 1 x cell per site whereas a 3 sectored site consists of 3 x cells. Whilst the capacity and coverage benefits of sectored sites is clear to see, they are far more expensive to implement given the additional transmitters and receivers, extra antennas and associated coaxial feeder cables along with a more expensive structure, typically a tower or head-frame on a rooftop, to support the antennas.

Figure 8 illustrates a typical 900 MHz GSM cell configuration. A number of transmitters are combined together via an RF combiner, in early systems these would typically be hybrid wide-band combiners and would support a small number (2 to 4) of transmitters. If the site was deployed as a single TRX cell the RF combiners would still be installed to enable easy capacity upgrade as and when appropriate and ensure coverage wasn’t lost when a second transceiver was added. The reason coverage could be lost is due to the attenuation of the RF combiner, typically 3dB for the hybrid combiner plus insertion loss, so 4dB was a typical total loss for a 900 MHz 2 port RF combiner. By adding this in from the beginning the site’s RF power budget could factor this in and therefore the overall network planning activity would be optimised. In the case of A1, the Tx/Rx antenna, the combined transmitter output would be connected to the same RF feeder cable as the primary receive path via a duplex filter. The duplex filter enables transmission and reception of the GSM frequencies and avoids any leakage of the high power transmissions into the sensitive receivers. The associated receive path consists of n x receivers, based on number of TRXs, and a receive multi-coupler which is an active amplifier to compensates for the splitting function of the signal received from the duplex filter to each of the receivers, effectively this cancels out the splitting loss as every dB is precious on the receive path. The diversity receiver is a similar to the main receive path with the exception of the duplex filter, as there is no transmit path to combine here.

Figure 8 illustrates just the RF components of the BTS, sitting below the TRX would be the digital signal processing which would manage the transmit and receive path, including realisation of receive diversity by selecting the strongest signal from either the primary or diversity receiver. Where multiple TRXs are deployed, slow frequency hopping would be managed by the baseband system to optimise RF performance.

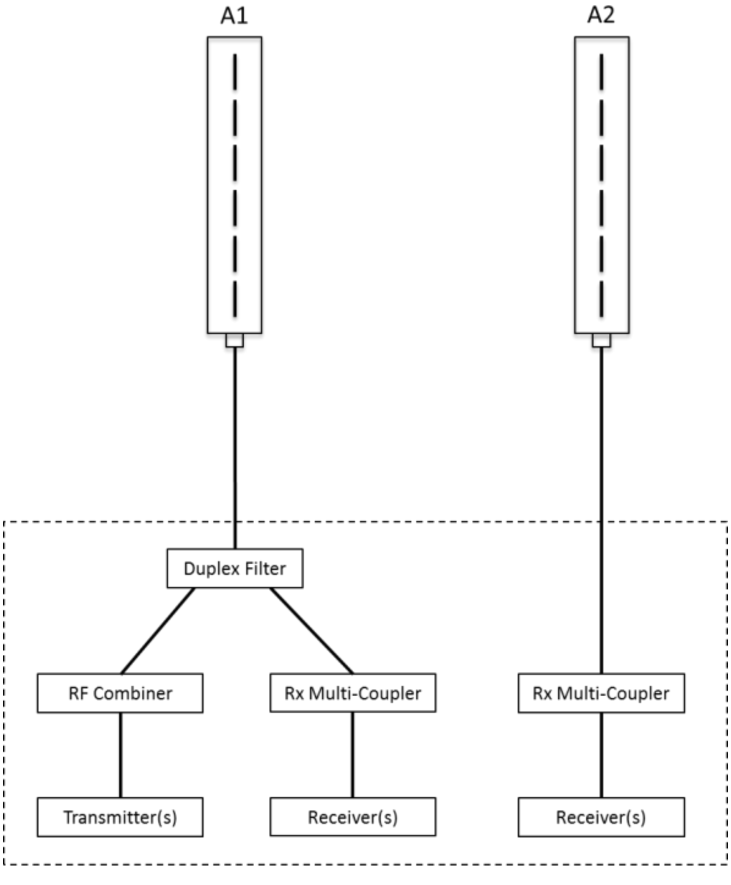


Figure 8: RF system configuration for 900 MHz GSM installation

An example of a 900 MHz GSM base station downlink link power budget (known as link budget) is calculated in Table 1 which shows that a maximum allowable path loss of -147dB could exist between the base station and MS.

Transmit power (BTS class 4)	+43dBm
Hybrid combiner and insertion loss	-4dBm
Insertion loss of duplex filter	-1dB
Coaxial feeder loss	-2dB
Antenna gain	+17dBm
MS receive sensitivity	-102dBm
Slow fading margin	-5dBm
Interference margin	-3dBm
Effective sensitivity	-94dBm
Maximum path loss	147dBm

Table 1: 900 MHz GSM downlink link budget.

Equation 1 is used to calculate free space pass loss:

$$32.44 + 20logF(MHz) + 20logD(km)$$

Equation 1: Free space path loss

From this equation it can be shown that 147dB of path loss equates to a distance far in excess of the 35 km cell radius imposed by the GSM standards TDMA radio interface. In reality there are many factors which impact this distance; these include atmospheric attenuation, diffraction, reflection, refraction and absorption. The uplink path, from the MS to the BTS must also be considered. The mobile phone will not transmit as much power as the base station as it runs on a battery and is held next to the head of the user, both limit the practical MS transit power and antenna gain. In a free space line of sight path the MS uplink budget would be less than the BTS downlink however this is not as much as may initially be thought, due to the improved receive sensitivity of the BTS, compared with the MS, and the diversity gain realised by the use of two receive paths at the BTS.

An example of a 900 MHz GSM base station uplink link budget is calculated in Table 2 which show that there is a 3dB difference in favour of the downlink.

MS transmit power (MS class 4)	+33dBm
Antenna gain	0dBi
EIRP	+33dBm
BTS sensitivity	-107dBm
Coaxial feeder loss	-2dBm
BTS antenna gain	+17dBm
Diversity gain	+3dB
Slow fading margin	-5dB
Interference margin	-3dB
Effective sensitivity	-111dBm
Maximum path loss	144dBm

Table 2: 900 MHz GSM uplink link budget.

Practical radio network planning is based on detailed propagation models such as Okumura–Hata (Okumara, Ohmori, Kawano, & Fukuda, 1968). Such models enabled reasonably accurate cell plans to be created from software based network planning tools however extensive drive and walk surveys were carried out to fine tune these models for the typical UK environments of dense urban, urban, sub-urban, rural and sparse rural.

Another consideration is the GSM specification itself. Due to the implementation of the TDMA radio interface which requires the use of a timing advance function, to ensure information arrives within a given time window despite the propagation delay, GSM limits the maximum cell radius to 35km. There is a GSM feature known as extended-cell which doubles this distance to 70km by halving the capacity of an extended cell TRX, therefore doubling the time duration of each TDMA slot. Extended cell feature was not widely deployed as in reality, sites needed to be closer than 35km because of other propagation restrictions, including the need for in-building coverage.

Original mobile phone networks were designed for outdoor coverage and initially were based on transportable phones which were mounted in vehicles and connected to an external antenna. The move to handheld mobile phones resulted in lower output power and effectively zero MS antenna gain, therefore reducing the performance of the link budget. The desire to use a mobile phone within buildings requires an external radio power planning level which takes into account the building penetration loss. Depending upon the materials of a given building this loss can vary typically from 10dB to as much as 30dB. Additional RF power budget is required to penetrate internal doors and walls. As a result of this, along with other losses, cell sites within urban and sub-urban areas were deployed much closer than the theoretical GSM maximum range of 35km.

Figure 9 shows the free space path loss for a 900 MHz signal out to the GSM 35km limit:

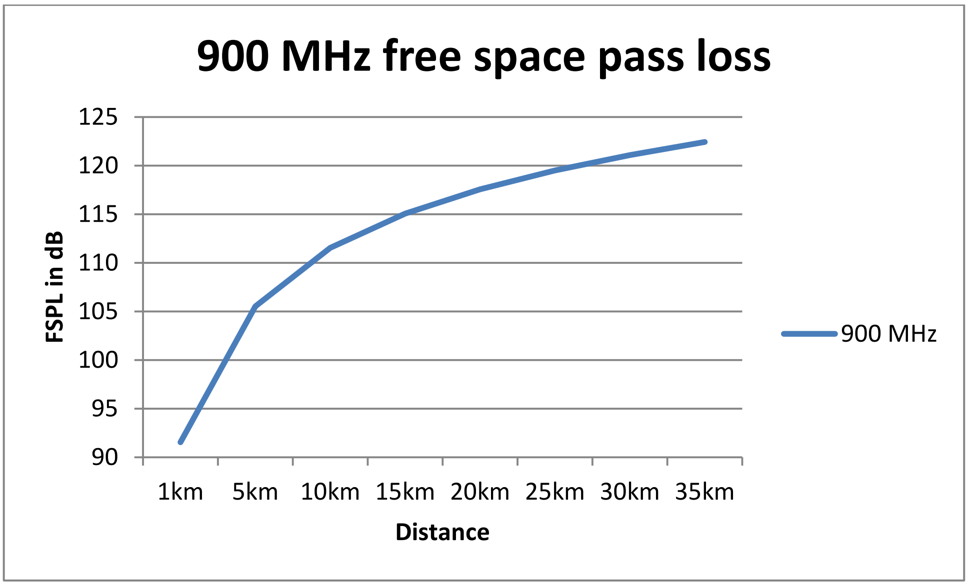


Figure 9: 900 MHz free space path loss between 1 and 35km

Rural cell sites would typically cover a much larger area than urban or sub-urban cell sites due to higher probability of line of sight and significant reduction in building density. As the number of mobile subscribers started to grow and their density in urban areas started to increase, coverage was not the only consideration for a mobile network operator. To manage an increasing subscriber density the MNOs had to increase their network capacity; at the cell site this meant adding new GSM TRXs and also sectorising existing omni sites to enable greater scalability. An interesting case study in cellular network capacity management is that of Mercury one2one whos aggressive go-to-market strategy generated significant volume of traffic on their network. Mercury also had to manage a network in the

1800 MHz band, as did Orange, and therefore required more cell sites for a given level of coverage than Cellnet or Vodafone.

3.4 Comparison of 900 MHz and 1800 MHz bands

Figure 10 illustrates the free space pass loss, out to 25km, for the 900 MHz and 1800 MHz frequency bands. It is noted that the delta is 6dB which, given the format of the FSPL calculation, is consistent irrespective of distance. GSM in the 1800 MHz band was originally known as the digital cellular system and whilst technically the same as GSM 900, it was expected to be deployed within urban centres rather than be used for wide area national coverage. The allocation of 1800 MHz only licenses to Mercury one2one and Orange changed this assumption. The DCS 1800 specifications defined lower BTS and MS transmit powers than GSM 900, this was particularly noticeable on the uplink as the maximum MS transit power was +30dBm. This lead to a greater imbalance between uplink and downlink than in many 900 MHz networks of the time which operated with +33dBm mobile phones.

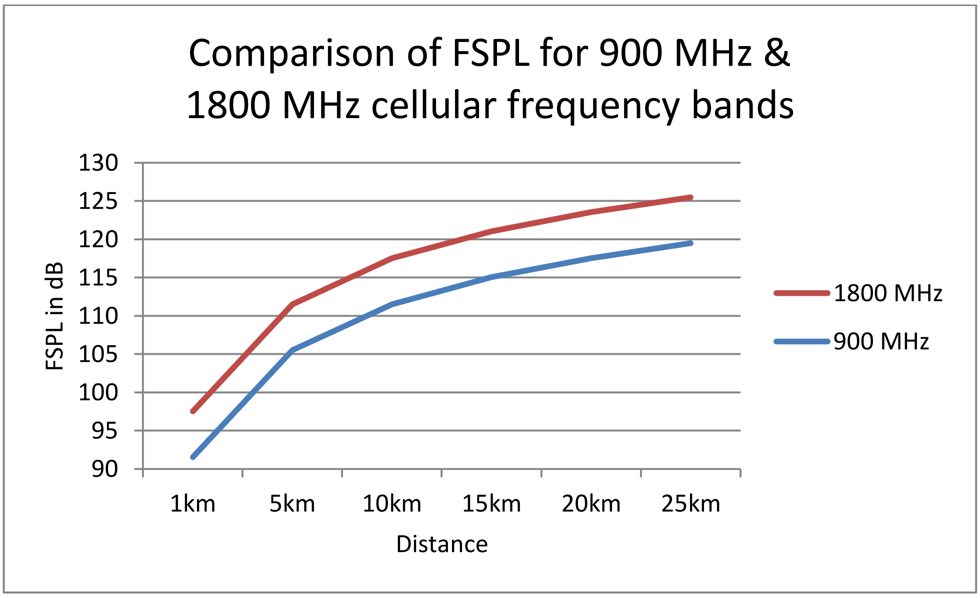
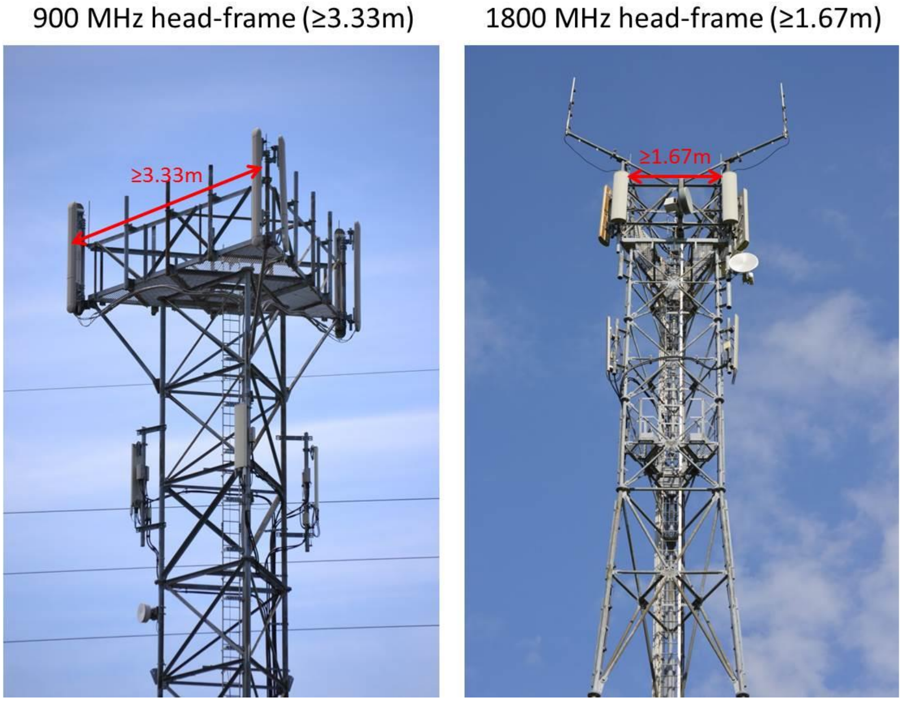


Figure 10: Comparison of FSPL for 900 MHz and 1800 MHz cellular frequency bands

As frequency increases the related wavelength reduces in size, the wavelength of a 900 MHz signal is 33.33cm while the wavelength of an 1800 MHz signal is half of this value, 16.67cm.

Given that space diversity antennas are spaced at a minimum of 10λ, the respective minimum head-frame size of a tower to support an 1800 MHz system is half the size, in the horizontal plane, as a head-frame to support a 900 MHz system.


900 MHz head-frame (≥3.33m)

1800 MHz head-frame (≥1.67m)

Figure 11: Minimum antenna spacing on towers with head-frames for 900 MHz and 1800 MHz [1] (2015)

Figure 11 highlights this by showing towers with head-frames for 900 MHz and 1800 MHz side by side, the red arrowed lines highlight the sector antenna face, i.e. A1 and A2. The supporting steelwork of the towers is of similar dimensions, the additional build out of the 900 MHz head-frame is very clear (typically greater than the minimum 3.33m spacing).

3.5 1800 MHz network rollout

As previously discussed , the UK licensed two DCS 1800 MHz network operators, DCS 1800 quickly became known as GSM 1800 and as such this term will be used for the remainder of this thesis. The two new operators were Mercury one2one and Orange (Orange was originally known as Microtel and then Hutchison Microtel). These two operators had to build out new networks rather than upgrade their existing networks, as was the case for the two 900 MHz operators. Mercury one2one and Orange adopted different go-to-market

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[1] Photo to highlight the relative sizes of head-frames only. Photos taken many years after initial deployments and antenna systems installed are not single band GSM space diversity systems. The ten wavelengths indicated is the minimum size, often the head-frame is wider than this (Orange GSM 1800 MHz was 2.6 metres wide).

strategies in terms of network coverage and tariffs, they initially implemented different antenna solutions. Mercury one2one deployed tower mounted low noise amplifiers from day one whereas Orange didn't. Orange did however retrofit tower mounted LNAs a short time after commercial launch.

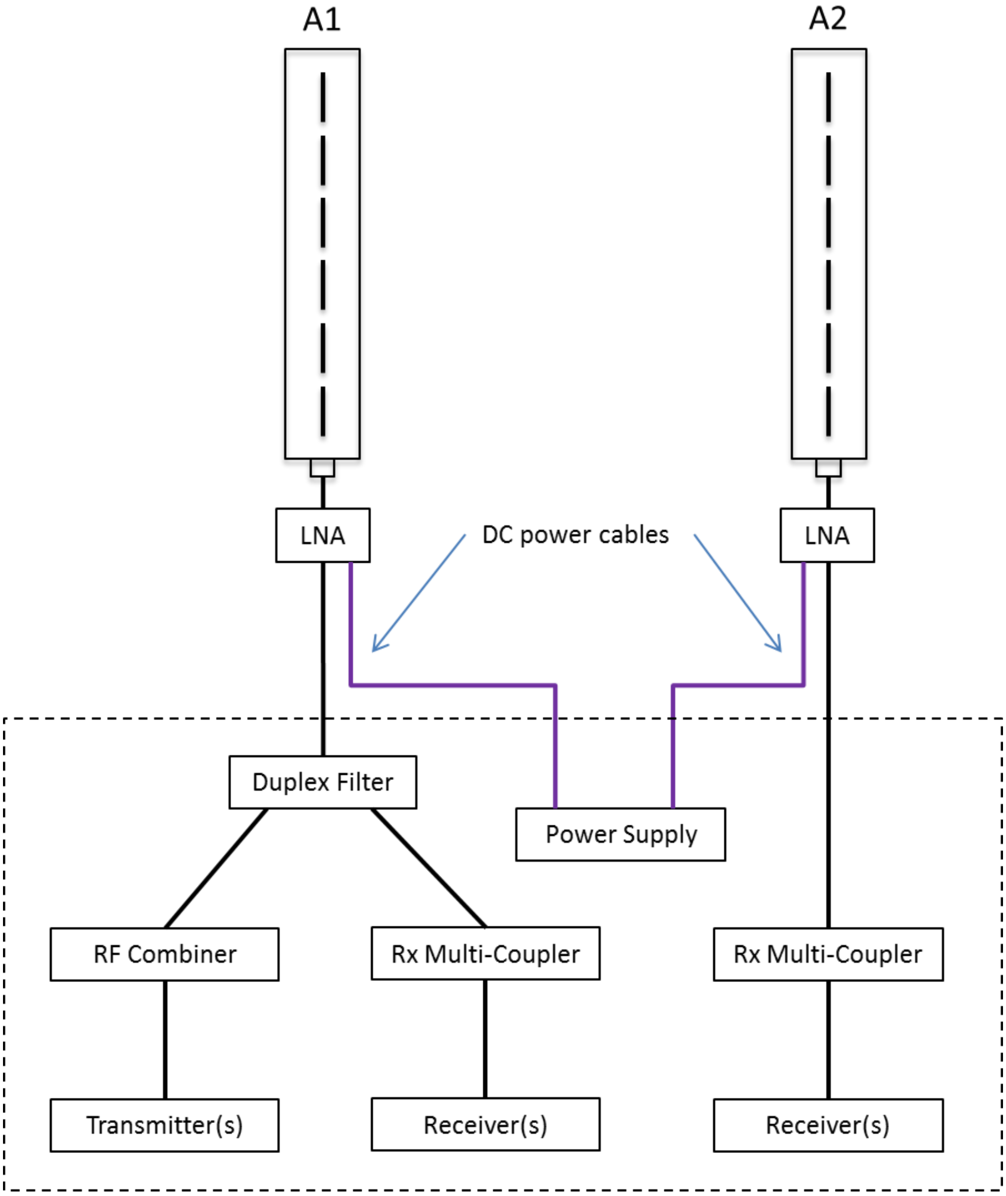


Figure 12: Mercury one2one configuration with tower mounted low noise amplifiers

Figure 12 illustrates the Mercury one2one RF path and antenna system configuration of their early installations. BTS equipment was provided by Ericsson and Nortel with a geographical split on a region by region basis, not a simple North/South split. The early LNAs were provided by Forum. In addition to LNA and Tower Mounted Amplifier, these units are also known as Mast Head Amplifiers, the three terms are used interchangeably within the cellular industry. Figure 13 is an early Mercury one2one cell site with original MHAs fitted, they were quite large units which required a DC power feed from the BTS equipment cabin and supported a single antenna, therefore six units were required for a three cell sector site.

Figure 13: Early Mercury one2one site with large MHAs (identified by red arrows (1998))

(Source: http://www.prattfamily.demon.co.uk/mikep/phot19.html)

The initial Orange site configuration was similar to that of the 900 MHz operators, given the 1800 MHz operating frequency the antennas were physically smaller than the 900 MHz antennas for a similar gain.

Figure 14: Early Orange cell site with Marconi antennas but no LNAs (1993) Source: Orange UK

Orange initiated a LNA retrofit system programme shortly after commercial launch and selected Forum as their supplier. Retrofitting LNAs to an existing site required the installation of a power distribution unit in the equipment cabinet which provided a DC power feed to each tower mounted LNA via a dedicated power cable. The main coaxial feeder cable had to be cut back to allow the insertion of the LNA in the RF path, a new coaxial tail was then added to complete the RF path to the original antenna. In addition to the DC power and coaxial connections, the LNA was connected to the main tower structure with an earth cable for electrical safety. The Orange LNAs were physically smaller than the original Mercury one2one units despite being from the same provider, they were simply a later variant.

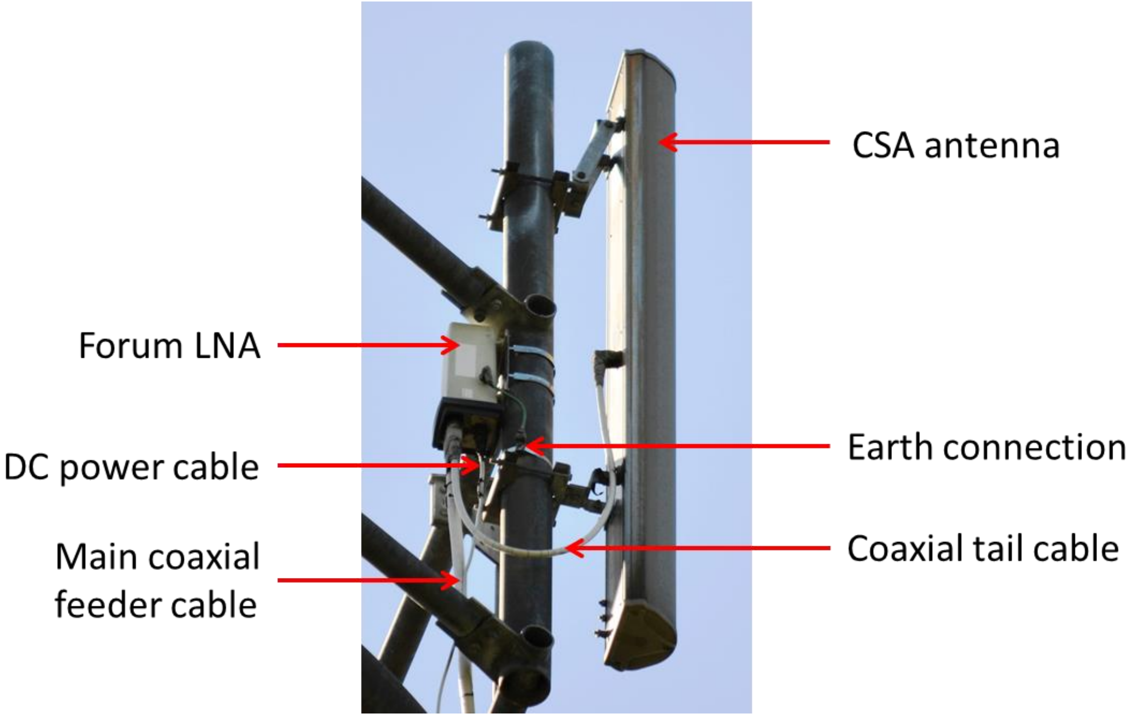


Figure 15: Forum LNA installation on Orange GSM 1800 MHz cell site (1999)

3.6 Mobile backhaul

An important aspect of cell site design is mobile backhaul which describes the connectivity between cellular radio base stations and the associated mobile network operator's core networks. Previously this was known as 'transmission' but during the 1990s, the term mobile backhaul was adopted.

GSM standards define the network architecture and interfaces between network elements. The BTS connects to the BSC via the Abis interface. The Abis interface, as with all original European GSM terrestrial interfaces, was based on the ITU-T standardised 2.048 Mbps frame, often referred to as an E1.

The interface between the BSC and core network is an interesting topic to review because whilst standardised, was subject to equipment manufacturers implementation of the GSM network architecture. The TRAU is a network component within the GSM BSS which connects to the core network of mobile telephone exchanges, generally known as the MSC. The MSC is a telephone exchange or switch with additional functionality to support subscriber mobility and authentication (VLR) which connects to the main subscriber register, the Home Location Register. The telephony switching function is based on E1 interfaces carrying traditional 64kbps A-law encoded PCM based digital voice signals, the Abis interface transports GSM coded voice which is 13 kbps and mapped with overheads to a 16 kbps sub-rate timeslot. The transcoder function of the TRAU converts between GSM coded voice and A-law PCM coded voice. The location of the TRAU determines where 16 kbps voice transmission or 64 kbps voice transmission is required, therefore it’s easy to understand the need for flexible placement of the TRAU to optimise a centralised or distributed BSC architecture.

Orange selected Nokia as the equipment vendor for its GSM 1800 network. The first base stations deployed in the Orange network were from the DF12 product range which consisted of indoor and outdoor variants, each of which could support 4 x GSM TRX. Typical configuration for the indoor rack was as 1 x TRX omni however quite often these would be connected to sectored antenna arrays via RF power splitters. The outdoor configuration required two cabinets to support the maximum configuration of 4 x TRX however these were most commonly deployed as three cell sectored sites in a 1+1+1 configuration. This refers to a single GSM TRX per 120 degrees of radio coverage. A single outdoor cabinet could be deployed for an omni configuration.

The Nokia BSC of the day was quite low capacity, supporting a maximum of 128 x TRX via Abis interface circuits. Based on the capacity of the BSC and the trunking efficiency which could be realised through a distributed BSC architecture, Orange decided to build remote BSC sites as aggregation nodes.

This distributed BSC architecture is illustrated in Figure 16:

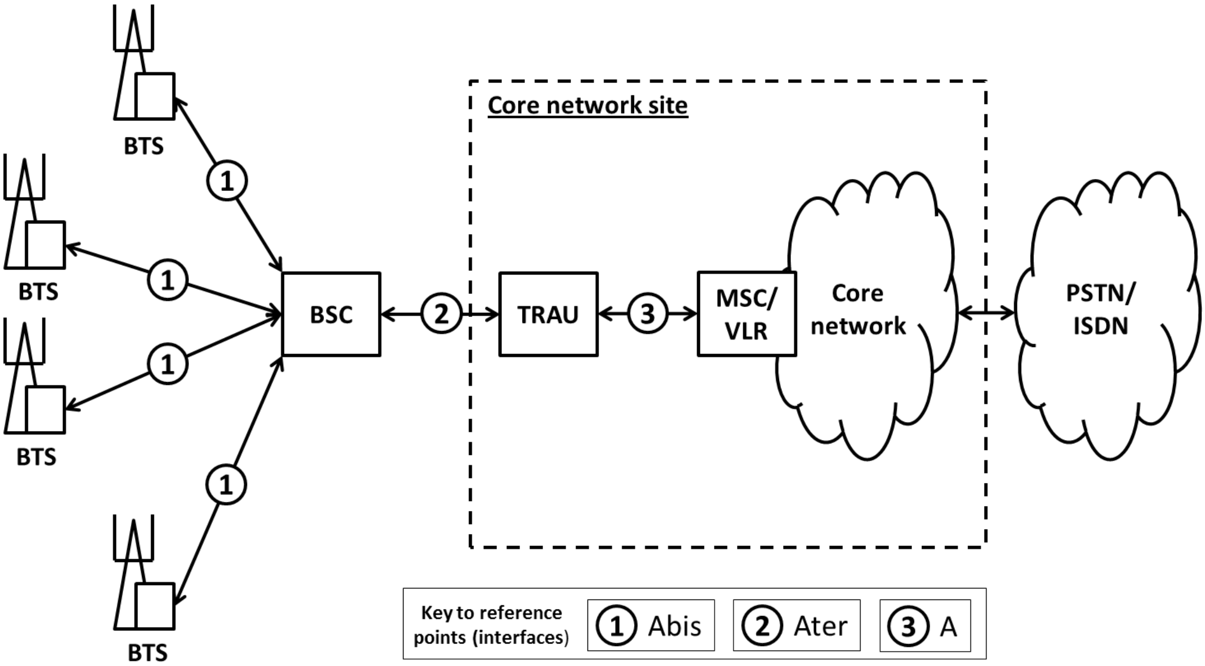


Figure 16: Distributed GSM BSC network architecture

In a distributed BSC architecture the BSC equipment is deployed to suitable geographical locations to support a number of locally connected BTS sites. The BSC also requires connectivity to the core network however rather than transmitting the Abis interface towards the core network site, the Ater interface is transported. There are pros and cons of both centralised and distributed BSC approaches, an operator will likely have deployed some centralised and some distributed BSCs. Those who selected a mainly centralised BSC architecture would typically have a small total number of higher capacity BSC platforms and have a need for careful management of Abis sub-timeslots on the transmission links between the BSC and distributed BTS sites. Operators who selected a mainly distributed BSC architecture would have more BSCs, typically lower capacity units however would gain from the statistical multiplexing gain of having BSCs acting as efficient switched concentrators to minimise the backhaul requirements towards the core network site.

3.6.1 Abis interface

To appreciate the backhaul transmission implications of a distributed BSC architecture requires a study of the Abis interface; there were some differences between equipment manufactures implementations however the examples which follow highlight the principles on which GSM backhaul transmission networks were designed.

The Abis interface of the Nokia DF12 GSM BSS carried the following traffic types

- Full rate voice traffic channels - mapped to 16 kbps sub-timeslots
- Transceiver signalling links - mapped to 64 kbps timeslots
- Operations and Maintenance (O&M) channel - mapped to a 64 kbps timeslot

The standard E1 frame is 2.048 Mbps and therefore supports 32 x 64 kbps timeslots (TS). TS0 is allocated for transmission link alignment and management (known as Frame Alignment Word/Not Frame Alignment Word (FAW/NFAW)) and is therefore not available to the Abis link. Consequently this leaves 31 x 64 kbps (1.984 Mbps) for the Abis payload. The BTS requires a 64 kbps O&M channel to download configuration information and manage alarms while the remainder of the payload is available for traffic channels and associated transceiver signalling. Each GSM transceiver has 8 x TDMA timeslots on the radio interface which map to 8 x 16 kbps sub-timeslots on the Abis interface. To support call setup and other TRX signalling activities a 64 kbps TRX signalling link is assigned for each TRX. Therefore; a single TRX requires 192 kbps [(8 x 16) + 64] of Abis transmission capacity. A complete E1 frame can support a maximum of 10 x TRX on a single BTS site (10 x 192 kbps + 64 kbps O&M channel + 64 kbps FAW/NFAW). As GSM has evolved equipment manufacturers have reduced the data rate required for TRX signalling to 32 kbps, even 16 kbps in certain cases, such that an increased number of TRXs can be supported on an E1 circuit; 12 x TRX became a common number for a single E1 to a single BTS site. Sites with a requirement for >12TRX will have n x E1 circuits delivered. A typical E1 Abis timeslot is illustrated in Figure 17, this examples is from a Nokia GSM BTS as deployed in the Orange network during the 1990s.

TS0	FAW/NFAW			
TS1	TRX1	TRX1	TRX1	TRX1
TS2	TRX1	TRX1	TRX1	TRX1
TS3	TRX2	TRX2	TRX2	TRX2
TS4	TRX2	TRX2	TRX2	TRX2
TS5	TRX3	TRX3	TRX3	TRX3
TS6	TRX3	TRX3	TRX3	TRX3
TS7	TRX4	TRX4	TRX4	TRX4
TS8	TRX4	TRX4	TRX4	TRX4
TS9	TRX5	TRX5	TRX5	TRX5
TS10	TRX5	TRX5	TRX5	TRX5
TS11	TRX6	TRX6	TRX6	TRX6
TS12	TRX6	TRX6	TRX6	TRX6
TS13	TRX7	TRX7	TRX7	TRX7
TS14	TRX7	TRX7	TRX7	TRX7
TS15	TRX8	TRX8	TRX8	TRX8
TS16	TRX8	TRX8	TRX8	TRX8
TS17	TRX9	TRX9	TRX9	TRX9
TS18	TRX9	TRX9	TRX9	TRX9
TS19	TRX10	TRX10	TRX10	TRX10
TS20	TRX10	TRX10	TRX10	TRX10
TS21	TRX SIG10			
TS22	TRX SIG9			
TS23	TRX SIG8			
TS24	TRX SIG7			
TS25	TRX SIG6			
TS26	TRX SIG5			
TS27	TRX SIG4			
TS28	TRX SIG3			
TS29	TRX SIG2			
TS30	TRX SIG1			
TS31	O&M			

Figure 17: Abis interface timeslot map within an E1 frame - Nokia DF12 BTS

3.6.2 Transmission technologies

There are a number of physical technologies available to extend an Abis interface from the BSC site to the BTS location. These include copper line based technologies, optical fibre and microwave radio systems. The capacity required of these transmission backhaul technologies will depend on the provisioned GSM radio interface capacity and network performance objectives, measured at the time against Erlang B as traffic was voice centric.

Considering the technologies in turn and applying them to the Orange GSM backhaul network of the 1990s. A new GSM cell site would either be provisioned with a single GSM TRX or with a three cell sector configuration, the backhaul requirements would therefore be 256 kbps [(8x16) + 64 signalling + 64 O&M] or 640 kbps [((8x16)+64)x3 + 64].

With the exception of mobile operators who were also the national incumbent fixed line operator, it’s unlikely that a new GSM operator would have access to raw copper or fibre cables. Therefore, to consume fixed backhaul services they would typically purchase leased lines from a fixed network operator, either part of the same company group, or in most cases from the national incumbent operator or a competitive challenger. Leased lines attract an upfront capital expenditure and on-going operational expenditure however it does effectively off-load some of the technical challenges of implementing backhaul solutions to a third party.

Early copper line technologies could support n x 64 kbps per copper pair and therefore with copper bonding a circuit of 2.048 Mbps could be delivered via High bit-rate Digital Subscriber Line (HDSL) technology over three copper pairs. As these copper line technologies developed the number of copper pairs required to deliver a given data rate decreased and/or the distance over which the service could reach was extended. Copper delivery was very common for n x 64 kbps and E1 based backhaul solutions when leased lines were ordered from the national incumbent.

Optical fibre based solutions can support significantly higher data rates than copper cables however the rollout of access and metro fibre transmission systems wasn’t very extensive in the 1990s. Given the low data rate requirements of the new GSM networks, fibre wasn’t essential in the backhaul transmission domain however there were some deployments in support of leased lines along with limited self-build from new GSM network operators. As traffic started to grow over the coming decade the use of optical fibre based communications would increase considerably.

Point to point microwave radio systems offer an alternative to wireline transmission and could be deployed by a fixed line provider as part of an end to end leased line or alternatively, directly by the mobile network operator to enable self-management of their mobile backhaul network. The decision to self-deploy microwave radio backhaul transmission was generally driven by an economic analysis, the total cost of ownership was generally lower than the combined CAPEX and on-going OPEX of leased lines.

3.6.3 Leased lines

The actual technology underpinning leased lines could be copper, fibre or microwave radio, as long as the leased line meets the performance criteria set out in the Service Level agreement, the fixed operator can implement the circuit with whichever technology is most appropriate to the particular deployment scenario. Given the geographical reach of the fixed network providing the leased lines, there could be a significant distance between the BTS and centralised BSC location. The leased line service may provide for aggregation of low speed access circuits, typically 256 kbps or 640 kbps per BTS site, to aggregate bearers based on n x E1 with a higher fill ratio towards the BSC. This aggregation is provided by TDM cross connect equipment which involves mapping at 8 kbps or 64 kbps.

A TDM leased line is effectively a transparent end to end connection over which the mobile service (i.e. Abis interface) is carried and the transmission network is under the operational control of the third party fixed network operator. Leased lines for GSM transmission may be n x 64 kbps or full 2.048 Mbps E1 circuits; this was determined during the transmission planning phase and depended upon network operator’s strategies and growth forecasts. Providing a full E1 would allow an operator to easily increase the number of TRXs on site by simply mapping the new sub-timeslots to the Abis interface, if the site had an n x 64 kbps circuit it would require an upgrade which would incur additional costs and therefore the local market conditions would determine the best approach. Generally a macro-cell base station, which provides wide area radio coverage, would be provided with a full E1 while micro-cells would often have n x 64 kbps circuits. It wasn’t unusual for early micro-cells to be limited to one or two TRXs with no upgrade path beyond this, therefore the network planner could be fairly certain that an upgrade was unlikely in the short to medium term as this would likely involve significant costs to swap out cabinets, BTS, etc.

TDM leased lines could be deployed for Abis and Ater interfaces in support of a distributed BSC architecture. There is a requirement for wide area connectivity between the cell sites and remote BSC location (Abis interface) and also between the BSC site and core network site (Ater interface). The BSC is effectively a switched concentrator and therefore requires significantly less capacity on the Ater interface than the sum of the Abis connection. The Abis interface is a direct and static mapping of TRX capacity to the backhaul; hence 128 kbps is required to support the 8 x TDMA timeslots from a single TRX which are mapped directly from the GSM radio interface to the backhaul. This direct mapping exists even though GSM TDMA TS0 on the air interface is typically used for radio interface broadcast control information and therefore doesn't actually send anything over the Abis interface, and likewise regardless of whether the other TDMA timeslots are carrying any actual user traffic. The Ater interface in contrast is more dynamic in its design and implementation, only carrying actual live traffic channels along with an amount of signalling to support call setup and BSC operation. The actual capacity requirements on the Ater interface are calculated in accordance with Erlang B theory and historically it was not uncommon for GSM MNOs to realise a statistical multiplexing gain of between 5 and 10 times when comparing the overall Ater load with that of the Abis. The distributed BSC leased line architecture is illustrated in Figure 18.

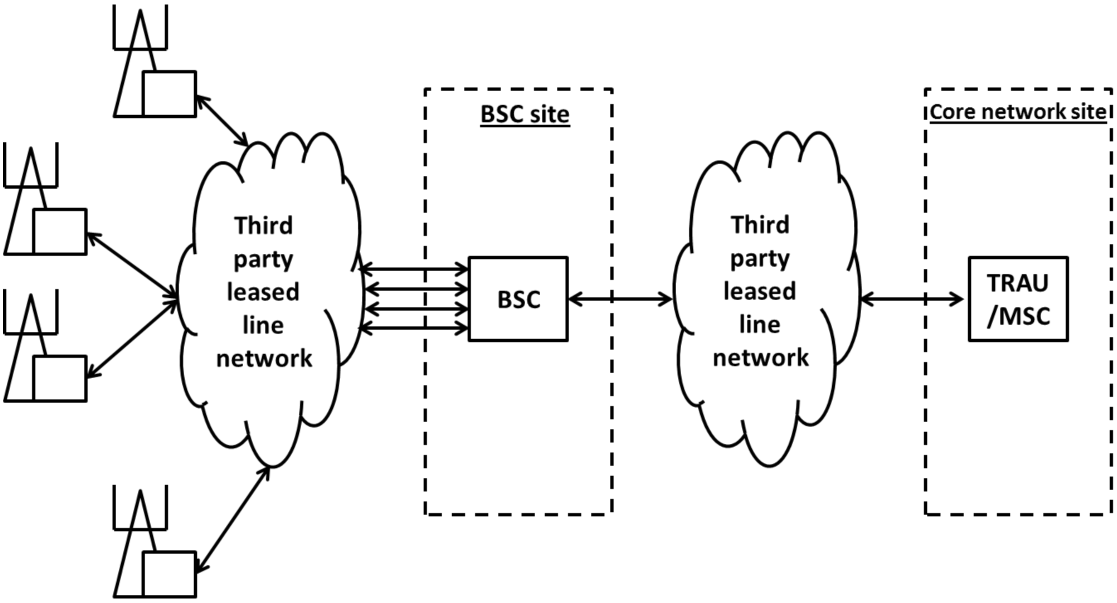


Figure 18: Distributed BSC architecture with backhaul transmission provided by E1 leased lines

The leased lines for Abis interface and Ater interface could be supplied by one or more fixed network providers with the MNO configuring the specific GSM interface mapping as appropriate. The connections between the BSC and core network will likely be implemented with higher availability through route diversity and redundant equipment to avoid a large scale geographical outage which could occur if an entire BSC or BSC site was lost due to transmission equipment failure or a copper or fibre cable break.

Whilst a leased line agreement allows an operator to off-load the responsibility for many aspects of the mobile backhaul network, it was typically more expensive than a self-provided solution based on microwave radio. The relatively limited capacity requirements of GSM (in comparison with current LTE networks) meant that point to point microwave radio systems were a viable alternative to leased lines in many networks. Self-provided microwave radio may not address 100% of mobile backhaul requirements however it would certainly address a high percentage and therefore reduce the MNO's overall TCO. Consequently GSM networks with up to 90% microwave radio backhaul connectivity were not uncommon.

3.6.4 Microwave radio

Point to point microwave radio links typically provided n x E1 of capacity where 'n' could be 1, 2, 4, 8 or 16. The multiplexing within the radio systems was based on the Plesiochronous Digital Hierarchy (PDH) of 2 Mbps (1 x E1), 8 Mbps (4 x E1) and 34 Mbps (16 x E1) with additional rates of 4 Mbps (2 x E1) and 16 Mbps (8 x E1). Whilst PDH type multiplexing took place within the radio baseband unit, the interfaces were always n x E1, effectively implementing skip-multiplexing between the traditional PDH process of 4 x E1 to an E2 (8.448 Mbps) interface and 4 x E2 interfaces to an E3 interface (34.368 Mbps). This enabled a simple and consistent network interface based around the primary building block of the 2.048 Mbps E1 circuit.

Microwave radio systems of the early GSM era had evolved from all indoor solutions (the active radio electronics was installed in the cabin next to the tower with an external waveguide connection to the antenna) for all frequency bands to split-mount systems with a component installed within the base station cabin (In-Door Unit or IDU) and an outdoor module (Out-Door Unit or ODU). The ODU could be installed at the base of the tower, on the tower close to the microwave antenna, or directly attached to the antenna. All indoor radios were still supplied for lower frequency bands and certain early implementations of higher capacity systems. The indoor component was either a baseband module or a combined baseband and modem module, the latter becoming the norm over time. The interconnection between the two modules would be a pair of coaxial cables and quite often, a separate DC power cable. Some manufacturers provided DC power over the coaxial cables and over time, a single coaxial cable system would be adopted for all requirements; transmit and receive intermediate frequencies, DC power and telemetry.

The number of E1 circuits and modulation scheme would dictate the RF channel bandwidth of the microwave radio system. Typical access microwave radio systems of the 1990s used 2 or 4 level FSK or QPSK. International standards for RF channel bandwidths were set for the original PDH data rates with intermediate steps added as shown in Table 3.

Data rate	Modulation scheme	Channel bandwidth
1 x E1	2 FSK	3.5MHz
2 x E1	4 FSK / QPSK	3.5MHz
4 x E1	4 FSK / QPSK	7MHz
8 x E1	4 FSK / QPSK	14MHz
16 x E1	4 FSK / QPSK	28MHz

Table 3: PDH microwave radio configurations

In addition to data rate, modulation scheme and channel bandwidth, another important consideration when planning a microwave radio link is the frequency band in which to operate. Prior to GSM it is reasonable to say that most microwave radio systems operated in bands between 4 GHz and 23 GHz. The introduction of a mass market for microwave radio based mobile backhaul resulted in a significant investment in research and development in the field of microwave radio engineering. This investment returned higher frequency radios, improved mean time between failures as well as ever greater system capacity and spectral efficiency; all trends which continue today. The distance between cell sites can be quite short so higher frequency radios offering link lengths of several kilometres were well suited and offered a high frequency reuse factor. Hence, 38 GHz became a popular band and in some countries was allocated to MNOs for self-managed mobile backhaul implementation. Assignment of managed spectrum enabled a faster and often cheaper rollout of microwave transmission, the alternative being a per link licence application to the national authority responsible for assigning spectrum. Once a frequency channel assignment is granted there is an associated annual licence fee which becomes an OPEX for the mobile network operator. This OPEX along with any annual site rental plus operations and maintenance costs must be added to the cost of the microwave equipment, installation and commissioning costs, to derive the overall total cost of ownership of the microwave radio system. This overall TCO can be compared with the TCO of third party leased lines to enable an operator to set their backhaul transmission network strategy.

3.6.5 Network planning

The fundamental decision of centralised or distributed BSC architecture will have an impact on the capacity requirements of the microwave radio backhaul network however it won’t have a major impact on the microwave network topology. The frequency band to be used will be determined by a link planning process which will consider link length, data rate, modulation scheme, channel bandwidth, radio equipment specifications for transmitter output power and receiver sensitivity, structural loading of antenna supporting structure, proposed location of RF transceiver/ODU, target atmospheric availability and equipment configuration.

Link length is the direct line of sight distance between the two ends of a microwave radio link. Point to point microwave radio systems are said to require a clear line of sight between the two ends of the link, the actual technical requirement is based on achieving a minimum of 60% clearance of the first Fresnel zone. Links between two microwave antennas are often drawn as straight lines (as in the diagrams in this thesis) or as lightning bolts; both sufficiently represent connectivity however in reality it is essential to appreciate that the transmission is in fact an expanding wavefront on which every point source conforms to Huygens’ principles. As a result of this it is necessary to maintain at least 60% Fresnel zone clearance to avoid significant diffraction which would result in a significantly attenuated received signal.

The data rate of the radio must meet or exceed the minimum demands of the Abis interface. In the case of a distributed BSC architecture; microwave radio may also be used for the Ater interface. During the 1990s the modulation scheme was set based on data rate and this dictated the channel bandwidth, however modern systems offer a greater flexibility to the network planner. The maximum transmit output power would typically be lower for higher frequency systems; a 38 GHz radio would typically have a maximum output power of +16dBm or +17dBm while a 7.5 GHz radio system would have an output power of +30dBm. The actual transmit power would be set to a level ≤maximum transmit power. Receiver sensitivity gets worse as the channel bandwidth increases; typical receiver sensitivity for a 1 x 10^{-6} bit error rate on a 38 GHz radio was around -87dBm in a 3.5 MHz channel with 2 FSK modulation, rising to about -72dBm in a 28 MHz channel with 4 FSK modulation. This means that upgrading the capacity of a link from a lower capacity to a higher capacity may not be possible in the same frequency band, with the same sizes of antennas, depending on how much head-room was available to turn up the transmitter output power.

Microwave antennas are parabolic by design and often referred to as dish antennas; sizes vary from 0.2 metres up to 4.6 metres although the smallest sizes are not possible in the lower microwave frequency bands. The objective was and is still today to balance the wind loading of the antenna on the supporting structure with the need to use as high a frequency band as possible, to ensure a channel is available and maximise frequency reuse.

The ODU is generally installed outside (configuration 1 in Figure 19), either at the base of the tower, on a working platform close to the antenna or directly mounted on the back of the microwave antenna (configuration 2 in Figure 19). There are pros and cons of these approaches. Mounting the ODU at the base of the tower allows easier and quicker access for maintenance in the event of a fault however it comes at a technical and commercial cost. The ground mounted ODU will require a waveguide to provide connectivity to the antenna which is likely some tens of metres up the tower. This waveguide is expensive and introduces attenuation, the amount of attenuation increases with frequency and therefore it’s very unlikely that higher frequency systems will be installed with waveguide. As an example, 20 metres of 7.5 GHz will introduce 1.2dB of attenuation while 20 metres of 23 GHz waveguide will introduce 5.6dB of attenuation. Waveguide above 26 GHz isn’t commonly available for long waveguide runs however short lengths of flexible waveguide are available to aid installation when an ODU is mounted very close to the antenna. From a microwave radio link engineering perspective the integrated ODU/antenna mount arrangement is ideal; there is no need for any waveguide as the ODU is directly coupled to the antenna so system loses are minimised and therefore the maximum link length for a given frequency band with a given size of antenna is achievable.

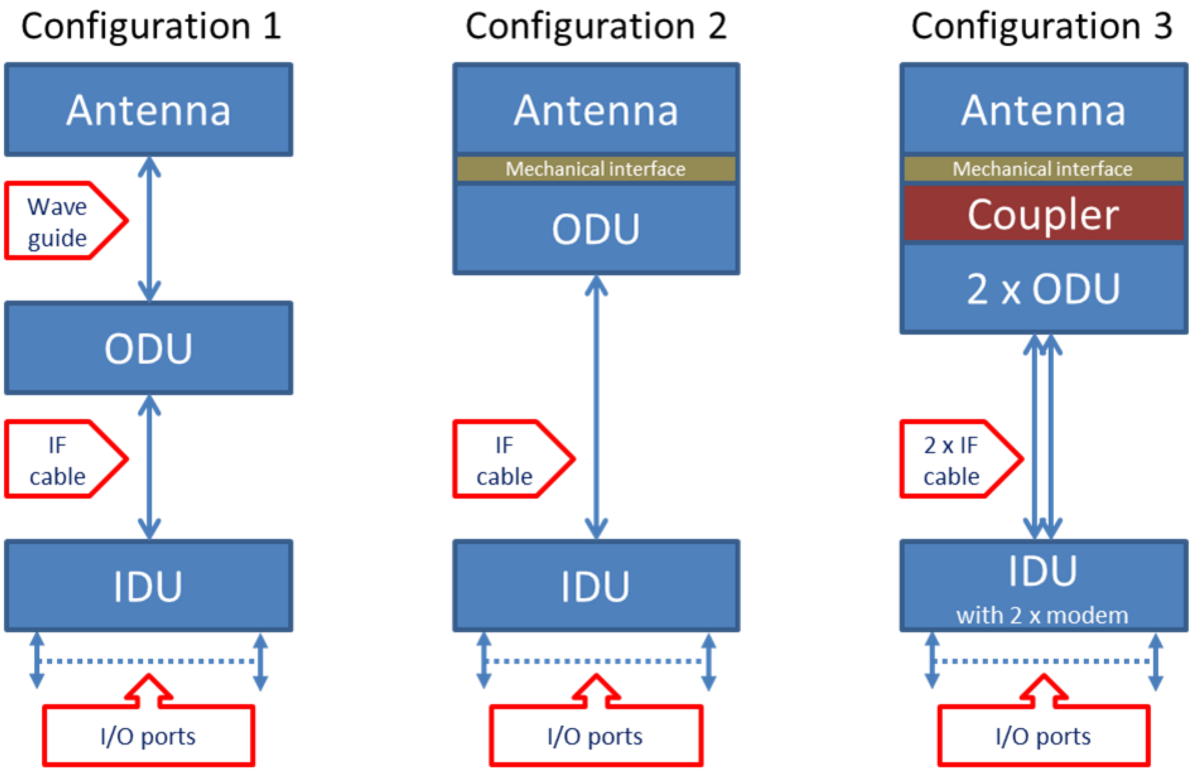


Figure 19: Point to point microwave radio configurations (Sutton, Radio Systems, Microwave and Millimetre Wave, 2015)

Atmospheric availability is typically referred to as an uptime percentage such as: 99.99%, 99.995% or 99.999%. This refers to the duration in which the link will operate within a given atmospheric environment (usually per annum); the actual atmospheric influences fall into two main categories, atmospheric ducting and multipath for lower microwave frequency bands and attenuation due to precipitation in bands typically above 15 GHz. The various losses are calculated by the network planning engineer for a given link location and a fade margin is produced based on the required atmospheric availability. This fade margin is the difference between the received signal level under normal operating conditions and the point at which the background bit error rate reaches 1 x 10^{-6}. Beyond this point a digital microwave radio system quickly drops off in performance and effectively fades out such that the link is no longer available. The fade margin effectively defines the level of headroom required in the received signal in order for the link to adequately meet its designed atmospheric availability.

Microwave radio systems for GSM backhaul were typically deployed as 1+0 (configurations 1 and 2 in Figure 19), or 1+1 configurations (configuration 3 in Figure 19). This refers to the equipment redundancy mode: 1+0 is a single radio system with one IDU and one ODU while 1+1 is a protected or duplicated radio system with two IDUs and two ODUs. If a modem or RF transceiver failed on a 1+1 system the second unit would take over, often in a hitless or near hitless manner such that the GSM services carried over the microwave link are unaffected. 1+0 links were the norm however 1+1 links were deployed in certain circumstances.

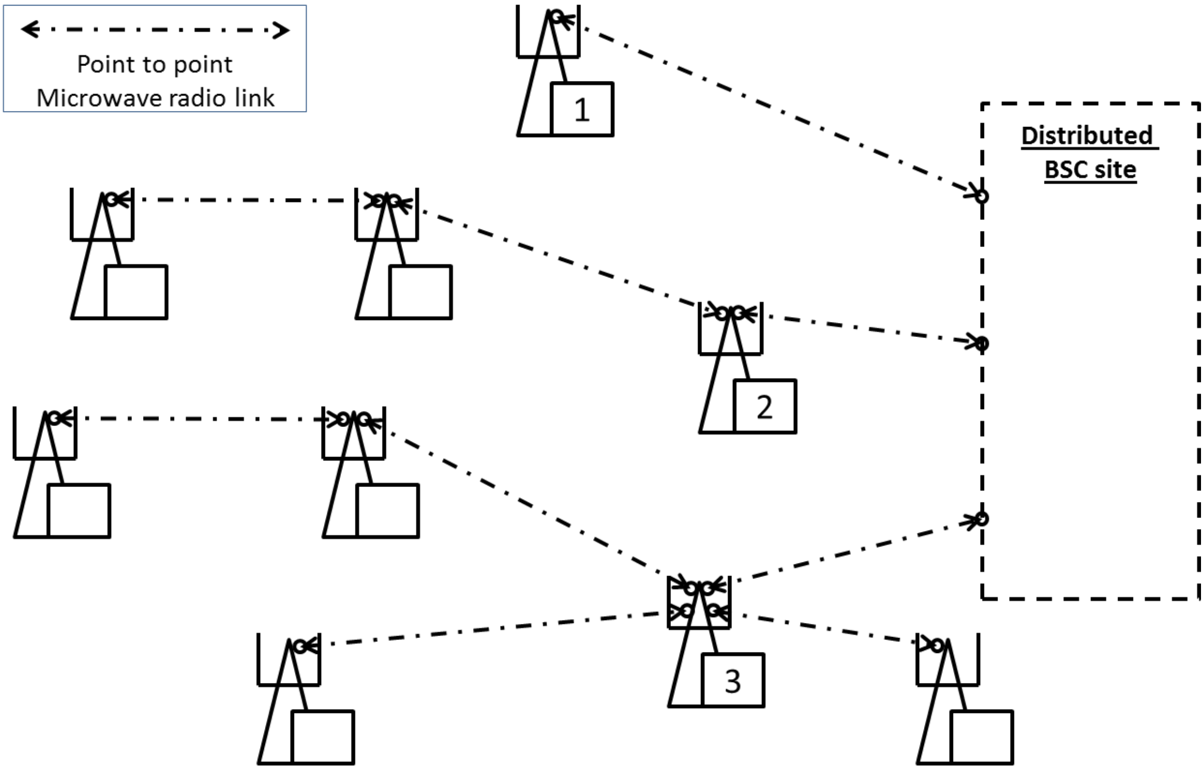


Figure 20: Microwave radio backhaul transmission topology

Figure 20 can be used to discuss both a centralised and distributed BSC architecture with microwave radio backhaul however the focus here is on a distributed BSC architecture as deployed by Orange. The diagram is a very simplified representation for the purpose of clarity, in reality the BSC site will be located at the centre of a large area of geographical coverage and have microwave radio links, or leased lines, connecting in all directions. The diagram has three microwave links (represented by long/short dashed lines) connecting between the BSC site and BTS sites, the first BTS site they connect to are numbered 1, 2 and 3.

BTS site 1 is on a direct point to point link to the core network site, a 1990s GSM BTS site would typically require <1 x E1 and therefore this link could be a 1 x E1 radio or more likely, a 2 x E1 radio. The cost difference between the two capacity variants is minimal however the 2 x E1 link will allow for a further site to be connected (sub-tended via a new microwave radio link) in the future, as network rollout continues or, to support capacity growth at site number 1. BTS site number 2 is the start of a chain of three links and is therefore acting as a relay site for the two sites behind it. This relay function could be required because the other sites have no direct line of sight to the core network site, or, because higher frequency radio equipment with smaller antennas can be used for the shorter hops, therefore saving cost in the overall TCO calculation. The link between the BSC site and site number 2 could be a 2 x E1 radio if sub-multiplexing was used (where the E1 frame is shared between several sites). Sub-multiplexing was implemented by some MNOs, however the cost of a 4 x E1 radio was not significantly higher than a 2 x E1 radio and would simplify site configuration and save the costs for the extra equipment along with planning and configuration work associated with sub-multiplexing.

The topology associated with BTS site number 3 is rather more complex. This site supports four sub-tended sites and therefore the link from the BSC site must support five Abis connections. A 4 x E1 radio could be used with sub-multiplexing at site number 3, this was quite a common approach during the early days of GSM with multiplexing equipment capable of mapping traffic at bit level between E1 frames. Another option would be deploy a radio with at least 5 x E1, in this case the closest match would be an 8 x E1 radio although these didn’t become available until mid-1990s as the aggregate rate wasn’t a standardised PDH interface. The only option before this would have been to deploy a 16 x E1 radio and as these were significantly more expensive than a 4 x E1 radio, sub-multiplexing may well have been cheaper, particularly if the number of sites connected to site number 3 would increase as network rollout continued. Given that five sites are dependent on the link between site number 3 and the core network site, the network planning engineer would review the design of this link and likely increase the atmospheric availability and/or implement 1+1 equipment protection on the radio hardware.

Figure 21: BSC site with point to point microwave connectivity for Abis and Ater interface circuits (2014)

From the previous discussion it is clear that a centralised BSC architecture will require higher capacity microwave links (or leased lines) from the core network site than the distributed BSC architecture, it was also not uncommon for mobile network operators to use a mix of leased lines and microwave, picking the most suitable based on a techno-economic analysis on a per site basis. The centralised architecture drove an early adoption of links operating in the Synchronous Digital Hierarchy; these radio systems offered a significant capacity uplift as they operated at Synchronous Transfer Module - level 1 (STM-1) of 155.52 Mbps. Once overheads were removed the STM-1 radio could carry 63 x E1 circuits however unlike the PDH radios they required an external multiplexer to break the E1s out from the aggregate line rate.

3.6.6 Frequency synchronisation

A less obvious role of the backhaul network is the delivery of network synchronisation to support the cellular mobile radio network. A TRX must operate on a specific RF channel as allocated during the network planning process and it is essential that this radio transmission occurs at the correct frequency and therefore the oscillator in the TRX will require a source of reference. The simplest way to discipline the oscillator with a suitable reference is to use the deterministic 8 kHz clock source which can be derived from the incoming 2.048 Mbps signal. A 2.048 Mbps signal is by definition synchronous given the exact placement of timeslots in time, within the frame structure. This reference signal is available due to the use of the HDB3 line code on the standard E1 frame and this is sufficient to deliver a frequency accuracy of +/-16 parts per billion which will ensure the GSM TRX meets the radio interface requirements of +/- 50ppb. The E1 sync signal will ultimately be traceable to an IUT-T G.811 frequency source in either the mobile operators network or leased line providers network. Whilst this results in multiple sources of frequency synchronisation the overall mobile system performance meets 3GPP requirements as all sources are conformant to the international specification, this results in a network that is pseudo-synchronous.

3.7 GPRS

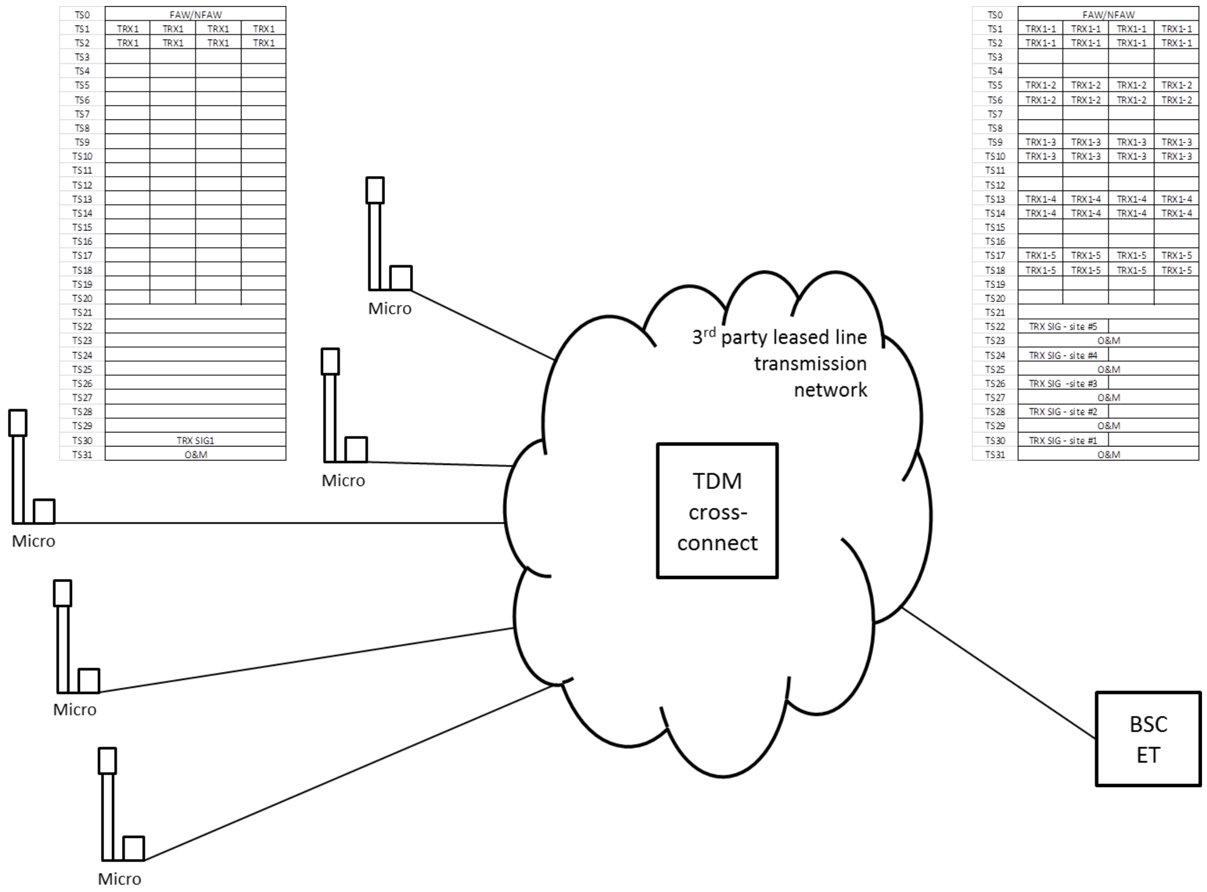
The introduction of General Packet Radio Service to GSM resulted in a significant changes to the mobile network architecture. GPRS was developed during the late 1990s and the world’s first GPRS network was launched in the UK by BT Cellnet (now O2) in June 2000. This launch was quickly followed by many other operators who could see the potential to develop new data services over GPRS packet data bearers. From a mobile backhaul perspective the Abis link would remain however it would now be modified to support packet data. It would also require mechanisms to enable the co-existence of circuit switched traffic and packet based data traffic. The most significant architectural change occurred within the core network however the BSC would have a new architectural peer called the Packet Control Unit. The PCU was implemented as a number of plug in units in the BSC by most vendors although some did implement the functionality as a standalone module. Whilst GPRS traffic shared the Abis interface it did not share the Ater interface, a new interface was specified between the PCU and new packet switched core network, the Gb interface was a narrow-band data networking interface based on Frame Relay (FR) technology. Very few operators actually implemented a FR network in support of Gb interface connectivity to the packet core network. In most cases MNOs chose to simply map FR over n x 64 kbps timeslots or allocate n x E1s, depending on capacity requirements. As the demand for data communications on the mobile network increased it was clear that GSM wouldn't scale to meet future demand. To address this concern two things happened in parallel; a higher capacity radio interface was developed for GPRS, known as EDGE which would further modify the Abis interface and result in greater capacity demands on the Gb interface, and, the specifications for the UMTS were developed. UMTS would be commonly known as 3G and would result in significant changes to the mobile backhaul network. The introduction of UMTS in parallel with GSM/GPRS forms the basis of the two research questions answered in the following chapters of this thesis.

3.8 Micro-cells

In addition to the large rooftop or tower mounted macro-cell base stations, a number of micro-cells were deployed. These micro-cells served two purposes, they were used to add radio capacity to an area of high-demand and also to provide coverage where small gaps existed within the cellular coverage map. The Orange micro-cell sites typically consisted of a single cabinet with initially a 1 TRX capacity and then later, 2 TRX capacity became available. The sites could be mounted on the sides of buildings or alternatively on relatively short columns, often designed to look like lampposts, in some cases the antenna system was integrated with a real-lamppost. Figure 22 contains two micro-cell installations, the left is a 1 TRX Nokia PrimeSite cabinet while the deeper cabinet on the right contains a 2 TRX Nokia Flexi-BTS.

Figure 22: Micro-cell installations with lamppost like columns (left image 1999, right 2015)

By the nature of their design the micro-cell column could not support the weight of a microwave radio antenna and as such is connected by a leased line. Given the low capacity of these GSM installations they would typically have been connected with copper lines using HDSL technology. The micro-cell backhaul service which Orange purchased was based on n x 64 kbps at the micro-cell and aggregate E1 bearers at the BSC site. This approach enabled several micro-cells to be combined via timeslot mapping onto a single E1 circuit which reduced the number of BSC E1 ports, known as Exchange Termination (ET) ports and therefore reduced the overall cost of deploying micro-cell sites. The micro-cell backhaul configuration is shown in Figure 23.



TS0	FAW/NFAW			
TS1	TRX1	TRX1	TRX1	TRX1
TS2	TRX1	TRX1	TRX1	TRX1
TS3				
TS4				
TS5				
TS6				
TS7				
TS8				
TS9				
TS10				
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TS26				
TS27				
TS28				
TS29				
TS30	TRX SIG1			
TS31	O&M			

TS0	FAW/NFAW			
TS1	TRX1-1	TRX1-1	TRX1-1	TRX1-1
TS2	TRX1-1	TRX1-1	TRX1-1	TRX1-1
TS3				
TS4				
TS5	TRX1-2	TRX1-2	TRX1-2	TRX1-2
TS6	TRX1-2	TRX1-2	TRX1-2	TRX1-2
TS7				
TS8				
TS9	TRX1-3	TRX1-3	TRX1-3	TRX1-3
TS10	TRX1-3	TRX1-3	TRX1-3	TRX1-3
TS11				
TS12				
TS13	TRX1-4	TRX1-4	TRX1-4	TRX1-4
TS14	TRX1-4	TRX1-4	TRX1-4	TRX1-4
TS15				
TS16				
TS17	TRX1-5	TRX1-5	TRX1-5	TRX1-5
TS18	TRX1-5	TRX1-5	TRX1-5	TRX1-5
TS19				
TS20				
TS21				
TS22	TRX SIG - site #5			
TS23	O&M			
TS24	TRX SIG - site #4			
TS25	O&M			
TS26	TRX SIG -site #3			
TS27	O&M			
TS28	TRX SIG - site #2			
TS29	O&M			
TS30	TRX SIG - site #1			
TS31	O&M			

Figure 23: Micro-cell Abis backhaul

Each micro-cell in the scenario described in Figure 23 is a 1 TRX base station with a n x 64 kbps transmission circuit between the cell site and third party leased line provider's transmission network. In the example shown in the timeslot map, top left of Figure 23, the micro-cell requires 128 kbps for timeslots from the GSM TDMA radio interface, 32 kbps for TRX signalling and a 64 kbps timeslot for an operations and maintenance channel. The 32 kbps TRX signalling links is an optimisation on the 64 kbps links which were used for the original (earlier) Nokia GSM BTS configuration. The timeslot map shown top right of Figure 23 is the aggregate of the 5 micro-cells and would be configured on the BSC ET card. The mapping between access and aggregate circuits allows for upgrades from 1 to 2 TRX per micro-cell, as and when capacity dictates. Whilst the upgrade is quite simple for a transmission perspective, there was a significant cost associated with upgrading the micro-cell cabinet and associated base station equipment. Later micro-cell sites were deployed with 2 TRX equipment from day 1 and simply provisioned with 1 TRX until the second TRX was required.

3.9 Ater and Gb interface

Given the geographical distribution of BSC equipment in the Orange network it is necessary to support Ater and Gb interface circuits on backhaul like infrastructure between the remote BSC site and the core network site. These interfaces were implemented with n x E1 circuits using the same underlying technologies as used for Abis interface circuits. The key difference is the availability of the Ater and Gb interface circuits must be higher than an individual Abis circuit given the aggregate traffic load and importance of the BSC to wide area geographical coverage.

3.10 Summary

Chapter 3 has reviewed GSM technology, discussed the introduction of GSM to the UK and explained cell site radio design. With an understanding of cell site design the chapter went on to explore the requirements of mobile backhaul and explained the application of copper line, microwave radio and optical fibre communications. TDM was reviewed in the context of the GSM terrestrial interfaces with particular emphasis on the Abis interface between the GSM BTS and BSC. The introduction of GPRS was reviewed and the implications on the BSC and core network considered, this was then considered in the context of remote BSC to core site connectivity requirements. Chapter 4 assumes the baseline explained in chapter 3 to be the starting point for overlaying UMTS on an established GSM and GPRS network. The first research question is examined and the research leading to a technical and commercially viable solution is explained.

4. Designing a 2G/3G converged mobile backhaul network

4.1 Introduction

The baseline review concluded with chapter 3, the thesis now moves on to the actual research and network design phase. This chapter starts with the author's analysis of the UMTS eco-system, details the spectrum available to Orange in the 2100 MHz band and reviews the relevant 3GPP standards. The implications of the choice of ATM as the 3G transport network layer technology is studied along with the UTRAN vendors equipment specifications. The detailed technical research conducted by the author is presented along with design considerations, additional vendor selection and outcomes, including the network strategy, target architecture and high-level designs to address the first research question; How is it possible to evolve a GSM/GPRS mobile backhaul network to support a converged GSM/GPRS and UMTS cellular mobile service? When the research question was asked there were no reference networks anywhere in the world. The author, in his role as Principal Network Designer, was tasked with this research which resulted in a new and innovative mobile backhaul network architecture and design. Tasks completed by the author included; analysing the 3GPP UMTS specifications, understanding the vendors UTRAN products, modelling the backhaul network capacity requirements, developing the target architecture and producing the high-level design.

4.2 Background

The 3G story, like 2G before it, started prior to the commercial launch of its predecessor. ETSI established a Special Mobile Group known as SMG5 in 1991 to explore the standardisation of a third-generation mobile communications system to be known as the Universal Mobile Telecommunications System. As part of an agreed global radio frequency assignment for UMTS, the 2100 MHz band was identified for 3G use in the UK. The initial release of the 3G standards, known as Release 99, was published in 1999 however it was not until the year 2000 that the UK held an auction for 3G spectrum in the 2100 MHz band. The spectrum auction was managed by the Radio Communications Agency (now an integral part of Ofcom) and commenced on the 6th March 2000. The use of an auction as a technique to allocate radio spectrum was new to the UK, 2G licenses had been awarded based on an assessment of the quality of proposals received from interested parties, as had been the case with the original licenses awarded to Cellnet and Vodafone to enable the operation of the analogue TACS networks. The Radio Communications Agency described the reason for this new approach as follows:

“Auctions are a fast, transparent, fair and economically efficient way of allocating the scarce resource of radio spectrum. Government should not be trying to judge who will be innovative and successful” (Radio Communications Agency, 2008).

To ensure the UK mobile communications eco-system continued to evolve in a competitive manner it was decided that a new entrant, a fifth network operator, would be enabled as a result of the auction process and therefore an amount of spectrum was reserved for this new entrant. A total of thirteen companies applied to participate in the auction and these included the four existing mobile network operators along with nine potential new entrants. The spectrum to be auctioned was split into five lots referred to as Licence A through to Licence E, licence A being reserved for the new entrant. The amount of spectrum allocated to each license would not be the same therefore operators had to make strategic decisions as to which licence they wanted to bid for. The largest spectrum allocation was reserved for the new entrant to compensate for their lack of 2G spectrum.

Orange won licence E and in doing so paid a fee of GBP4.095 Billion. Once a licence was acquired the process of designing and building a 3G network could start. Licence E consisted of a total of 25MHz of spectrum in the 2100 MHz band as follows:

Mode	Spectrum	Number of carriers
FDD	1969.7 - 1979.7 paired with 2159.7 - 2169.7	2
TDD	1915.0 - 1919.9	1

Table 4: Orange 3G spectrum allocation

This process was further complicated at the time as Orange had a change of ownership, having been recently bought by Mannesmann of Germany however subsequently the German firm was bought by Orange’s UK rival Vodafone Airtouch. Orange was subsequently sold to France Telecom during May 2000 and became part of France Telecom Group.

The process of developing a 3G network strategy, target architecture, designs and network plan started in earnest with large teams dedicated to various aspects of the end to end solution. The focus of the research presented in this thesis is the technical strategy, target architecture and high-level designs developed by the author for the UMTS mobile backhaul network. Prior to commencing such a task it is important to research the technology, understand the equipment manufacturers products and roadmaps, align with internal business strategy and then secure a suitable budget to enable the solution to be delivered. As Principal Network Designer for mobile backhaul within Orange the author was technical design authority and managed this process. The starting point wasn't a blank piece of paper as the existing GSM/GPRS network was the baseline on which UMTS would be installed and therefore a new backhaul solution must support GSM/GPRS and UMTS traffic.

4.3 UMTS standards

The starting point for a technical understanding of UMTS is the 3GPP standards, from where a comprehensive overview of all technical specifications for the system can be found in a series of documents known as specifications. The high-level principles behind the architecture is set out in 3GPP specification on General UMTS Architecture, amongst other things this document defines the term UE (User Equipment) rather than MS to refer to the mobile phone (3GPP, 2000). The term UE is adopted as it is anticipated that many new forms of UE will be available with UMTS, not all necessarily being mobile in the same manner considered appropriate when the term MS was adopted in GSM. The UMTS radio access network is known as UTRAN and consists of a radio base station and network controller, similar in concept to GSM however that's where the similarities end. (3GPP, 2000) TS 23.121 provides a detailed overview of the UMTS architecture and protocols in the specification, Architecture Requirements for Release 99. From these documents, equipment vendors papers/product descriptions and early text books (Korhonen, 2003) it is possible to construct the diagram in Figure 24.

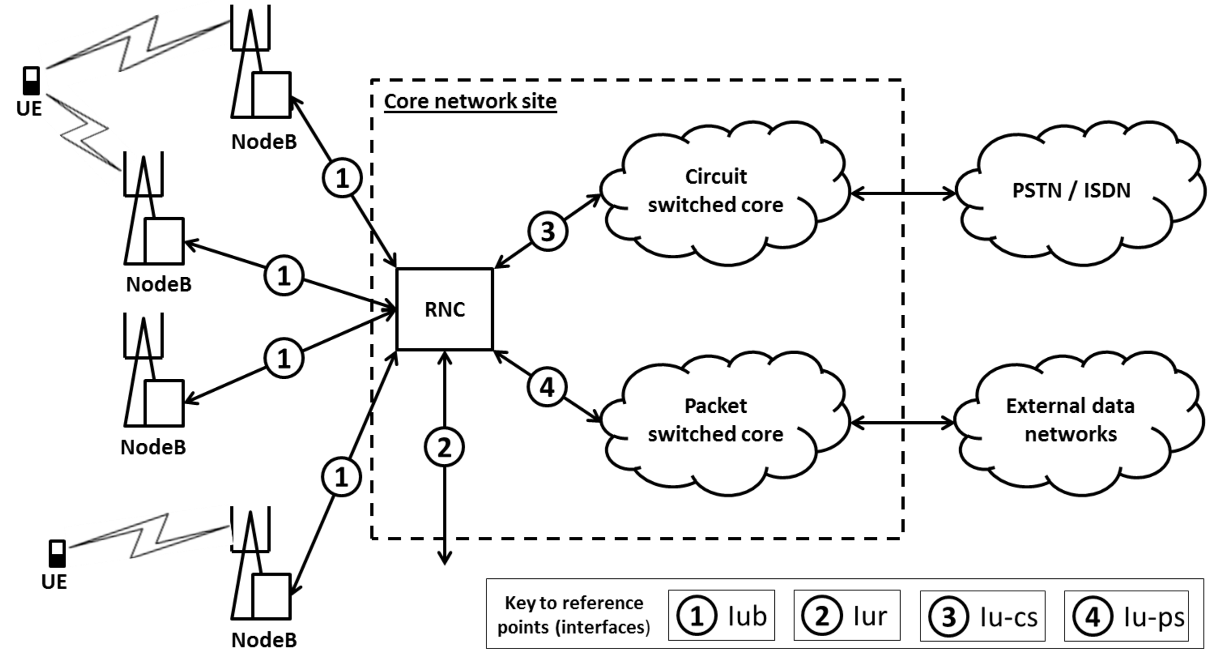


Figure 24: UMTS network architecture and UTRAN interfaces

Figure 24 illustrates the UMTS network architecture and highlights the transmission interfaces between radio base stations, known as NodeB, and the RNC along with interfaces between the RNC and core network. The core network consists of two parallel entities, one for circuit switching and one for packet switching, as with GSM and GPRS.

The UMTS radio interface is based on Wideband Code Division Multiple Access technology which differs considerably from the GSM radio interface. Wideband channels are nominally 5 MHz wide and all users are code multiplexed within this channel. An important feature of WCDMA is soft and softer handover, this improves the system's link budget in comparison with GSM and therefore extends the receive access level minimum below the levels of GSM, this is helpful given the higher free space pass loss of the 2100 MHz band. Softer handover refers to mobility between cells of the same physical NodeB while soft handover is mobility between NodeBs. The features are enabled by the use of rake receivers within the UE and NodeB, the rake receiver has a number of sub-receivers commonly known as fingers, these are correlators and each is assigned to a different multipath signal to counter the effects of fading. The fingers can also receive signals from different cells and as such can ease the process of handover by executing a soft handover between adjacent cell sites rather than a hard handover as implemented in GSM. The soft handover works when moving between cells on the same frequency however as UMTS has a frequency reuse factor of 1, meaning all cells operate on the same frequency, this isn't a problem. As capacity is increased with the addition of a second carrier, inter-frequency mobility requires a hard handover however the system tries to manage mobility between the same channels if possible. The use of soft handover has implications for mobile backhaul due to the implementation of macro-diversity combining , in support of soft handover.

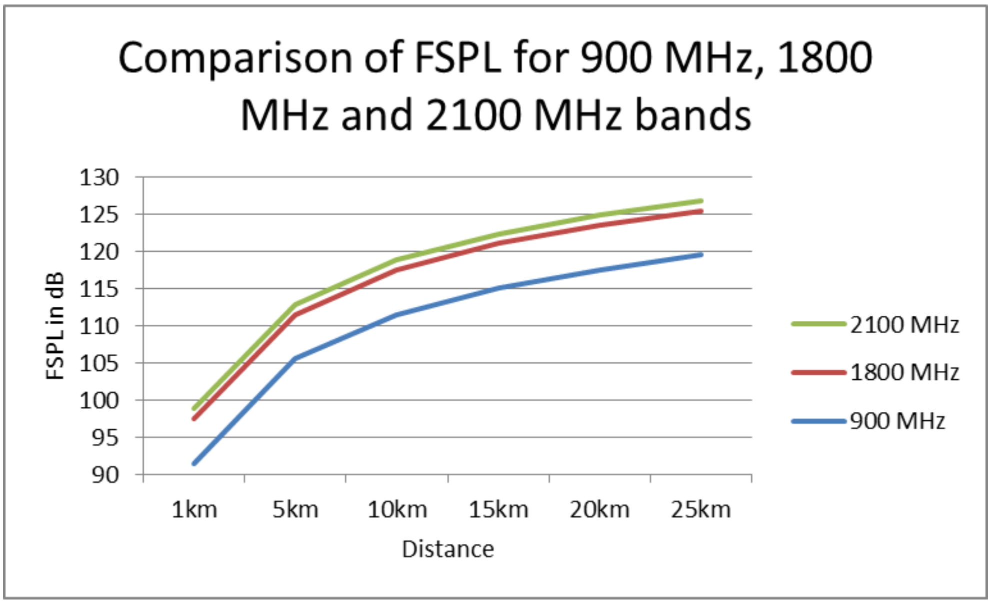


Figure 25: Comparison of FSPL for 900 MHz, 1800 MHz and 2100 MHz bands

Figure 25 illustrates the FSPL for UMTS 2100 MHz bands, even with an improved receiver sensitivity when compared with GSM, 900 MHz operators required a significant number of infill sites, particularly as capacity started to grow. This was less of an issue for the 1800 MHz operators who typically had a denser cell site grid at this stage.

UMTS interface naming is more logical than that of GSM, the Iub interface refers to the interface between UMTS base station and RNC, hence Iub (Interface - umts - base station). The Iur interface is a new concept specific to UMTS and its use of WCDMA. This is the Interface between UMTS RNCs, hence Iur, this interface supports mobility which is managed within the RAN in UMTS whereas this was a core network function within GSM. The Iu-cs interface is the interface to the UMTS Circuit Switched core network while the Iu-ps is the interface to the UMTS Packet Switched core network.

4.3.1 ATM

3GPP Release 99 specified the use of ATM technology as the 3GPP Transport Network Layer for UMTS, this applies to the Iub, Iur, Iu-cs and Iu-ps interfaces. ATM is a layer 2 technology and was selected due to its flexibility to handle multiple types of traffic as UMTS was designed from first principles to support voice, data and video traffic. ATM can utilise any layer 1 transmission technology and has the ability to logically combine lower speed circuits to form a higher speed link, a technique known as Inverse Multiplexing for ATM, or IMA. ATM utilises a fixed 53 octet cell structure and can therefore be switched at high speed in hardware, a key advantage of ATM over variable length packet switching technologies at the time. ATM enabled an appropriate Quality of Service to be applied to the different traffic types and therefore ensures that voice, data and video traffic could coexists on the same network without any detrimental behaviour.

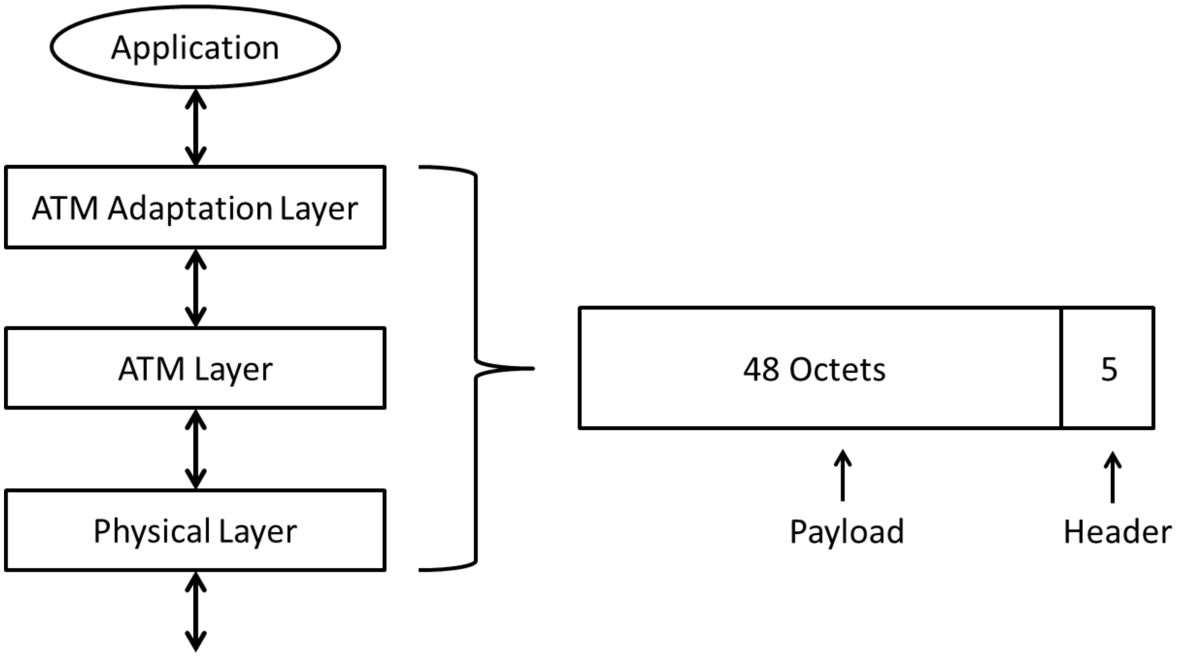


Figure 26: ATM network layers and cell structure

ATM standards define three layers; the ATM Adaptation Layer (AAL), the ATM layer and Physical layer. AAL is service specific, this layer includes a Segmentation and Reassembly function which splits an incoming information stream and allocates blocks of 48 octets (or bytes) to the payload area of an ATM cell, the process is reversed at the receiving end of the link. There are 5 defined AAL's known as; AAL-0, AAL-1, AAL-2, AAL-3/4 and AAL-5. AAL-2 is used to carry voice traffic while AAL-5 is used for data traffic in R99 UMTS transmission. The ATM layer adds a 5 octet header to the ATM cell, this contains addressing information in the form of Virtual Path Identifier and Virtual Channel Identifier along with QoS information and a Header Error Checksum. The physical layer manages the connection to a transmission system which, in the case of UMTS backhaul, was typically E1 or SDH based.

From a mobile backhaul perspective the Iub interface is the area of focus, the RNC is a high capacity platform with a mix of E1 and STM-1 interfaces and as such will be installed on core switch sites. Given the centralised location of the RNC all other UTRAN interfaces will be implemented between core network sites and therefore will utilise core ATM network connectivity.

4.3.2 Iub interface

The 3GPP Release 99 Iub interface is split into two horizontal and three vertical components as illustrated in Figure 27

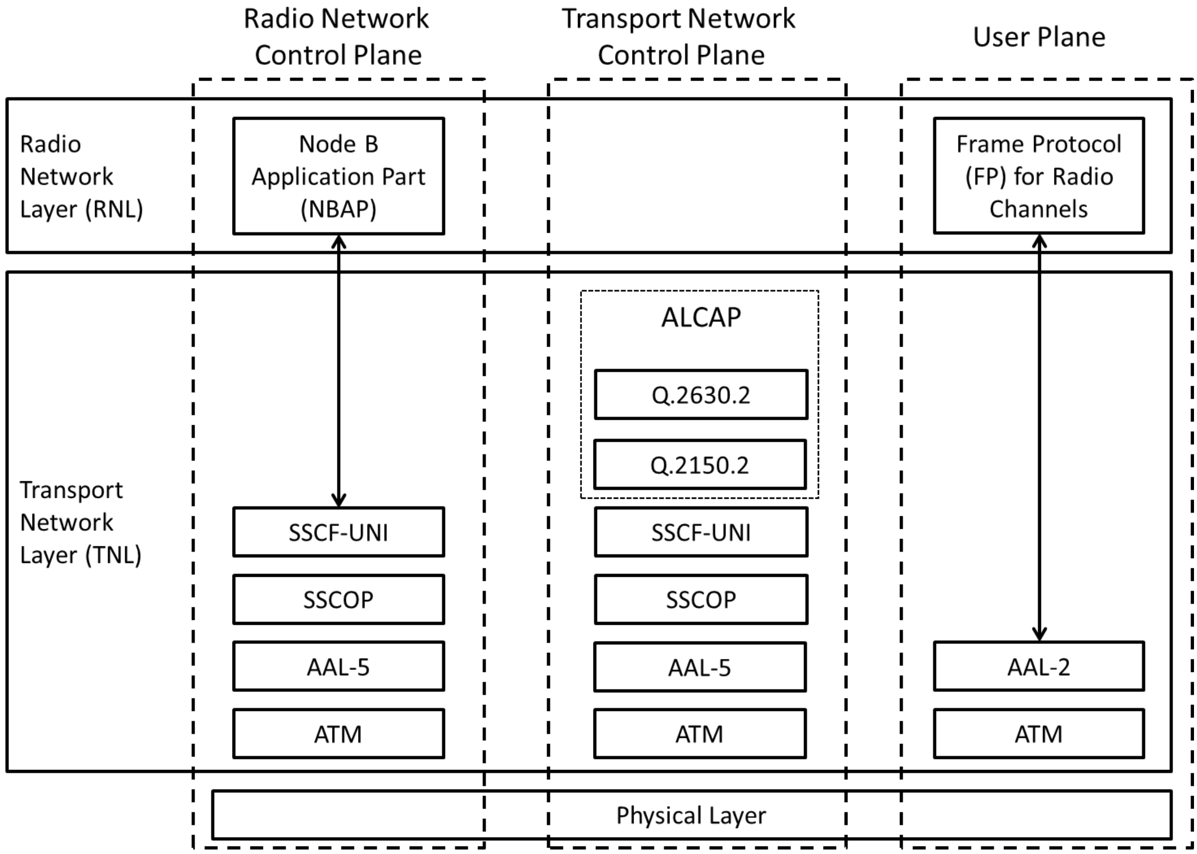


Figure 27: Iub Interface Protocol Structure

3GPP defined the UTRAN interfaces with a split between the radio network layer (RNL) and transport network layer (TNL), this flexibility would allow the TNL to evolve from ATM to IP in a later release of the UMTS standards. The RNL contains the user plane frame protocols for the release 99 radio channels along with NodeB application part (NBAP) signalling in the radio network control plane. The release 99 TNL is based on ATM and as such makes use of standardised ATM features, a dedicated transport network control plane is required to setup and tear down AAL2 connections for the user plane. The transport network control plane utilised services of access link control application part (ALCAP) based on ITU-T recommendation Q.2630.2. ALCAP multiplexes different users onto one AAL2 transmission path using channel identifiers, a maximum of 248 channels can be multiplexed onto one AAL2 bearer (ref 3GPP TS 25.426). The radio and transport control planes are implemented with AAL-5 whereas the user plane uses AAL-2, for real time and non-real time communications.

4.4 Existing GSM/GPRS backhaul

The high level microwave backhaul topology was illustrated in Figure 20, this is engineered with chains of microwave radios which could consist of 1, 2, 3 or 4 radio links (Appendix 1, PLAN141). This creates a hub and spoke architecture with the BSC site at the centre of a network of distributed BTS providing wide area radio coverage. In most cases the BTS site providing the onwards microwave radio path would act as a simple line of sight repeater, there would be no interaction between the local BTS and the onwards microwave radio circuit.

Figure 28 reviews the physical network connectivity for an Abis interface circuits over a single point to point microwave radio link. The transmission interface card on the BTS supported n x E1 interfaces, n typically being 1 however there were a few exceptions based on BTS capacity requirements, in these cases n would typically be 2 or 3. Connections between the BTS and microwave radio link go via a digital distribution frame, this is effectively a flexibility points which enables an E1 circuit to be cross-connected between any two pieces of equipment, in this case between a BTS and IDU. The IDU connects to the ODU via an IF cable, the microwave link is then transmitted between two parabolic antennas and received by the far-end ODU, the process is then reversed and final connection to the BSC is made via the DDF at the BSC site.

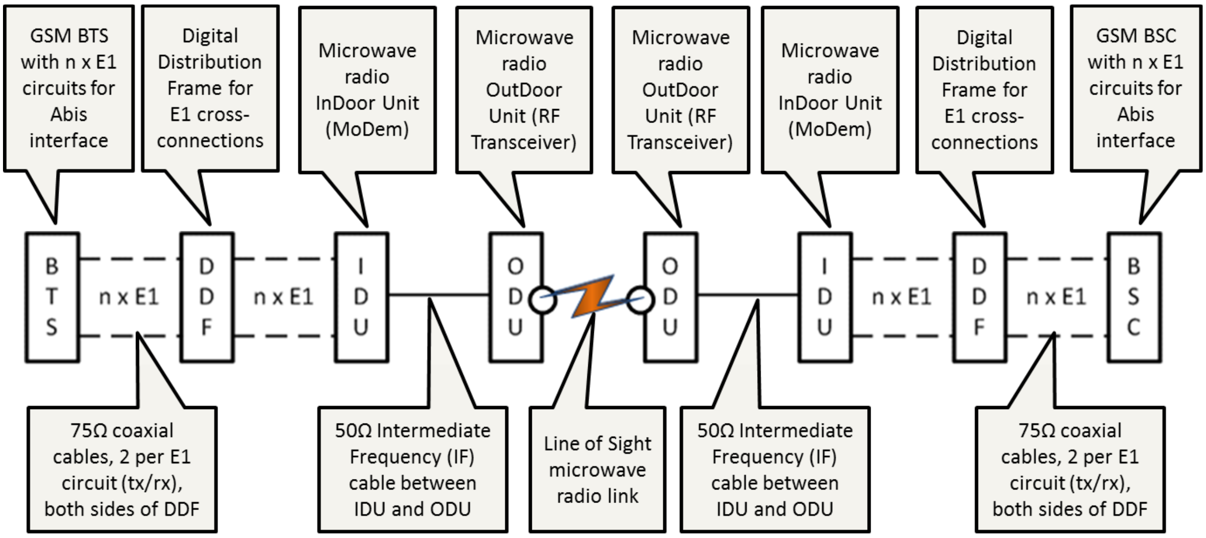


Figure 28: Abis interface physical connectivity over a single microwave radio link

The physical connectivity for a chain of two or more links is similar to that described above, the first site out from the BSC being identical to that described whilst the Abis interface of the second site will travel over the its local microwave radio links to the intermittent site which is acting as a point to point microwave radio repeater site. At the intermediate site (highlighted by dashed lines in Figure 29) the n x E1 circuits are cross-connected via the DDF for onwards transmission via dedicated E1 tributaries of the microwave radio link facing the BSC site. At the BSC site the E1(s) are connected to the BSC via the DDF.

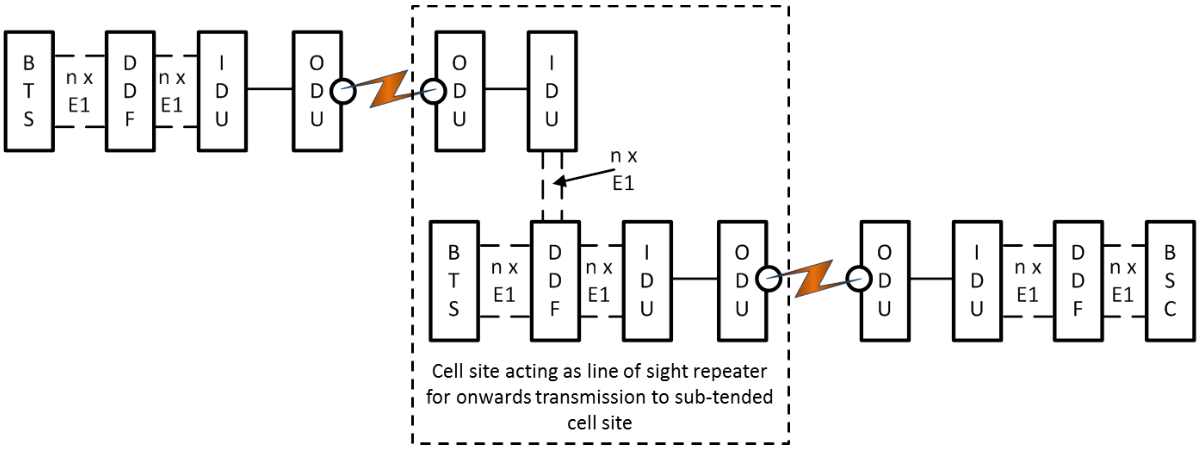


Figure 29: Chain of two microwave radio links with intermediate BST site acting as line of sight repeater

Having acquired a knowledge of UMTS network architecture and principles, ATM technology and a detailed understanding of the existing GSM/GPRS mobile backhaul network; the next step was to understand the network nodes and their specific implementation by the selected equipment vendor.

4.5 UTRAN equipment

Orange UK selected Nokia as their UTRAN equipment provider; the NodeB was the Ultrasite WCDMA BTS (NodeB) product and the RNC was the IPA2800 RNC196 product. A NodeB transport interface card would typically support n x E1 interfaces; the exact number represented by ‘n’ is vendor specific however 4 and 8 x E1 configurations were common. Nokia supported 8 x E1 circuits on the variant of the Ultrasite WCDMA BTS transmission interface card selected by Orange. The interface card was designated ‘IFUD’, InterFace Unit version D, the 8 x E1 circuits were presented as 75Ω, 43 type coaxial connectors to the front panel of the IFUD plug in unit, often simply referred to as a ‘transmission card’. The IFUD was located next to the NodeB ATM cross-connect card, designated ‘AXUA’, ATM Cross-Connect version A. The two cards together made up the Iub transmission interface system. Connectivity to the Iub interface was via the E1 connectors while onwards connectivity within the NodeB was via the backplane of the Ultrasite rack.

NodeB Iub ATM E1 interface could be configured as a UNI in which a single E1 circuit provides an ATM connection, or as an IMA group in which n x E1 circuits could be configured as an ATM connection. In the case of IMA, ‘n’ could be anything from 1 to 8 on the Ultrasite NodeB. In this case an Iub interface could scale from 2Mbps to 16Mbps. The Nokia NodeB portfolio is illustrated in Figure 30, ranging from the compact MetroSite through internal and external Optima and Optima Compact products to the full height rack variants of the UltraSite Supreme. The indoor variants would be installed within a walk-in enclosure or internal room while the outdoor variants would be installed with no additional environmental protection. The triple mode UltraSite products on the right of Figure 30 refer to GSM, EDGE and UMTS combined capabilities within a single cabinet, this configuration was not deployed by Orange.

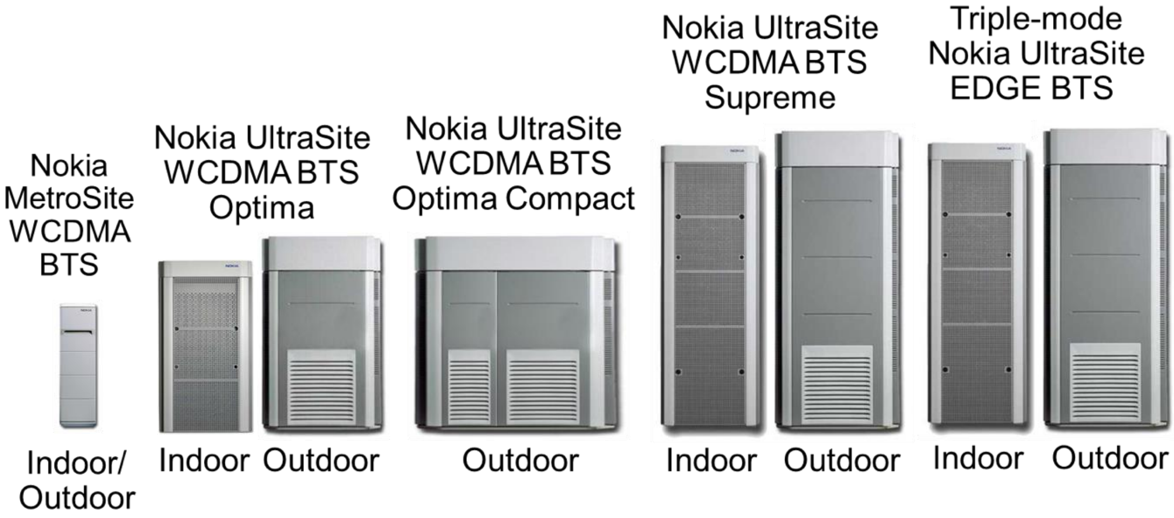


Figure 30: Nokia WCDMA base station (NodeB) product range (Source: Nokia)

Acquiring legal agreements which are often known as ‘site rights’, to install a cell site is a complex and often lengthy and expensive process. Sites could be installed on third party towers, rooftops, green-fields (self-build tower/column) or street-works. In addition to the structure the number of cabinets on site often resulted in additional rental charges. To support additional cabinets what is known as a ‘plinth upgrade’ is required. New cabinets were being added to sites to support GSM/GPRS traffic growth while the introduction of UMTS would result in even more cabinets. To mitigate the need to constantly acquire upgrades to add ever more cabs to sites, Orange aimed to upgrade a large number of sites from external cabs to walk in enclosures as once a large enclosure was deployed to site, there was no need to seek further permissions in install additional equipment within the enclosure. The activity was initiated in response to the site build programme required for the national rollout of UMTS. It wasn’t possible to upgrade every site in this manner however significant numbers were upgraded with a range of walk in enclosures.

Figure 31: Type 3F Enclosure at site reference CHS0029 in Stretton, Warrington, Cheshire (installed in 2001 and removed in 2017 (photo 2015))

An RNC, as described earlier, is a high capacity network controller and as such would have significant interface capacity , often a mix of E1s and STM-1s. The STM-1 interfaces were unstructured ATM Virtual Container level 4 (VC-4) interfaces rather than structured VC-4 which would carry 63 x E1. The ATM VC-4 interface had a payload capacity of 149.76 Mbps. The Nokia RNC 196 was available in 5 different configurations known as configuration 1, 2, 3, 4 and 5. The choice of configuration would determine the RNC capacity and number of physical ports, this is detailed in Table 5.

Configuration	RNC Capacity			Physical Interfaces	
	Iub Mbps	NodeB	Carriers	STM-1	E1
1	48	128	384	16	64
2	85	192	576	16	96
3	122	256	768	16	128
4	159	320	960	16	160
5	196	384	1152	16	192

Table 5: Nokia RNC 196 configurations

The different configurations offered a pay as you grow type model to the mobile network operators. Configuration 1 supported an Iub interface throughput (downlink + uplink) of 48Mbps across a maximum of 128 connected NodeBs with a maximum of 384 x 5 MHz WCDMA FDD carriers. A typical NodeB would consist of one or three cell sectors and as such this configuration mapped to a maximum of 128 x 3 cell sector sites with 1 x Carrier per cell sector, or, a mix of omni and sectored cell types of various carrier configurations. 16 x STM-1 interfaces was standard across all configurations while the number of E1 interfaces increased with configuration step. Each configuration of the RNC 196 had a maximum throughput which was significantly less than the sum of its physical interfaces, this was an important network design and planning consideration. The Nokia RNC 196 and its 5 configuration steps, as per Table 5, is illustrated in Figure 32.

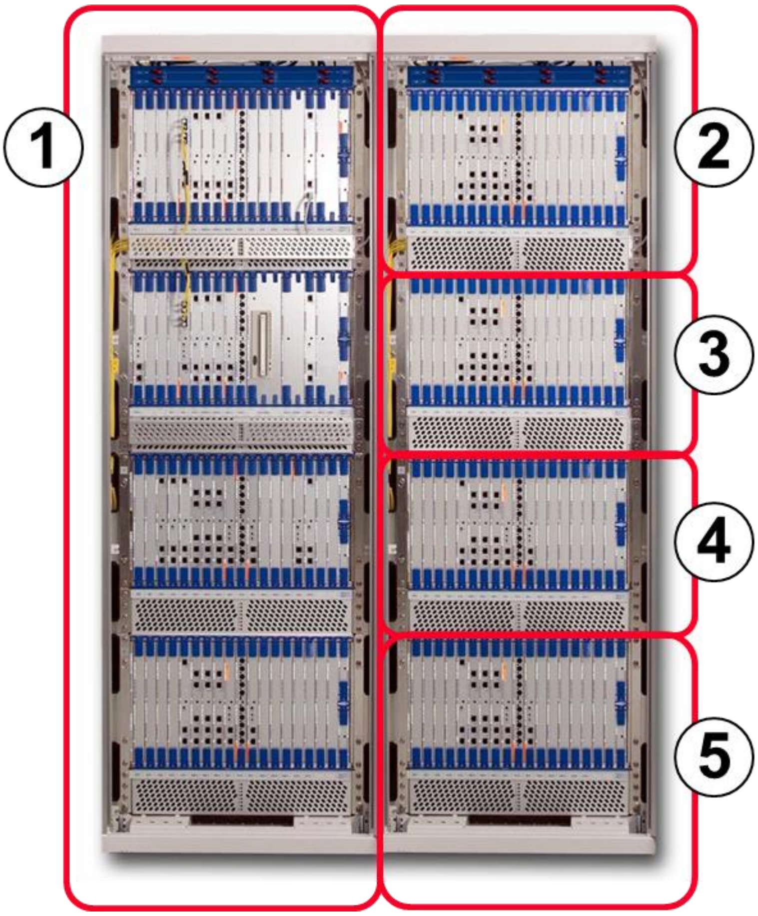


Figure 32: Nokia RNC 196 configurations (Source: Nokia)

Whilst the RNC Iur interface is out of scope for this research it is nonetheless essential to understand the role of the Iur interface and how this impacts Iub network dimensioning. The soft handover feature of WCDMA was described earlier and is illustrated in Figure 33 which shows two radio connections from two separate NodeBs to a single UE. If the NodeBs of a soft handover connection are hosted off separate RNCs, the Iur interface will relay traffic between them. The RNC with the connection to the core network becomes known as the Serving RNC while the secondary RNC becomes known as the Draft RNC. From an Iub interface perspective the more sites which make up the connection, known as the active set, the greater the overall backhaul traffic will be in support of the UE. This is because the uplink and downlink Iub will transmit identical user plane information to and from the RNC via multiple paths, therefore increasing the overall backhaul overheads to be carried in support of reliable communications. The same also applies to the radio interface. Figure 33 illustrates the concept of MDC with a scenario of 3 connections making up an active set to a UE, The MDC splitting and combining function is in the SRNC from where an Iu stream is split for downlink transmission and an Iub transmission combined for onwards transmission as an Iu interface to the core network. Whilst called combining in reality the MDC function simply selects the uplink stream with least errors. The combing of the uplink actually takes place at the NodeB where maximal ratio combining occurs.

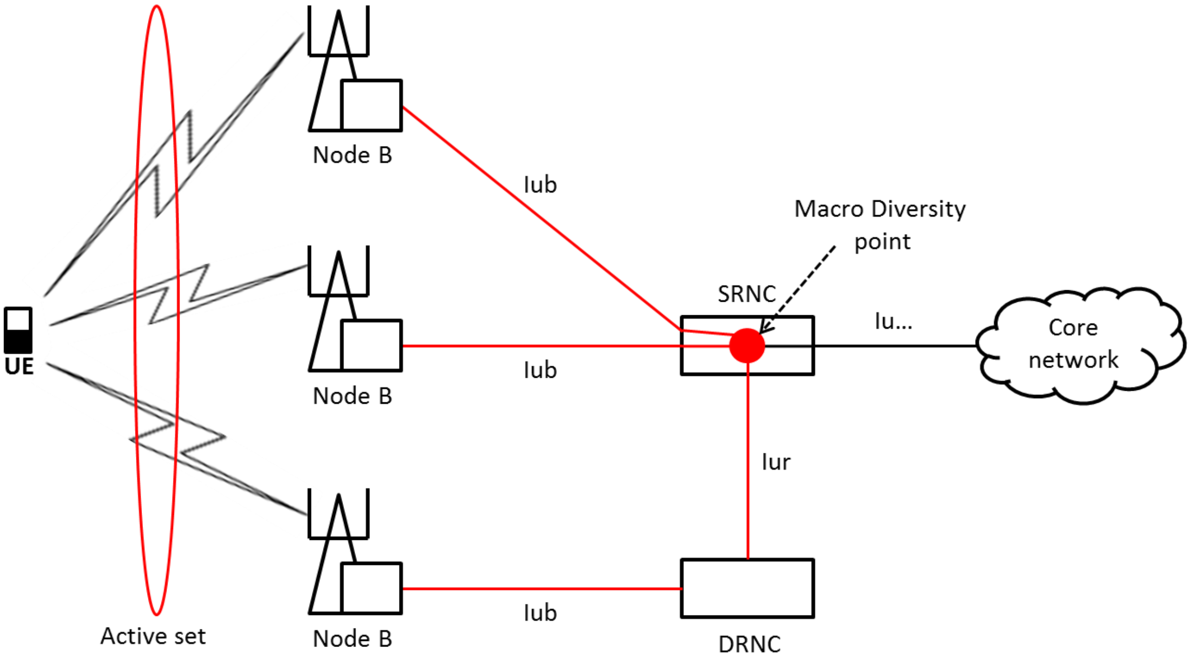


Figure 33: Use of Serving and Drift RNS's in support of MDC

4.6 Target network architecture and design

With knowledge of UMTS architecture, protocols and technology along with ATM and the existing mobile backhaul network, the author started to explore potential solutions for an integrated GSM (including GPRS) and UMTS mobile backhaul network. The existing GSM network consists of two network domains known as access and core, access being the Abis and Ater interfaces while the core contained the TRAU and A interface along with circuits switched and packet switched network equipment and associated databases, billing systems, operational support systems etc. The technology deployed for the Abis and Ater interfaces was effectively the same, either n x E1 point to point microwave radio systems or E1 leased lines. The decision to deploy UMTS would result in significantly more network traffic as subscribers migrated to the new data centric products and services however key decision about UTRAN architecture would also determine traffic levels and requirements. Of particular note here is the decision to centralise all RNCs on core network sites whereas the equivalent GSM node, the BSC, was distributed. The decision results in significantly more traffic on the transmission systems which previously supported limited Ater interface traffic, assuming a fully converged architecture was implemented.

UMTS offered mobile network operators a check-point at which they could review their current mobile backhaul network solution and decide whether this continued to be the best approach. In the case of Orange UK this review was to analyse whether the predominantly self-build approach was still the best solution when compared with a third party outsourced backhaul solution. To make such a comparison it was necessary to understand what a predominantly self-built combined GSM/GPRS and UMTS backhaul solution would be. Predominantly self-build refers to maximising the use of transmission systems directly planned, deployed and maintained in house as compared with a third party leased line solution. The network was never going to be 100% self-build as some macro cell sites couldn’t be reached with point to point microwave radio systems and, as previously explained in section 3.8, micro-cells were designed to use third party n x 64 kbps leased lines with aggregate bearers. It was reasonably straightforward to get quotes for third party backhaul solutions, once the number of sites to be upgraded to UMTS was known and the initial network plan completed to map them to a RNC on a core network site. The third party provider would work on a connectivity model as a basis to quote against. Other inputs would include provisioned capacity, any aggregation or over-booking figures and details of hand-off circuit towards NodeB and RNC. A view of future network growth also helped to understand the on-going costs and therefore model a TCO over a period of years. In the case of Orange UK the model was to consider TCO over a period of 10 years.

4.6.1 Network architecture

UMTS was to be rolled out to existing GSM cell sites as an upgrade which involved the following activities:

- Upgrading of the site electricity power supply
- Deployment of NodeB hardware

- Deployment of 2100 MHz antenna system
- Upgrade of mobile backhaul solution
- Implementation of Iub interface (Appendix 1, PLAN342)

A network plan was developed which identified the need for 17 x RNC in the initial UMTS rollout phase, these would be deployed and configured as detailed in Table 6.

RNC site reference	RNC Configuration (Figure 32)	Number of E1 ports
1	2	96
2	2	96
3	2	96
4	3	128
5	4	160
6	3	128
7	4	160
8	2	96
9	2	96
10	2	96
11	2	96
12	2	96
13	2	96
14	2	96
15	2	96
16	3	128
17	2	96

Table 6: Initial RNC deployment plan

A total of 1856 x E1 ports would be available across the 17 RNCs, this is in addition to the 16 x STM-1 circuits per RNC. STM-1 ports are ATM VC-4 (rather than 63 x E1 channelised interfaces).

Whilst the radio plan specified what was required at the cell site, the rate at which UMTS would be added to the GSM network and the deployment of RNCs across 17 core network sites, it didn't specify the design of the interconnectivity between the cell site and RNC. The interconnectivity in support of the Iub interface and integration with existing GSM/GPRS requirements was developed as the mobile backhaul network architecture and implemented via a dedicated upgrade project as part of the wider UMTS rollout programme (Appendix 1, PLAN591).

The implementation of a self-deployed UMTS backhaul solution was realised in parallel with GSM and GPRS interfaces as illustrated in Figure 34. The GSM BTS and UMTS NodeB are separate cellular radio base stations which will be co-located at the same cell sites. The Abis transmission route between the cell site and BSC site will support parallel Iub transmission. The Ater and Gb interface connectivity between the BSC site and core network will be combined with Iub traffic between the BSC site and the core site.

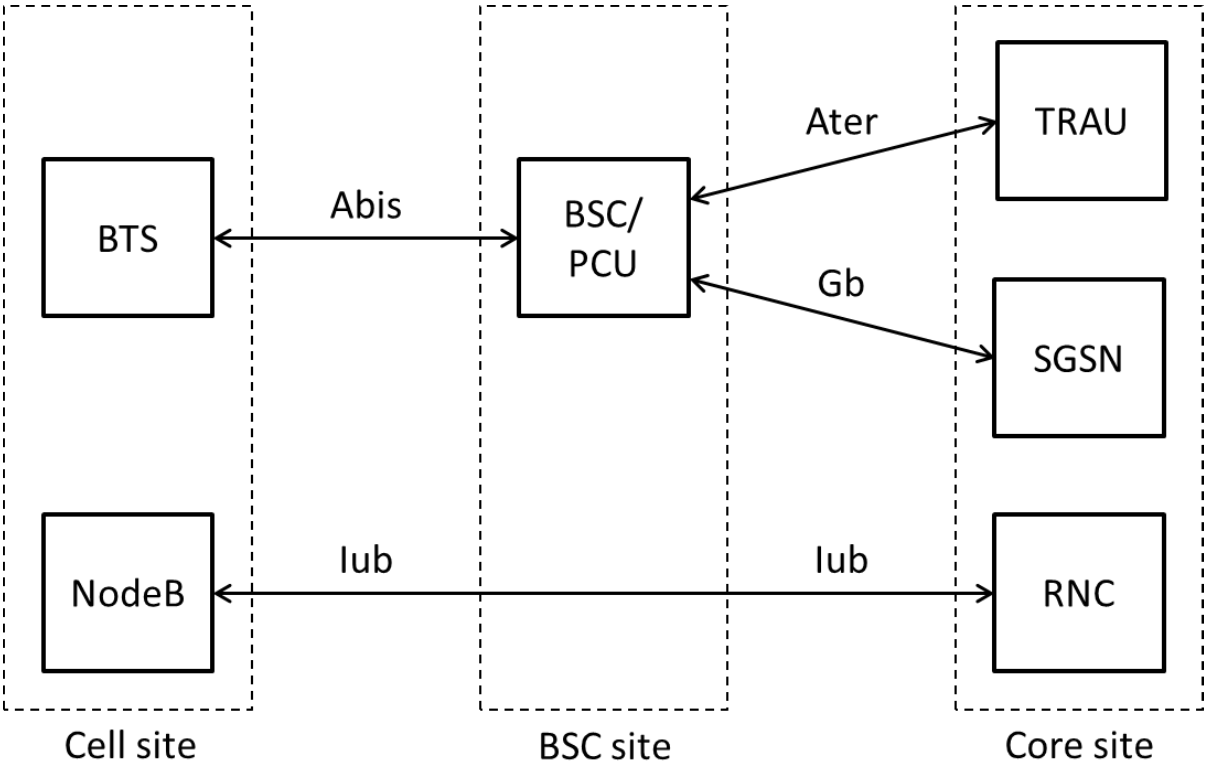


Figure 34: Mapping Iub interface overlay to existing GSM/GPRS network architecture

A typical BSC site would support 75 to 150 GSM BTS sites with a range of configurations (sectors and TRX count). Taking an example from an operational BSC site in an urban area which covers a mainly urban and sub-urban environment with a small amount of rural coverage containing some strategic roads and railways. The site count is as follows:

- 100 x macro-cell BTS (90 x 3 cell sectors, 10 x >3 cell sectors)
- 20 x Micro-cell BTS (10 x 1 TRX omni and 10 x 2 TRX omni)

Of the 100 macro-cells, 90 are the standard 3 cell sectors design and will have between 1 and 6 TRX per cell sector, 10 have greater than 3 cell sectors, 1 has 4 cell sectors and 8 have 6 cell sectors. Macro-cells are a mix of Nokia Talk Family (DF34) and Nokia UltraSite BTS equipment. 10 of the micro-cells are 1 TRX Nokia PrimeSite and 10 are Nokia FlexiTalk products.

Whilst UMTS will be rolled out in a phased manner with urban macro-cells first followed by strategic road and rail routes, suburbs and the rural areas, the business strategy called for all GSM sites to be upgraded in the fullness of time. As such any backhaul strategy and target architecture had to consider the complete rollout and scale to meet this, along with scaling for capacity growth in line with business forecasts (Appendix 1, SPEC616). In addition to this, GSM/GPRS had to continue to scale as more subscribers are added and traffic per subscriber increases. As a result of the following had to be added to the model for designing the backhaul network for the example BSC site:

- 100 x macro-cell NodeB
- 20 x micro-cell NodeB

The majority of macro-cell NodeBs were deployed with 3 cell sectors with 1+1+1 WCDMA carrier configuration, meaning 1 x 5 MHz FDD carrier per cell sector. The micro-cell NodeBs were single sector (omni) configuration however like the GSM/GPRS micro-cells, connected to 3 sectored antennas via an RF splitter. Macro-cell equipment was Nokia UltraSite or Nokia Optima while the micro-cell equipment was Nokia MetroSite.

Table 7 details the existing GSM backhaul requirements of the BSC site being modelled, each macro-cell BTS has a dedicated E1 circuit between the cell site and BSC equipment. This dedicated Abis interface circuit terminates on the base station interface equipment (BIE)/transmission unit (TRUA) card on the BTS and exchange termination (ET) card on the BSC. Each GSM micro-cell is provided with a sub-equipped E1 interface to the BIE/TRUA card on the BTS which is then aggregated through the third party leased line network and presented as an E1 supporting multiple micro-cells to an ET card on the BSC.

Site type	E1 circuits	E1 circuits at BSC site	E1 circuits to core site
GSM macro	100	100	10 (Abis) + 2 (Gb)
GSM micro	20	5	Supported by above
UMTS macro	100	100	100
UMTS micro	20	20	20

Table 7: Backhaul circuits against site type and network controller location

The UMTS NodeB requires a minimum of a full E1 to manage expected traffic demand for data services. At launch UMTS could support up to 384 kbps on the downlink and 64 kbps on the uplink per UE, therefore an E1 would only support a small number of data users. As the Iub interface is simply transiting the BSC site the number of E1s either side would be constant, driving significant investment in new network capacity, particularly on the GSM Ater and Gb interface transmission routes. Given the research objective was to optimise the overall backhaul solution to deliver the capabilities required by the radio networks while minimising overall TCO, it became obvious from this sample site model that an alternative solution was required.

Figure 35 illustrates the initial concept for adding a transport network optimisation node to the BSC site. The BSC site itself was renamed to transport Node (TN) to represent its wider network role now it was to support UMTS along with existing GSM and GPRS traffic.

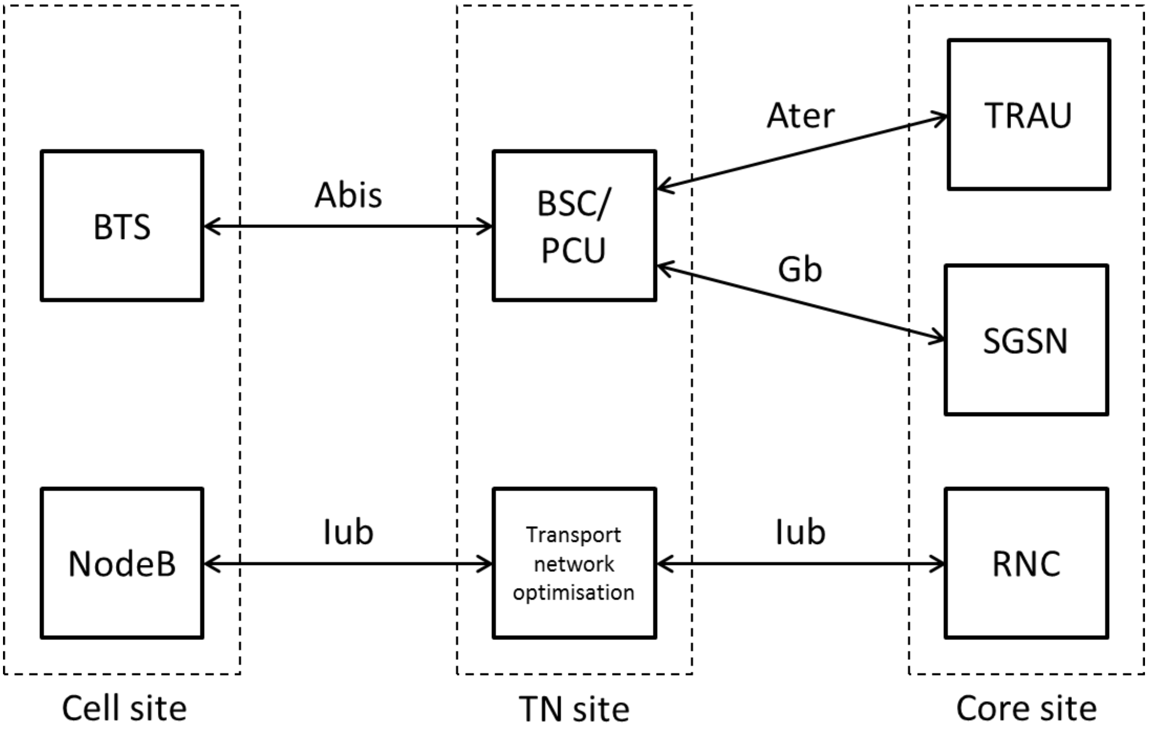


Figure 35: BSC site re-designated as a transport Node (TN)

The terms transmission network and transport network are often interchanged with their meaning being rather ambiguous. Typically if the term transmission is used it refers to layer 1 technologies such as optical fibre and microwave radio systems and protocols such as TDM with PDH and SDH being relevant examples. Transport generally refers to layer 2 and above and therefore the introduction of ATM in UTRAN resulted in the need for transport network designs in addition to the underlying transmission network design. When designing a transport network the transmission layer would typically be included however the overall term transport network design is generally applied rather ambiguously. Where the term transmission is used in this thesis it refers to layer 1 however the transport could refer to any layer, including layer 1 as this provides a service to the higher transport layers.

The elevation of the BSC site to a TN effectively splits the access domain into two clear segments, the first being between the cell site and TN with the second being between the TN and core network site. To acknowledge this and represent the differing requirements between these two domains, the term metro network was introduced to describe the segment between the TN and core network site. This resulted in three transport network domains known as; access - metro - core. The access and metro transport network domains are considered to be backhaul as shown in Figure 36:

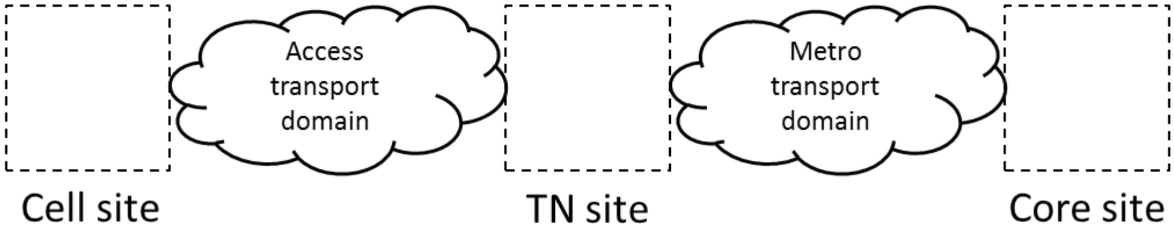


Figure 36: Access and metro transport network domains

4.6.2 Network design

From the high-level target network architecture above it is possible to start the network design process. The network design activity that was undertaken was split into several components as follows:

1. Cell site backhaul design
2. Access transport design
3. TN site transport design
4. Metro transport design
5. Core site transport design

Each area had its specific requirements however the end to end design would ultimately provide the service to the subscriber and must be optimised as a single functional domain to guarantee maximum performance and lowest TCO. The end to end design imposed certain additional requirements which included:

- Network synchronisation - frequency reference for transmission and radio interface
- Quality of Service - supporting different classes of services such as voice and data
- Provisioning - minimise site visits and automate via network management system
- Operations and maintenance - network management
- Mean time between failure - network elements
- Mean time to repair - including fault detection and repair
- Network availability - generally expressed as an uptime percentage such as 99.xx%
- Scalability - ability to increase capacity in a timely and cost-optimised manner

4.6.2.1 Cell site design

Cell sites are split between macro-cells and micro-cells, the initial rollout focused on macro-cells as they provide the wide area coverage and therefore enabled UMTS for a wider market than micro-cells would do. While some micro-cells were deployed specifically as coverage solutions the vast majority were there to add capacity, not an issue with a new technology deployment as there are only limited subscribers initially.

Two main variants of the Nokia UltraSite WCDMA BTS (NodeB) were selected for deployment in the Orange UK network, the UltraSite Supreme and UltraSite Optima Compact. In general, the Supreme was deployed where walk in accommodation was available on site while the Compact was deployed for all-outdoor installations. Due to the deployment of large walk in enclosures to many sites, the former was the most popular however not insignificant numbers of all outdoor macro-cells were deployed too. The backhaul design would be the same for both cabinet variants however the local interconnectivity would differ due to either indoor or outdoor racks/cabinets.

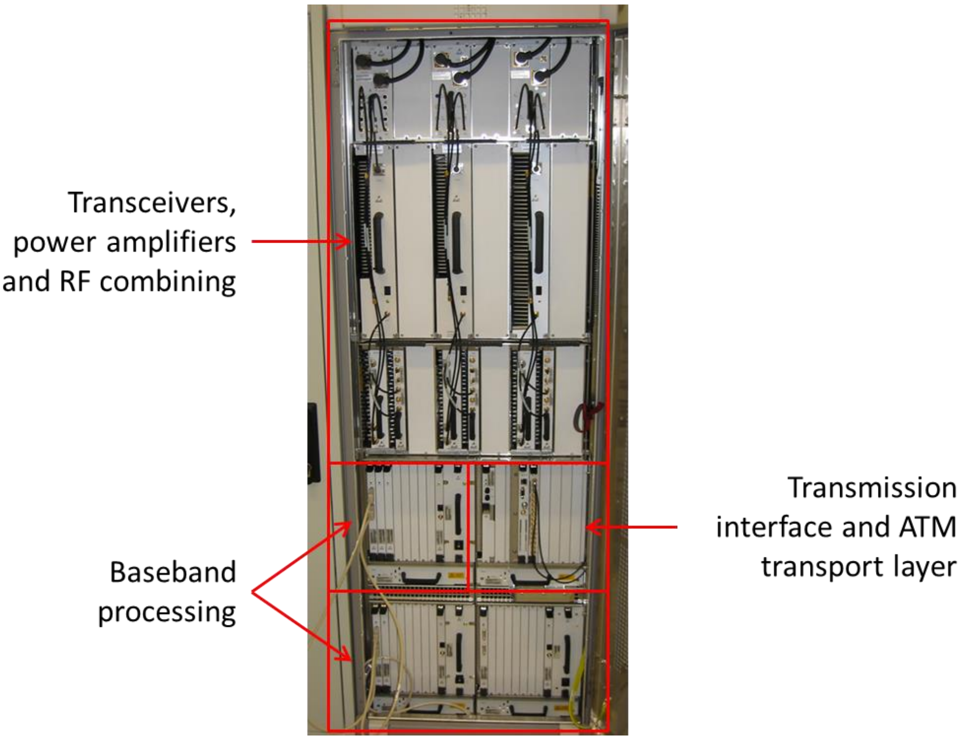


Figure 37: Nokia UltraSite Supreme cabinet with RF, baseband and transport network functionality

The NodeB consists of three primary functions, these are highlighted in Figure 37. The interface to the cellular antennas is at the top of the image while the power amplifiers and transceivers complete the RF section. The baseband processing takes up 3 cartridges while the remaining cartridge supports the ATM cross-connect unit and n x E1 transmission interface. While the ATM and transmission components are of primary interest to the design of the mobile backhaul network, the protocol architecture and requirements within the backhaul connection must be understood to properly design and configure the network. To understand this requires a knowledge of the Nokia Iub interface implementation. Figure 38 is a generic view of the Iub interface user plane, this was referred to as the user plane shown previously in Figure 27. From Figure 38, it is clear that the radio protocols of PDCP, RLC and MAC terminate in the RNC, therefore UMTS is a centralised network architecture rather than a distributed network architecture as implemented with GSM (from a network protocols perspective). The UE maps the user data to the radio protocol stack, in Figure 38 this is an IP data session however it could be voice traffic. The user data communicates with a peer outside of the UTRAN while the NodeB acts as a relatively simple layer 2 relay which maps the radio protocols via a framing protocol to an ATM network carried over TDM. The ATM network is shown as a single layer which includes both AAL-2 and ATM functions. The TDM component of the Iub interface is E1 based at the cell site and a mix of E1 and STM-1 based circuits on the RNC. The mapping between E1 and STM-1 will be explained later.

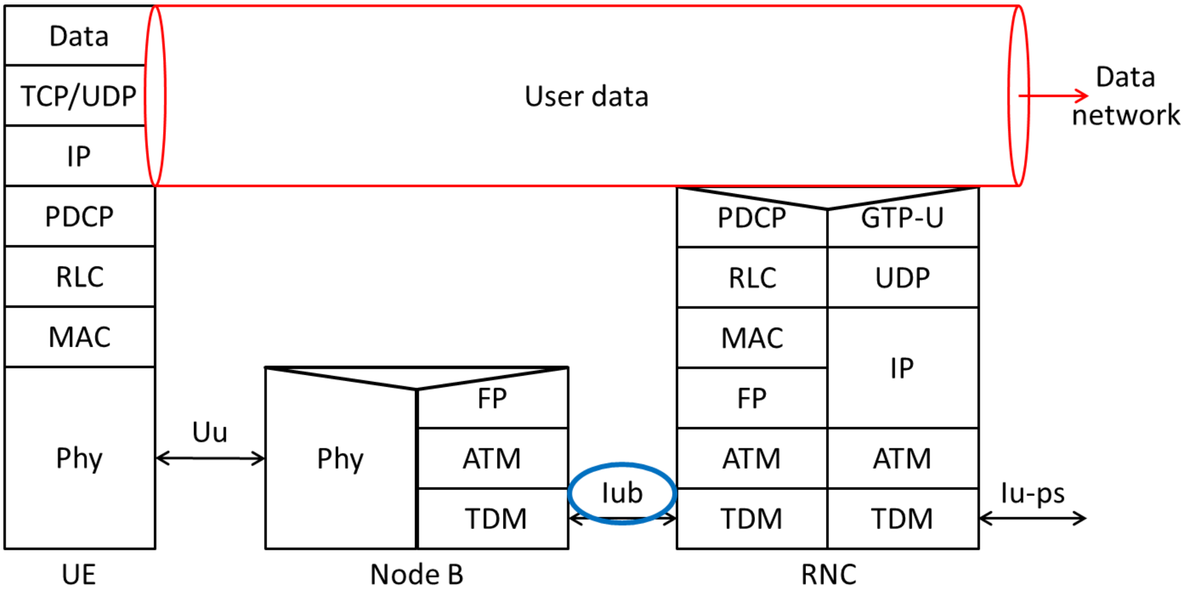


Figure 38: UTRAN architecture highlighting user plane protocols of the Iub interface

The transmission interface (IFUD) and ATM cross-connect (AXUA) manage the Iub interface connection while the AXUA also manages local connectivity within the NodeB. The following communication flows are required on the Iub interface:

VC Type	VP number	VC assigned	AAL	VC CoS
O&M	1	32	5	UBR
C-NBAP	1	33	2	CBR
D-NBAP	1	34 - 39	2	CBR
AAL-2 Signalling	1	40 - 45	5	CBR
User Plane	1	46 - 63	2	CBR

Table 8: ATM configuration for NodeB

Each NodeB requires one instance of O&M and one instance of C-NBAP. Each cell sector of a NodeB, between 1 and 6 sectors will each have an instance of D-NBAP and AAL-2 signalling. A typical three sectored NodeB can have up to 3 x WAM, Wideband Application Manager cards, each supporting up to 3 x signal processing cards, therefore up to 9 user plane connections will be required, the assigned VC numbering allows for scalability beyond this, in support of 6 cell sectors operation. The single instance of C-NBAP terminates to WAM number 1, this module is always fitted, any additional WAM modules will have three rather than the four termination points of WAM number 1, these are for D-NBAP, AAL-2 signalling and user plane traffic and will use the next VC number in accordance with Table 8. The ATM flows and terminations are illustrated in Figure 39:

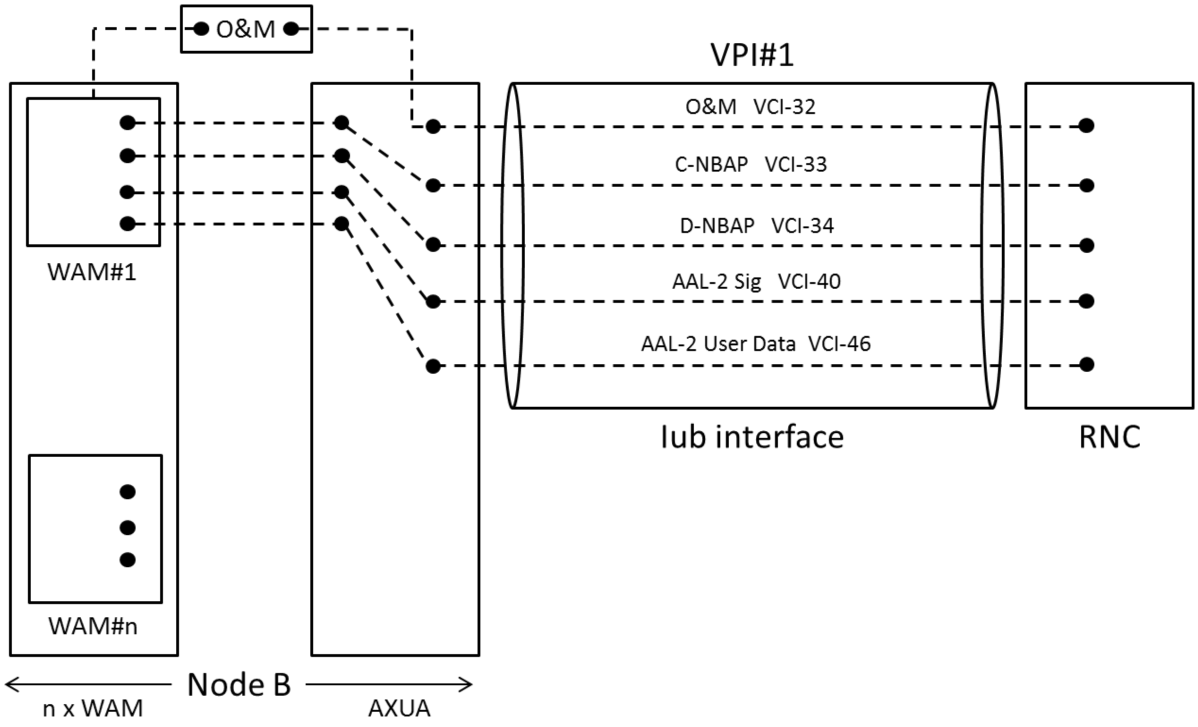


Figure 39: ATM configuration on Iub interface

4.6.2.2 Access transport design

The access transport design is focused on the connectivity between the cell site and the TN. The vast majority of sites will connect to the network via a geographically distributed TN site however a small number will connect directly to a core network site; in this case the sites connecting to the core site directly will not transit through the metro network. Designs for both solutions are required.

Starting with cell sites which will connect via a TN site. Pre-UMTS these sites typically had one, possibly two or in a few extreme cases, three x E1 Abis circuits between the BTS and BSC (located at the TN site). Adding UMTS would require additional E1 circuits on the bulk of sites however the busiest GSM sites would have 2 x E1 deployed for initial Iub configuration, as GSM/GPRS loading was a good indication of initial UMST traffic demand. Only the top 100 sites would be upgraded to 2 x E1 Iub from day 1, all others would start with a single E1 circuit and be upgraded to 2 x E1 based on traffic levels increasing to a pre-determined threshold.

Figure 20 illustrates three common microwave radio link topologies which were deployed for GSM and GPRS. Each of these chains of links had to be reviewed to understand the technical upgrade requirements necessary to add an Iub circuit in parallel with the existing Abis connectivity. This review starts with the simplest topology, a single point to point link. The microwave radio system was most likely to be 2 x E1 so depending on the configuration of the GSM BTS, there may be a spare E1 circuit available for UMTS, if this is the case then an upgrade to the microwave radio system is not required to enable an E1 transmission path between the NodeB and TN site. In this case the second E1 would be allocated to the Iub interface of the NodeB; this will connect from the IFUD to the microwave radio IDU via the DDF. At the TN site the circuit will terminate to the DDF for onwards connection to the metro network.

If the GSM BTS was using both E1s of the 2 x E1 radio system then a microwave radio system upgrade would be required. The next capacity step would be 4 x E1 however the network planning process would determine whether this could be deployed in the same frequency band, therefore reusing the same antennas and, as appropriate, any waveguide.

The second topology is a chain of three microwave radio hops with each cell site acting as a line of sight repeater for the next in the chain, therefore extending the geographical coverage area of the TN beyond local line of sight. In the base case each GSM BTS will have 1 x E1 circuit for Abis transmission. The first hop will be a 4 x E1 radio, the second likewise with the third and final hop being a 2 x E1 radio. The third hop would be suitable as the spare E1 could be allocated to Iub, likewise the second hop would have sufficient capacity if it was a 4 x E1 radio however the first hop would be capacity constrained and therefore require upgrading to higher capacity microwave radio systems. The first hop would have to support a minimum of 6 x E1 to provide an E1 for Abis and an E1 for Iub to each site in the chain. A microwave radio capacity of 8 x E1 is an option however the cost differential between an 8 x E1 radio and 16 x E1 radio is minimal and therefore the more strategic choice would be to deploy a 16 x E1 radio. The choice of a 16 x E1 radio is a greater challenge from a microwave radio link planning perspective as the wider RF channel and higher order modulation scheme results in the requirement to achieve a higher received signal level for a given performance level.

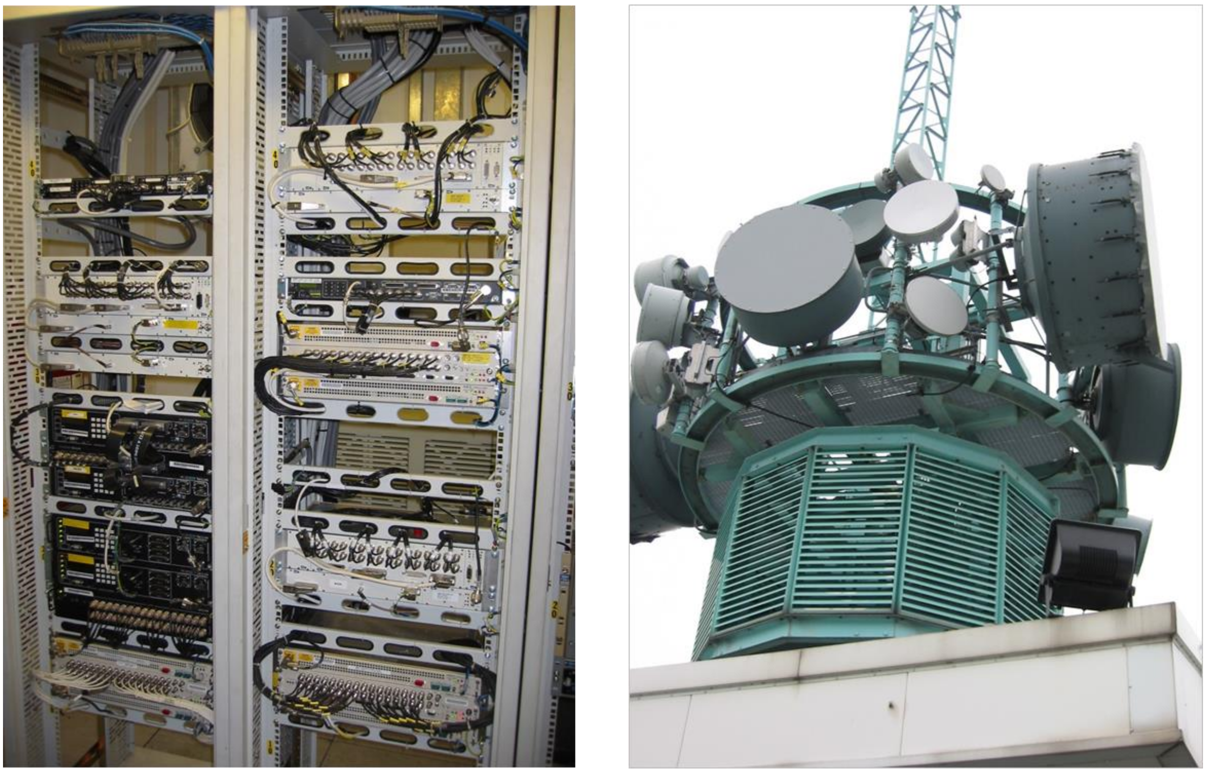


Figure 40: Microwave radio IDU’s (left) and ODU’s plus antennas (right) at a TN site (2010)

The third topology that was illustrated in Figure 20 is a variation on the linear chain and comprises a chain and star based topology. The first hop from the TN connects to a cell site which is effectively acting as a mini transmission node (known as mini-node), supporting four additional sub-tended sites, therefore the first hop already supports 5 x E1 for Abis transmission. In this scenario the first hop from the TN is likely to be an 8 x E1 radio system and therefore has 3 spare E1 ports. The topology behind the mini-node is complex as there are two single hop links and a chain of two links. Each single hop link is likely to be a 2 x E1 radio while the first hop of the two hop chain from the mini-node is likely to be a 4 x E1 radio with the last hop being a 2 x E1 radio.

In this scenario only the microwave link between the TN and mini-node will need to be upgraded, from 8 x E1 to 16 x E1. Given that five sites are dependent on this link and therefore a failure would result in a large geographical outage, this microwave radio system will be implemented as a 1+1 radio, therefore both IDU and ODU will be duplicated and operating in hot-standby mode to improve overall network availability.

There are many other variants of access transport network topologies, chains of 1, 2, 3, 4 or more links are possible in certain scenarios while many variations of chain and stars, spurs etc. can be found in the live network. Generic upgrade rules will be issued to cover all scenarios, as per the use case discussed above.

4.6.2.3 TN site transport design

The scale of connectivity required between the TN site and core network site must increase significantly as UMTS is deployed, therefore the TN site design and metro transport design plays a key role in reducing overall TCO while ensuring the satisfactory performance of the new 3G mobile service. Existing Abis circuits continue to be terminated at the BSC via the DDF along with core network facing Ater and Gb interface circuits.

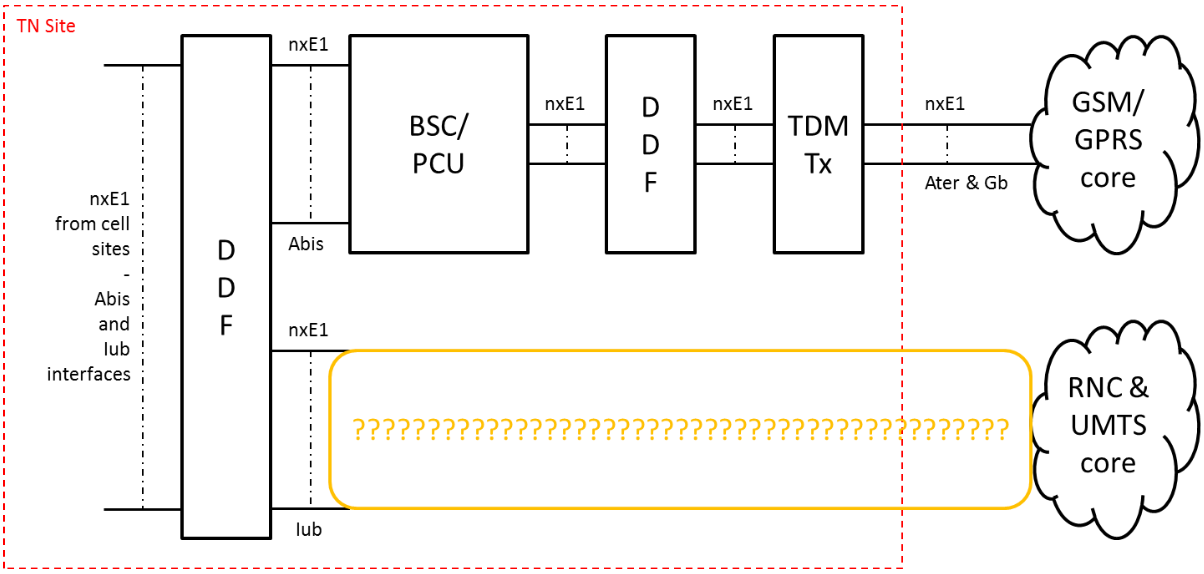


Figure 41: UMTS network architecture and design questions at TN site

Figure 41 illustrates a TN site, in red dashed lines. E1 circuits to and from cell sites connect via self-provided microwave radio or leased lines to the DDF, Abis circuits terminate to the BSC while Iub circuits require a solution for onwards transmission to and from the RNC. The Iub interface will have to span the access network, in parallel with Abis, and the metro network, in parallel with the Ater and Gb interfaces to reach the RNC location. The existing transmission between the BSC and GSM core was based on TDM technology, typically PDH with n x E1s. The synchronisation signal for the BSC was derived from the HDB3 line code on the incoming Ater E1 circuits.

Adding the Iub interface would result in significantly higher capacity demands on the metro network. Taking the example from Table 7, the metro network increases from 12 x E1 circuits to 132 x E1 circuits with PDH based TDM transmission being used for the metro network. This assumes 1 x E1 per NodeB however traffic predictions suggested that a reasonably large number of NodeBs will require a second E1 within the next few years, therefore the solution must scale in a cost-effective manner. The actual traffic requirements and growth projections were provided by the business planning team, the author converted these to transmission network requirements represented as a number of E1 circuits per NodeB.

The overall network architecture and design requirement was to deliver a converged backhaul solution and therefore transmission and transport network alternatives had to be considered. After a technical review of the available technologies, platforms based on the following solutions were investigated:

- PDH transmission
- SDH transmission
- ATM transport

Figure 42 highlights the scope of the design work, the question marks illustrate the opportunity for a new and innovative solution, ideally a solution that is fully integrated in such a way that it serves the diverse requirements of GSM/GPRS and UMTS within a single metro network.

PDH transmission could be used however as the majority of TN sites were connected to the core network via leased lines; the CAPEX and OPEX would be very expensive. A small number of TN sites were connected to the core via self-provided microwave radio solutions, typically 16 x E1 radios, which didn’t have enough capacity and therefore would need to be upgraded and even then, microwave radio systems of the day were unlikely to deliver the capacity required in a cost-effective manner. A small number of TN sites had been connected to the recently deployed Orange Wideband Transmission Network (WTN), which was an optical fibre based network built on leased dark fibre which supported wavelength division multiplexing. The WTN was built to interconnect core network sites and offered a short return on investment when compared with the high number of leased E1s in use prior to WTN implementation. The TN sites on WTN are a special case and will be explained later.

SDH transmission would be a new solution for the vast majority of TN sites (except those on WTN); this would deliver n x E1 via a synchronous transfer module (STM) payload. STM-1 is the lowest level of SDH transport bearer; it operates at 155.52 Mbps and supports 63 x E1 circuits mapped to a VC-4. This use of a VC-4 is known as channelised VC-4 as E1s are aggregated via a strict multiplexing structure and mapped to the VC-4 along with overheads which indicate their position within the payload, this enables E1 circuits to be dropped and inserted within a STM-1 frame without the need for multiple external multiplexers as used in PDH higher order circuits. Leased STM-1 circuits were expensive and therefore ideally should be optimised to maximise real throughput.

ATM transport could support the native ATM traffic from UMTS while allowing legacy TDM E1s to be carried through the use of AAL-1 CES. As a layer 2 technology ATM will require an underlying transmission solution, given the capacity required for the metro transport domain, an STM-1 based solution is most appropriate.

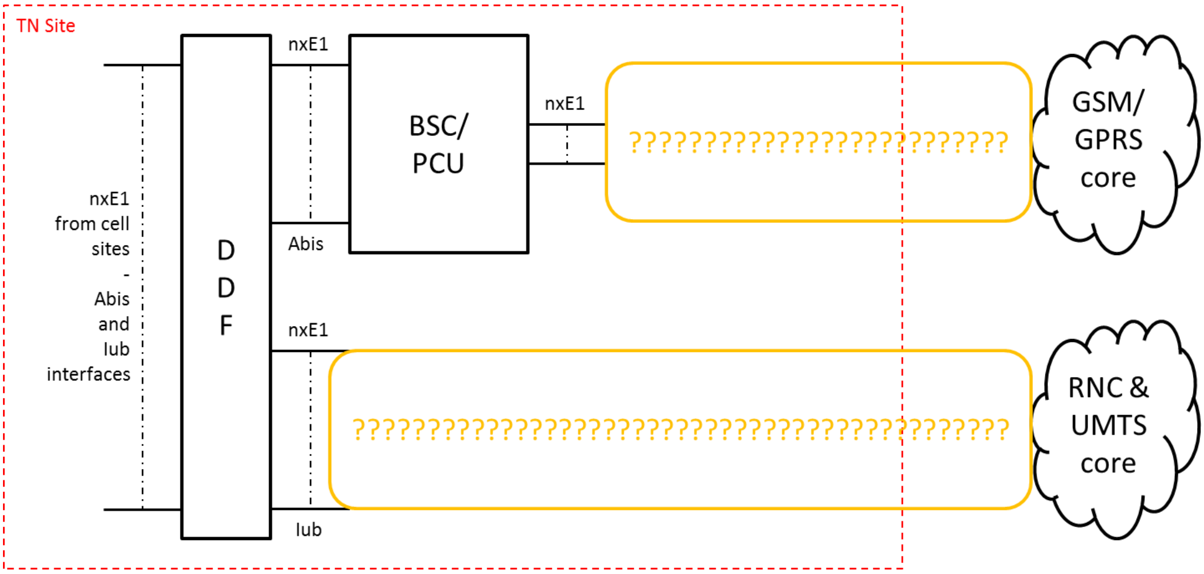


Figure 42: Overall network architecture and design questions at TN site

Leased STM-1 circuits were readily available from fixed network operators and offered significant geographical reach, therefore could be deployed in support of TN to core network metro connectivity. Given the geographical significance of the TN site, the upgrade to an STM-1 fibre based leased line involved the implementation of a diverse route to maximise availability in the event of a fibre break, which typically has a long MTTR. A leased STM-1 offered a VC-4 payload which could be utilised for a high-speed ATM connection which mapped to the unstructured VC-4, rather than the structured 63 x E1 TDM like transmission. The NodeB mapped all voice and data traffic to the Iub interface as AAL-2 while using AAL-5 for control and user signalling. The lub interface defined within 3GPP was specified with an ATM service category of CBR; this is implemented to ensure QoS however comes at a cost in terms of inefficiency on the STM-1 link between the TN site and core network site. An alternative to this approach is to utilised CBR between the NodeB and TN site then switch to rt-VBR between two ATM cross-connects/switches, this effectively decouples the relationship between provisioned Iub circuits and the capacity utilisation on the STM-1 link, saving significant OPEX by negating or delaying the requirement for a second STM-1 circuit. The use of rt-VBR did require an additional level of traffic management however this is simple enough to manage and is justified by the associated OPEX savings. As previously mentioned ATM supports a circuit emulation service, therefore as the TN site is also a BSC site, the Ater and Gb interface circuits can be emulated over the ATM STM-1. As a result of this any parallel backhaul requirements can be cancelled/decommissioned in favour of a single converged backhaul solution for GSM/GPRS and UMTS as shown in Figure 43. Since the CES uses AAL-1 and CBR and there is no option to switch these circuits to rt-VBR, the sum of CES circuits is subtracted from the available Iub capacity which can operate as rt-VBR.

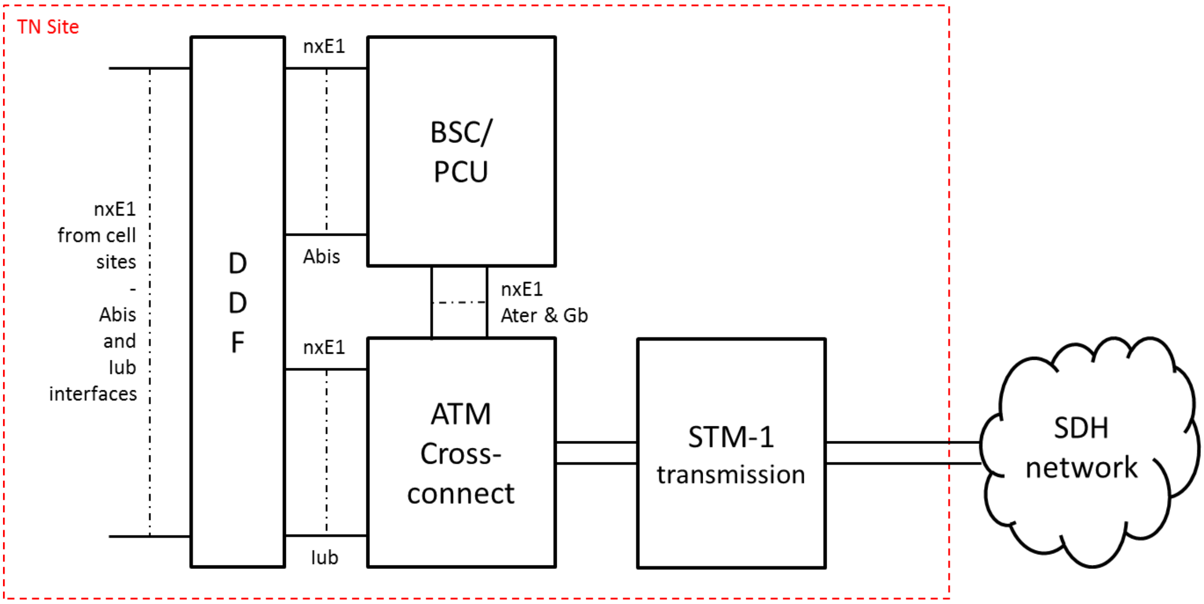


Figure 43: TN site design with ATM based metro transport network

The introduction of an ATM cross-connect or switch to the TN site enables a converged mobile backhaul solution for the metro network. The use of rt-VBR for UMTS traffic enables wide area coverage to be rolled out without a high metro backhaul costs due to the statistical multiplexing gain realised through the use of rt-VBR. This enabled far more than 63 x E1 circuits to be carried over an STM-1. After an extensive market analysis and vendor selection process, Lucent Technologies were selected as the AXC provider with their Packet Star ATM Cross-Connect (PSAX) product family. A PSAX would be deployed at the TN site and n x PSAX, as necessary, at the core network site.

4.6.2.4 Metro transport design

The metro transport network then consists of an STM-1 transmission circuit which connects between the AXC platforms on the TN and core network sites. Given the number of cell sites connected to a TN it is vital that the STM-1 transmission, and supporting interfaces to and from the PSAX, provide a high availability end to end circuit. To this end a detailed technical specification was required to enable Orange to go to market and source leased STM-1 circuits from third party fixed line network operators (Appendix 1, SPEC1000). The target architecture for the metro network solution is illustrated in Figure 44.

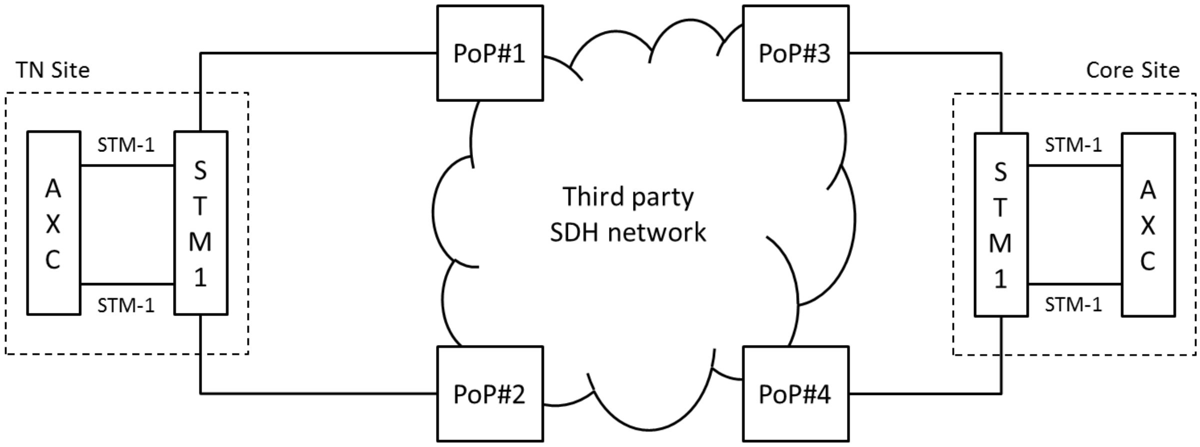


Figure 44: Metro transport network architecture

The STM-1 circuit is required to provide metro transmission connectivity between the TN site and switch site. This route will carry the majority, if not all, of the traffic between these two nodes and therefore must be designed in such a way as to minimise the probability of a service affecting outage from a single failure. The single failure could be equipment or fibre related. The STM-1 service should have total diversity through the fixed operators network and as such should not pass through any common point of failure or building. The term separacy is often used along with diversity to describe a protected circuit. Within the technical specification developed by the author for this aspect of delivery, it specified that the minimum separation between fibres should be 5 metres and the cables should enter the Orange sites via separate ducts and only come together within the equipment rack

The TN site to the left of Figure 44 connects to the STM-1 transmission equipment via two optical STM-1 interfaces; the specification states that (see appendix 1 for further details of network architecture and design documents issued as outputs from this research): The vendor shall supply an STM-1 single mode optical interface (1310nm) conforming to ITU-T G.957 I-1 or S-1.1 (ITU, 2006). The multiplexing structure shall comply with G.707 (ITU, 2014).

The Orange equipment that terminated the STM-1 has the following power ranges:

Optical Output Power	-8 to -15 dBm
Optical Input Sensitivity	-8 to -31 dBm

Table 9: PSAX STM-1 interface power levels

Multiplex section protection (MSP) provided protection of the connection within the Orange site. MSP 1+1 non-revertive unidirectional protection shall be supported in accordance with ITU-T G.841 Section 7 (ITU, 2003).

The equipment is to be installed into an Orange provided 19” rack and should not require rear access. The power will be taken from two independent -50V DC feeds (Orange provided). The equipment should have no single point of failure and should be capable of maintaining service in the event of the loss of a single PSU or single power feed.

It is expected that the supplier will offer a contracted availability of 99.99% on this type of circuit. The actual performance of the circuit should exceed 99.999% due to its resilient design.

From the technical specification and network architecture diagram it is clear that a fully diverse transmission solution is required to fulfil the needs of the metro transport network. This also determines the metro side configuration of the PSAX which must be equipped with

2 x STM-1 interface cards operating as an MSP pair to interface with the STM-1 transmission equipment from the leased line provider. Both the PSAX and STM-1 transmission equipment will operate in 1+1 mode with diverse STM-1 transmission cards and two power supply units, each powered from a different PSU on site. The target architecture minimises the probability of a wide area outage due to a transport network failure. The third party connectivity leaves the TN site by two separate optical fibre cables in two separate ducts; each terminates to a separate point of presence (PoP) on the third part network. The connectivity across the SDH core network is traffic engineered to ensure path diversity while the onwards connectivity to the core network site is once again via diverse PoPs and diverse cable routes to the core network site.

A small number of TN sites already have SDH connectivity to the core network; this is provided by the Orange Wideband Transmission Network (WTN). WTN was a national core optical network which connects all core network sites and a small number of TN sites. The first batch of TN sites to be connected to the core were used as optical amplifier sites and through the use of ROADM technology, dropped and inserted an STM-1 as 63 x E1 to the TN site for Ater and Gb interface backhaul. A number of the E1s were used for the Ater and Gb interface circuits however this left a number of unused E1 ports. Early NodeBs were connected to these E1 ports to defer the need for a PSAX investment on the WTN connected TN sites. As the number of NodeBs and/or the capacity they required increased, a PSAX would be added to scale the metro network solution over WTN. The addition of a PSAX was enabled by implementing a second STM-1 via the ROADM, this time as an ATM VC-4 payload. The Ater and Gb interface traffic remained on the first E1 based STM-1 along with a small number of NodeBs, the NodeBs arriving at the core site as E1s (non-PSAX traffic) were treated in the same way as local E1s and connected to the RNC E1 ports.

4.6.2.5 Core site transport design

The core network site was provided with diverse STM-1 connections from the metro network which were terminated to the third party STM-1 transmission equipment or WTN and then connect via an MSP interface to the AXC. The AXC will separate the Ater, Gb and Iub traffic and send the Ater to the TRAU, the Gb to the SGSN and the Iub to the RNC. The core site has a number of local cell sites directly connected; therefore these do not pass through a TN and as such won't arrive via a metro network connection. As previously presented in Table 5 the RNC had a number of E1 ports in addition to STM-1 ports, given that the STM-1 ports need to serve metro connections for Iub along with Iur between RNCs and Iu-cs plus Iu-ps for UMTS core network connectivity, the E1s would be used for directly connected cell sites. The 16 x STM-1 interfaces on the RNC are allocated as follows:

STM-1 card and port number	Function
1 – 1	Iu-cs # 1 (MSP across cards 1 and 2)
1 – 2	Iu-cs capacity growth
1 – 3	Iu-ps # 1 (MSP across cards 1 and 2)
1 – 4	Iu-ps capacity growth
2 – 1	Iu-cs # 1 (MSP across cards 1 and 2)
2 – 2	Iu-cs capacity growth
2 – 3	Iu-ps # 1 (MSP across cards 1 and 2)
2 – 4	Iu-ps capacity growth
3 – 1	Iub
3 – 2	Iub
3 – 3	Iub
3 – 4	Iub
4 – 1	Iub
4 – 2	Iub
4 – 3	Iub
4 - 4	Iub

Table 10: RNC STM-1 port allocation

Due to the number of available cards and ports per RNC it was important to allocate these in the most efficient manner. The Iu-cs and Iu-ps interfaces carry all of the traffic from the RNC to the core network and therefore had to be protected. Protection was implemented with MSP across cards to enhance availability. This utilised 4 ports while capacity growth dictated the need for an additional four ports to be reserved. As detailed in Table 10, this filled cards 1 and 2. All Iur traffic was carried within the Iu-cs connection and switched out at the first core ATM node, for onwards connection to adjacent RNCs. Based on network planning inputs it was decided that there weren't enough ports to protect the access network traffic on the Iub interface, the connection were fibre based STM-1 within the controlled environment of the core network site so failure probability was low however there was an accepted risk. To mitigate this risk somewhat, sites were allocated across STM-1 ports and cards to minimise the size of geographical outage in the event of a fibre, port or card failure.

4.6.3 End to end mobile backhaul solution design

The creation of a metro transport domain resulted in new designs for all interfaces which passed between the TN and core network site, it also achieved the objective of creating a converged transport network solution for all backhaul requirements. The cell site and backhaul design, STM-1 metro design and Lucent PSAX product (the selected AXC platform) are key to the end to end solution, along with the choice of ATM service class, rt-VBR for the vast majority of Iub interface traffic on the metro domain. The solution based on third party leased STM-1 is illustrated in Figure 45 for Iub and Figure 46 for Ater and Gb interfaces.

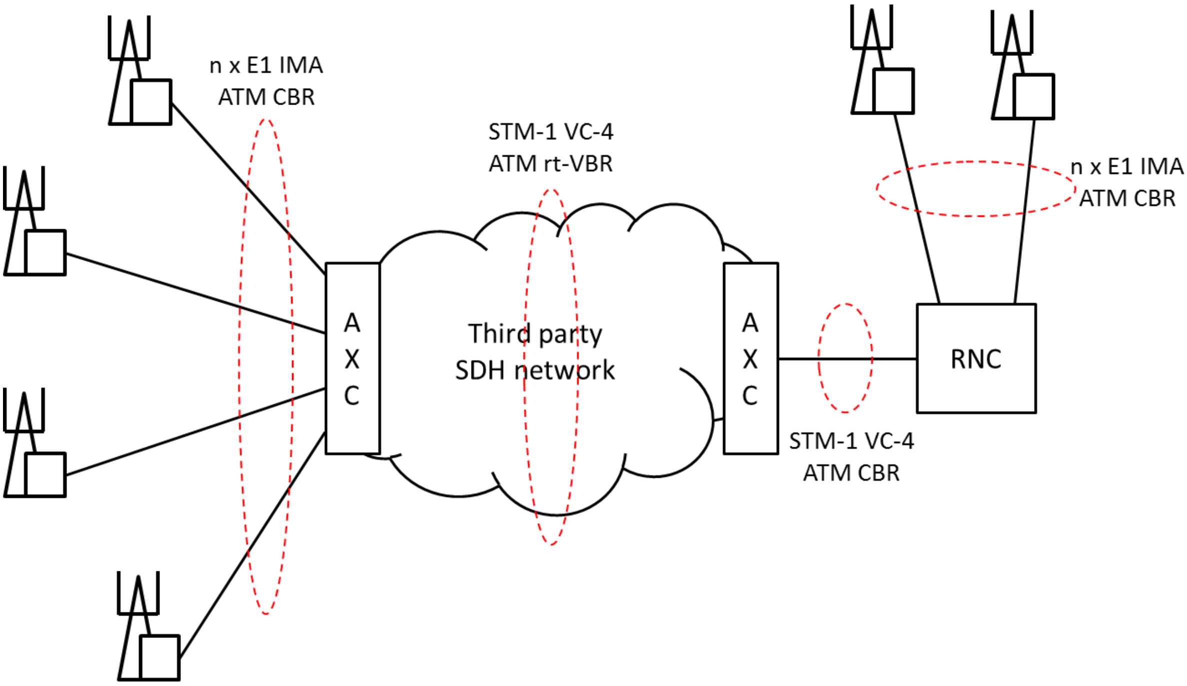


Figure 45: Iub backhaul solution (leased STM-1)

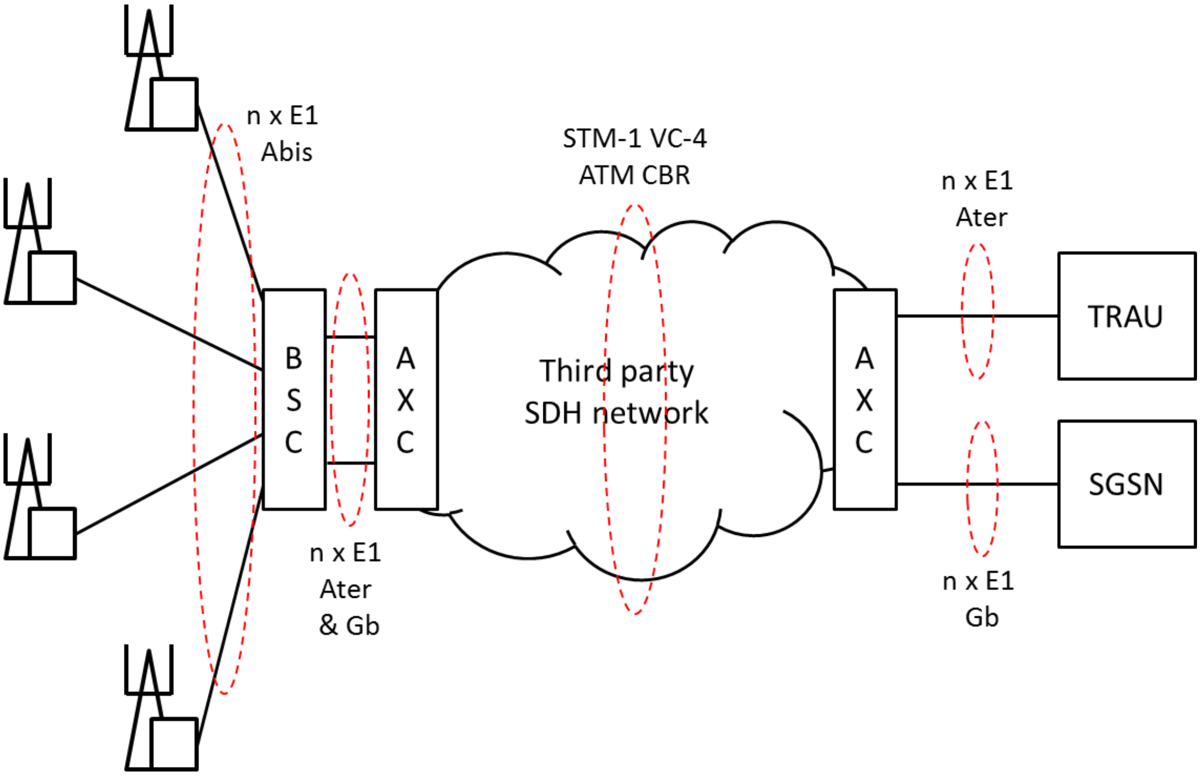


Figure 46: Ater and Gb backhaul solution (leased STM-1)

For clarity Figure 46 only illustrates connectivity from the metro to the TRAU and SGSN, any BTS sites directly connected to the core network site would connect to a local BSC. The local BSC would connect via n x E1 for Ater and Gb to the TRAU and SGSN respectively. Figure 47 and Figure 58 illustrate the metro network designs for TN sites connected to the WTN.

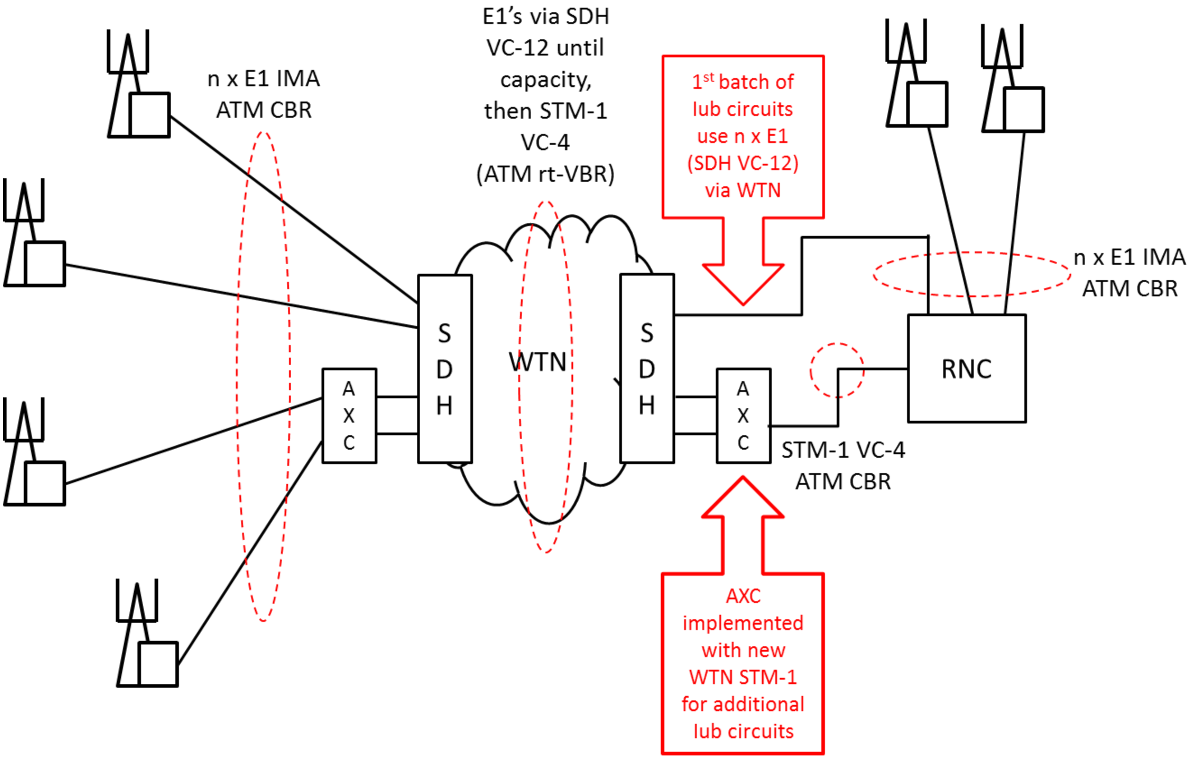


Figure 47: Iub backhaul solution (WTN)

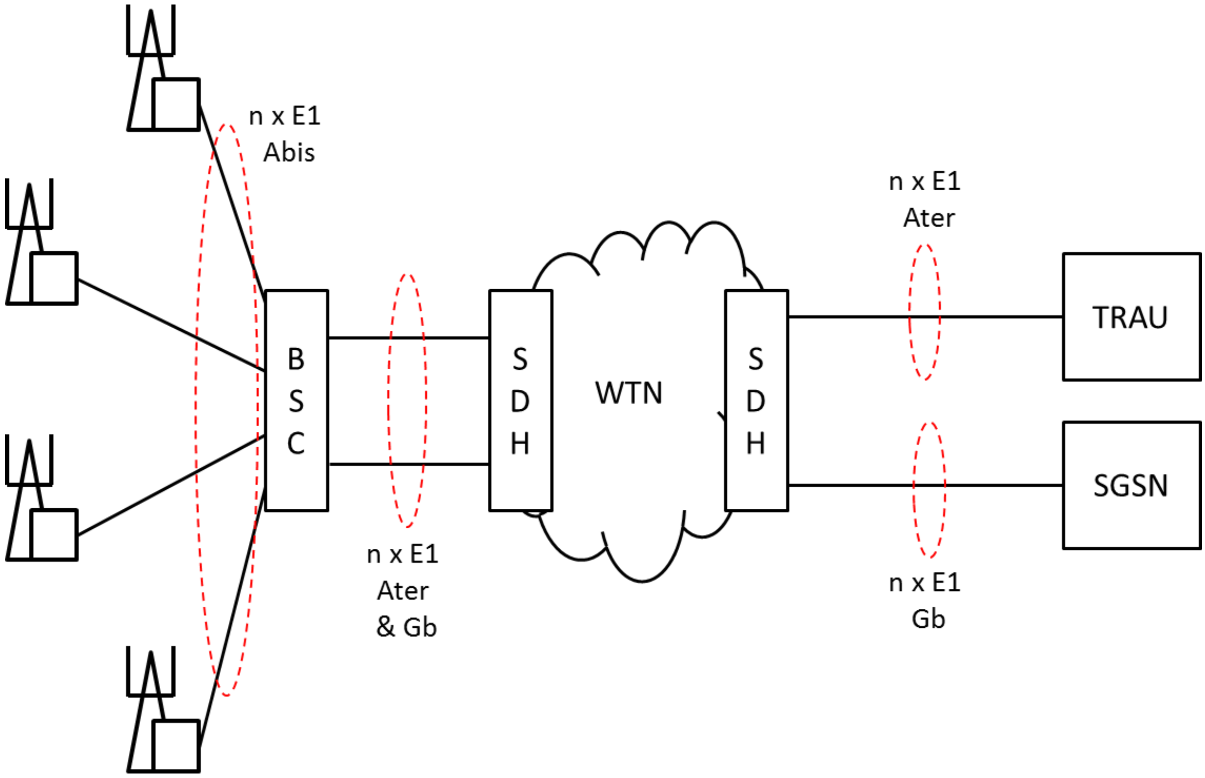


Figure 48: Ater and Gb backhaul solution (WTN)

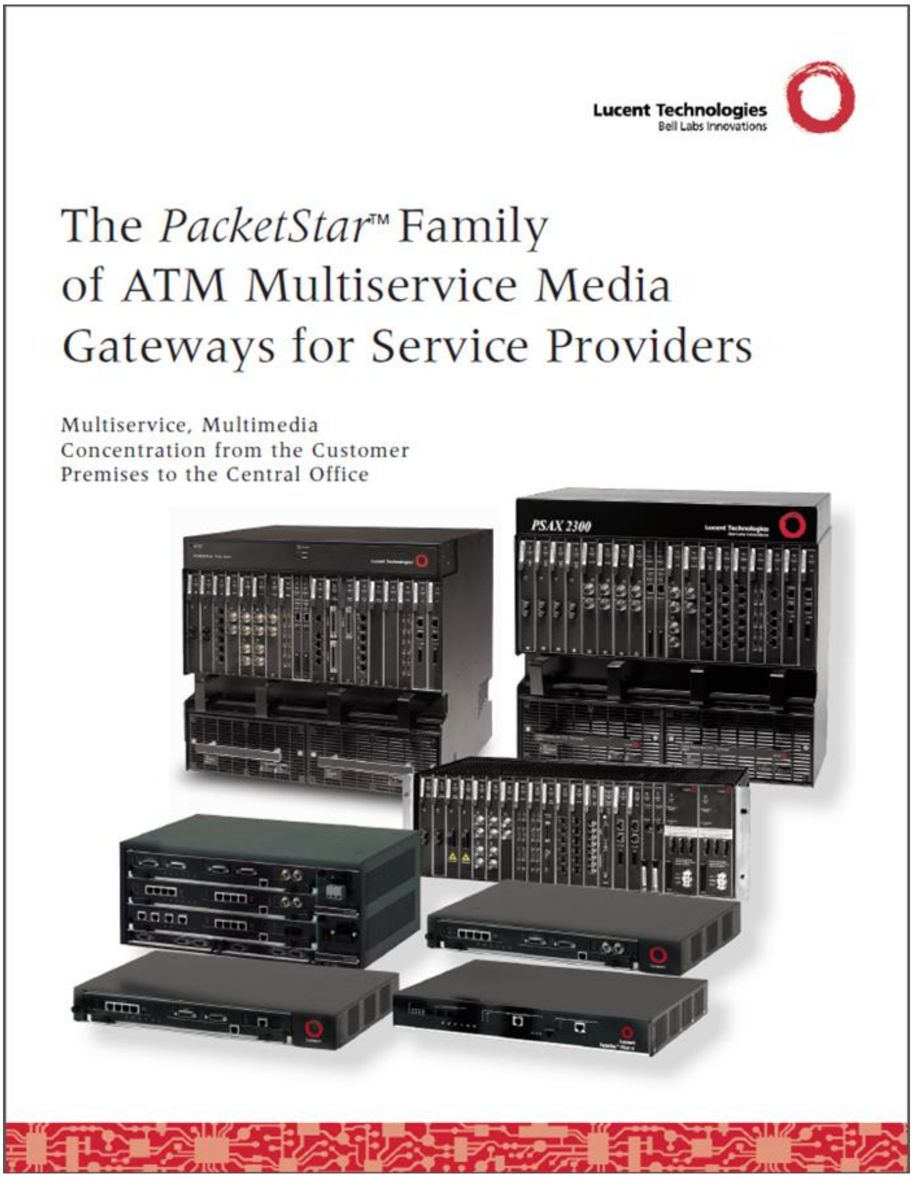
4.6.4 ATM Cross-connect

Any network architecture and design is influenced by the practical realisation of the network through the selection of specific network elements. The size of chassis, power supply requirements, number of card slots, internal switching capability and external interfaces are also important considerations. This section reviews the Lucent PSAX platform and explains the specific configurations selected for the TN and core network sites, it was vital to ensure the platform could scale to meet projected network growth in a cost effective manner, hence careful allocation of card slots to enable future upgrades was necessary.

The Lucent PSAX (described as AXC in architecture and design descriptions) product family includes the following platform variants:

- PSAX 15
- PSAX 50
- PSAX 100
- PSAX 600
- PSAX 1000
- PSAX 1250
- PSAX 2300
- PSAX 4500

The PSAX 15 and 50 are customer premises equipment (CPE) while the PSAX 100 and 600 are designed for edge implementation. PSAX 1250, 2300 and 4500 offer higher capacity and were typically used deeper in the ATM core network. After a detailed techno-economic analysis the PSAX 2300 was selected for the TN site while the PSAX 4500 was selected for deployment to core network sites, terminating multiple metro networks from PSAX 2300s. As network rollout and capacity scaled, additional PSAX 4500 platforms would be added to core network sites.



Lucent Technologies
Bell Labs Innovations

The *PacketStar*™ Family
of ATM Multiservice Media
Gateways for Service Providers

Multiservice, Multimedia
Concentration from the Customer
Premises to the Central Office

Figure 49: PSAX product family (Source: Lucent Technologies)

The Lucent platforms can support a wide range of services however their use in the Orange metro network was quite specific with a sub-set of capabilities required. The Orange network design requirements dictated that the platform must be configured in such a way as to maximise network availability, therefore redundant features are implemented as follows.

PSAX 2300:

- Dual power supply units to be installed, each with a DC power supply from a diverse source

- 2 x CPU2 cards to provide redundancy (1+1) due to the critical nature of this card within the PSAX chassis.
- 2 x stratum cards to provide redundancy (1+1) due to the critical nature of this card within the PSAX chassis.
- 2 x 1 port STM-1 MSP cards to provide a protected interface between the PSAX and STM-1 transmission system

The PSUs, CPU2s and Stratum cards have fixed locations with the PSAX 2300 chassis, the remaining 15 slots can be populated as required. Due to the mid-plane implementation the chassis is split into three segments, slots 1 to 4 are segment B1, slots 5 to 8 are segment B2 while slots 9 to 15 are within segment B3. Each segment has a maximum throughput of 650 Mbps. The STM-1 MSP cards are placed in slots 1 and 2 while slots 5 and 6 are reserved for future STM-1 connections. Access circuits will be E1 based and therefore terminate to one of two card types, 21 x E1 port multi-service (MS) cards will support CES for Ater and Gb circuits while 21 x E1 port IMA cards support Iub interface circuits. Two of each E1 access cards are deployed in the base configuration, MS cards in slots 9 and 10 with IMA cards in slots 12 and 13. Slot 11 was reserved for future MS expansion while slots 14 and 15 were reserved for future IMA expansion.

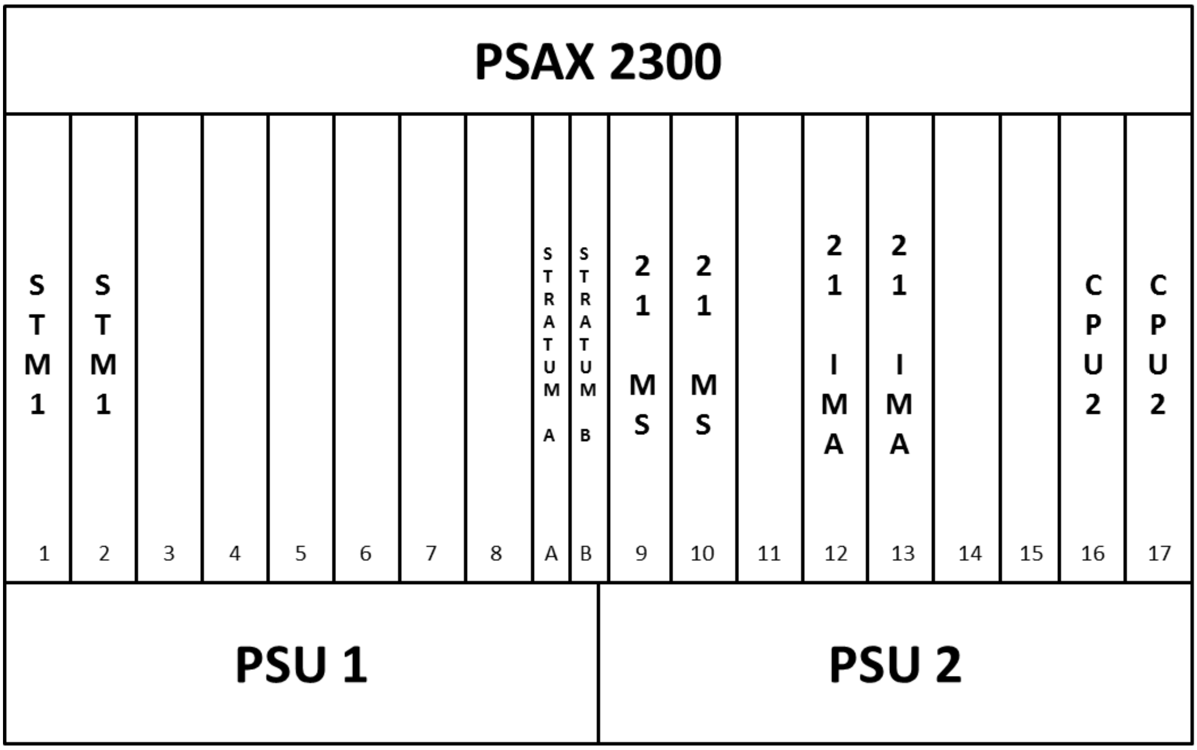


Figure 50: Lucent PSAX 2300 launch configuration

Given the number of GSM BTS sites connected to a BSC, it’s vital that the previous link diversity between primary and secondary Ater and primary and secondary Gb circuit routes is maintained, these interfaces always scale in multiples of two to ensure continued operation in the event of a circuit route failure. To realise this the primary Ater and Gb circuits were connected to the 21 x E1 MS card in slot 9 while the secondary Ater and Gb circuits are connected to the 21 x E1 MS card in slot 10. The Iub interface circuits are split across the two 21 x E1 IMA cards with adjacent sites being on separate cards, where practical, these are the cards in slots 12 and 13.

The overall capability of the TN site is significant and as previously explained, results in the need for a high-availability metro transport network architecture and design. This is illustrated to the right of Figure 51 in which two STM-1 MSP cards are installed in slots 1 and 2 to provide a fully protected interface between the PSAX 2300 and STM-1 transmission equipment, the same design is implemented irrespective of whether the SDH network is a leased service or WTN. The MSP connections consists of 1 working STM-1 path and one standby path, protection switching can be realised in <50ms in the event of a failure of a card or the optical connection between the two pieces of equipment.

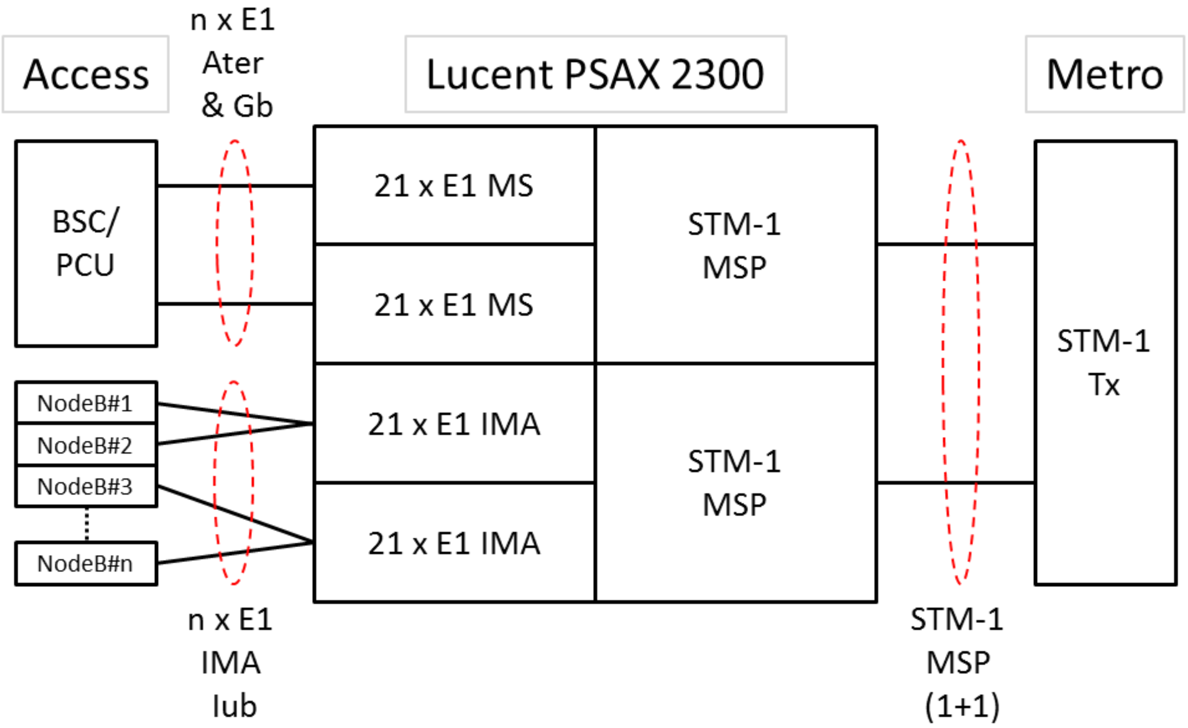


Figure 51: Logical representation of PSAX 2300 connectivity between access and metro domains

PSAX 4500:

- Dual power supply units to be installed, each with a DC power supply from a diverse source
- 2 x CPU2 cards to provide redundancy (1+1) due to the critical nature of this card within the PSAX chassis.
- 2 x stratum cards to provide redundancy (1+1) due to the critical nature of this card within the PSAX chassis.
- 2 x 1 port STM-1 MSP cards to provide a protected interface between the PSAX and STM-1 transmission system - each PSAX 4500 will support 4 x MSP pairs towards the metro network

The PSUs, CPU2s and Stratum cards have fixed locations within the PSAX 4500 chassis, the remaining 15 slots can be populated as required. Due to the mid-plane implementation the chassis is split into three segments, slots 1 to 4 are segment B1, slots 5 to 8 are segment B2 while slots 9 to 15 are within segment B3. Each segment has a maximum throughput of 1.2 Gbps (compared with 650 Mbps on the PSAX 2300 platform). The STM-1 MSP cards are placed in slots 1 and 2, 3 and 4, 5 and 6, 7 and 8, to support a total of 4 x STM-1 metro circuits, therefore 4 x TN sites connect back to 1 x PSAX 4500 at a core site (RNC location). The base build will be 2 x PSAX 4500 per core site, therefore supporting up to 8 x TNs; additional PSAX 4500 platforms will be added as UMTS network rollout progresses. Any additional installations will have the same base build as the initial two units. Connectivity to the RNC will be a single (unprotected STM-1) interface from the card in slot 9 while capacity growth will be managed through the second STM-1 card in slot 10. Local E1s will initially terminate directly to the RNC E1 ports, network rollout and capacity forecasting had highlighted that there wouldn't be enough ports to accommodate all requirements, therefore the core site PSAX 4500s would provide local access via 3 x 21 port E1 IMA cards, in slots 13, 14 and 15. This ensures maximum scalability at lowest cost on an end to end basis.

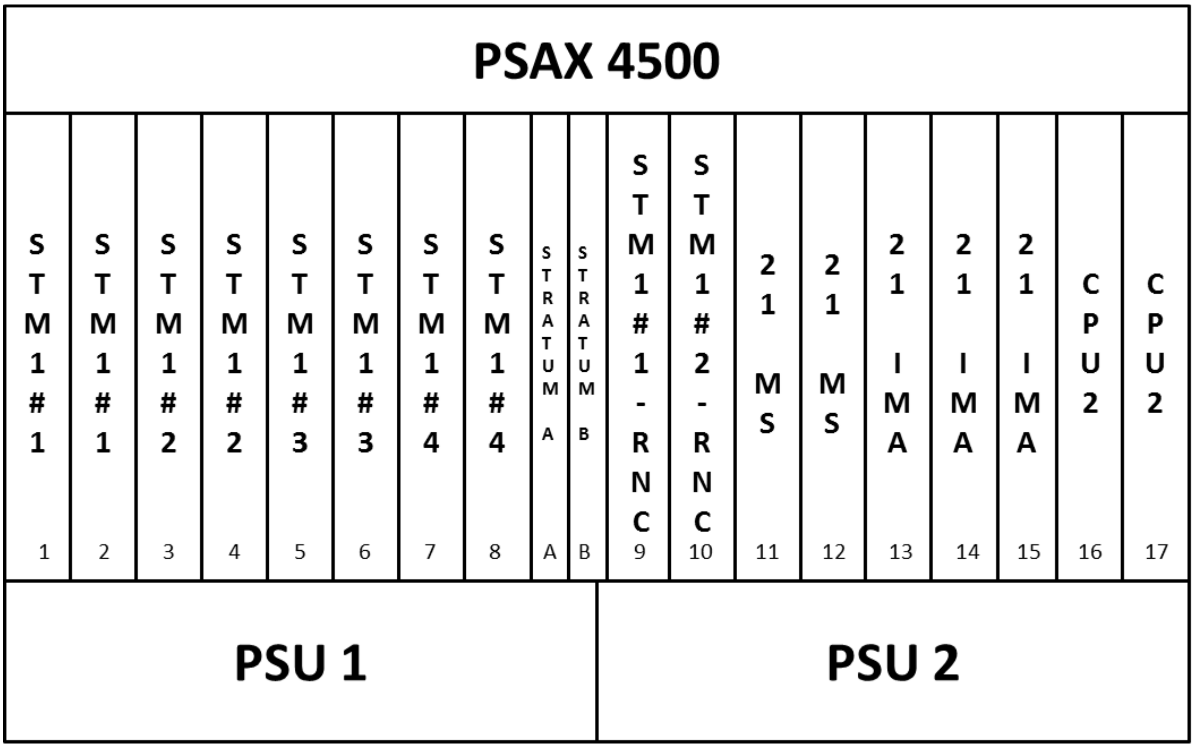


Figure 52: Lucent PSAX 4500 launch configuration

To maximise overall system availability and strike the right balance in the techno-economic analysis, the highest risks of failure are mitigated through the use of local connectivity and metro fibre diversity while unprotected interfaces are used where the risk of failure is minimal and/or mean time to repair is low. The connections between the PSAX 4500 and RNC are simple fibre tails, via an optical distribution frame, between racks in the same core network site. The core network sites have controlled environmental conditions and access security management. The GSM Ater and GPRS Gb interfaces must be terminated on the PSAX 4500 as E1s for onwards connectivity to the TRAU and SGSN respectively, this is managed through the two 21 x E1 port MS cards in slots 11 and 12.

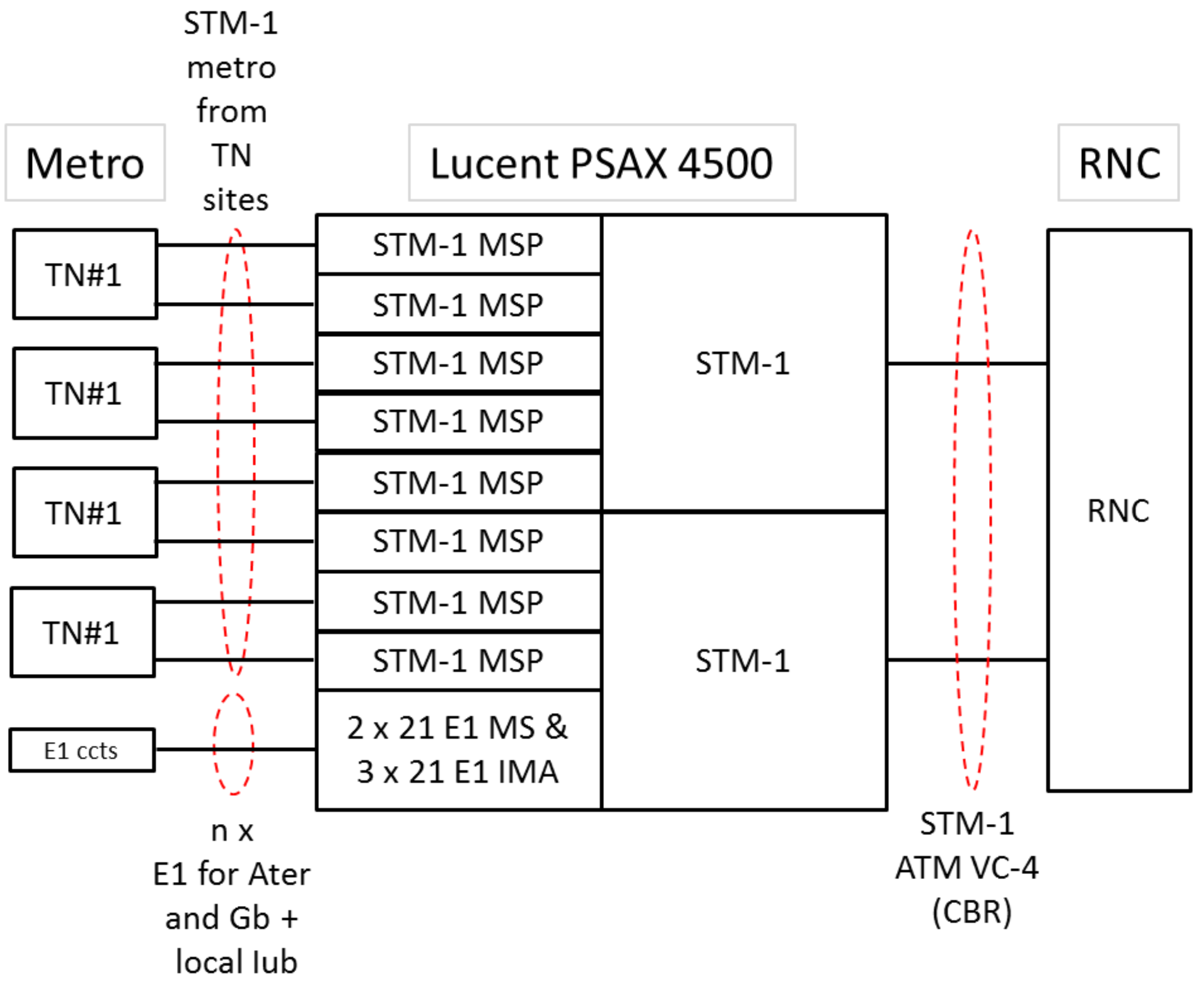


Figure 53: Logical representation of PSAX 4500 connectivity between metro domain and RNC

4.6.4.1 TN installation

To be able to support 21 x E1 circuits on a single interface card, be it MS or IMA, the ports are implemented as 120Ω balanced E1s as these take up far less space than 75Ω unbalanced coaxial cable connectors. The Orange network was implemented with 75Ω unbalanced coaxial interfaces for E1 circuits and therefore a conversion had to take place, this requires the use of a BALUN which converted the unbalanced coaxial circuits to balanced circuits on twisted pair cables. Given the large number of circuits supported on a single cards, and even the larger number which could be supported across an complete PSAX installation, the BALUNs were fitted to rack mounted panels, each supported one card, therefore 21 x E1 BALUNs. The panels were installed on top of the PSAX chassis and cabled to the interface cards, the coaxial based inputs and outputs connect to the front of the BALUN panels, this can be seen in Figure 54.

Figure 54 shows a PSAX 2300 installation at CHS0909, a TN site on Frodsham Hill in Cheshire. The photo was taken after the initial installation however before network integration as the 2 x STM-1 connections, making up the MSP circuit towards the metro domain are not yet connected. It is likely that at this stage the leased STM-1 transmission hadn't been delivered.

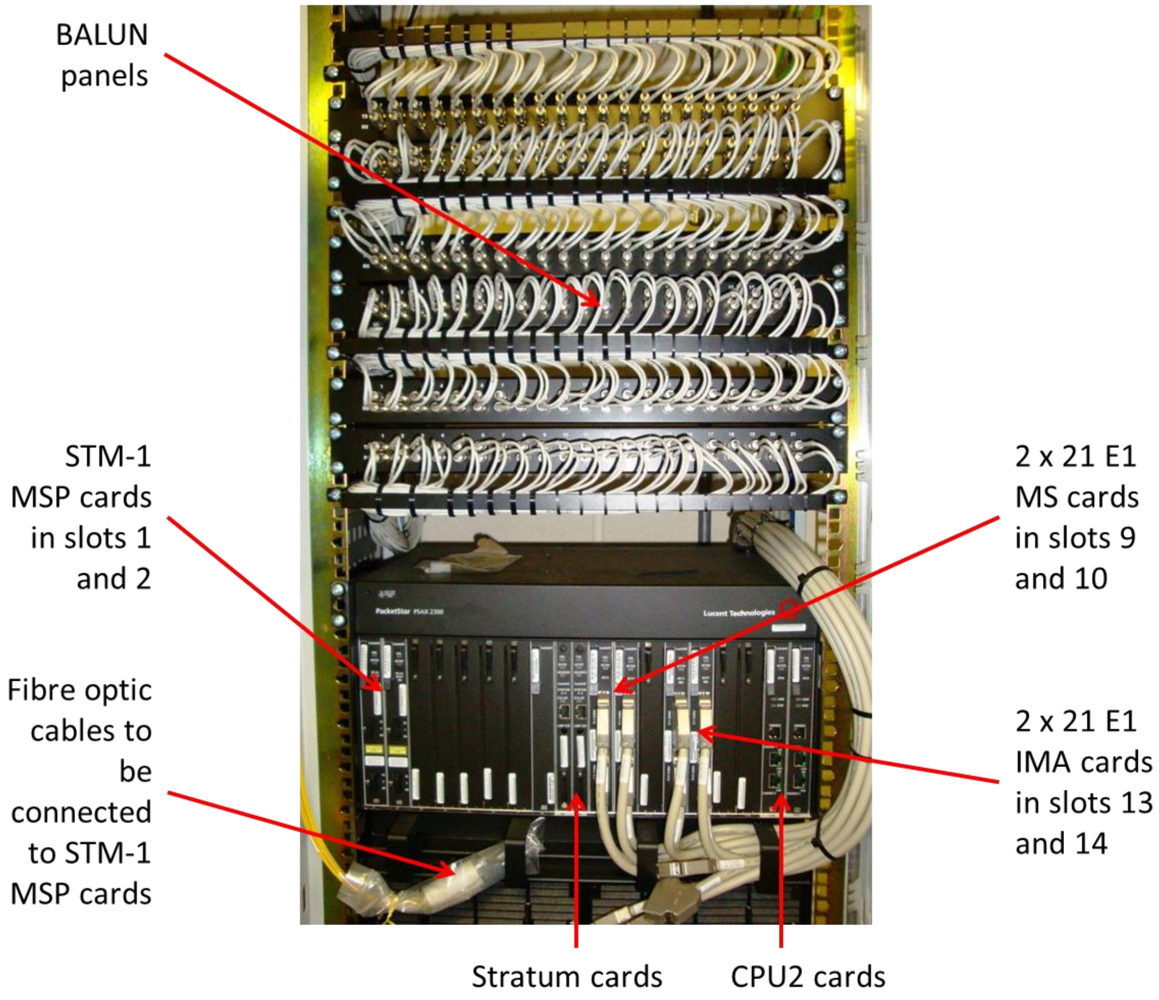


Figure 54: PSAX 2300 after initial installation (STM-1 MSP connections not yet in place (2006))

The metro network introduction enabled the consolidated GSM/GPRS and UMTS mobile backhaul network to be implemented in an efficient and cost-optimised manner as per the original design objective. The design significantly changed the way the network was implemented and scaled, it also impacted other less obvious considerations which nevertheless had to be dealt with as part of the network design exercise. The highest profile additional challenge was that of network synchronisation. As previously explained, the cellular mobile radio network requires an accurate frequency synchronisation source to ensure the BTS and NodeB radios operate on the correct frequencies and general frequency alignment is available across the network to support mobility handovers. Prior to the introduction of the ATM based metro network, there was clear traceability of an E1 circuit across the network and as such the HDB3 line code could be used to provide a deterministic 8 kHz clock reference for the BSC and onwards transmission to the BTS sites, the introduction of ATM changed this and therefore a new solution had to be developed.

The solution of choice was to deploy a GPS based synchronisation source at the TN site however due to certain vulnerabilities, such as GPS jamming and space weather incidents causing interruptions to the GPS signal, careful consideration was given to local holdover and backup synchronisation sources, in the event of a GPS outage. Figure 55 illustrates the original GSM network synchronisation architecture and the new combined GSM and UMTS network synchronisation architecture (Appendix 1, PLAN362).

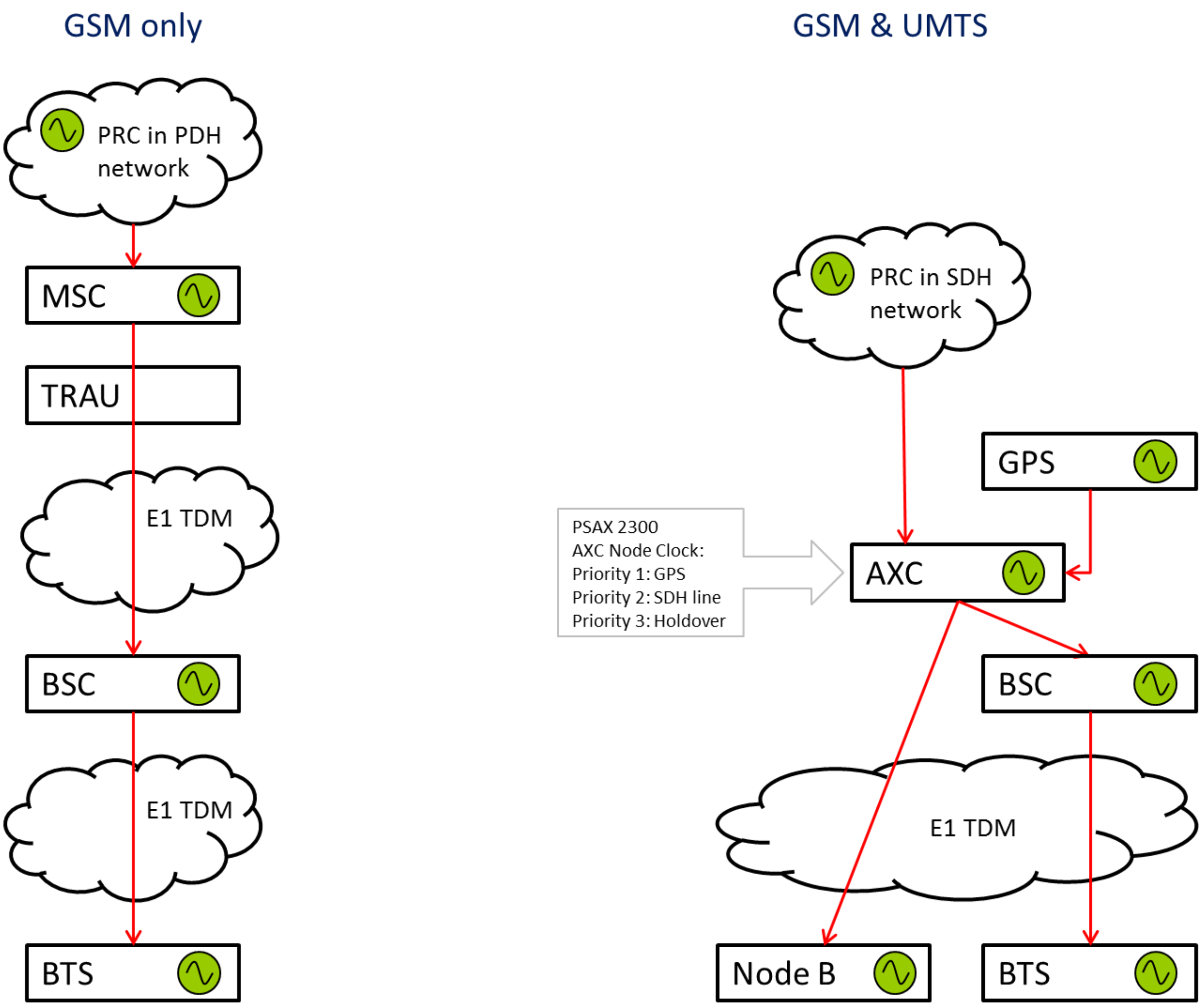
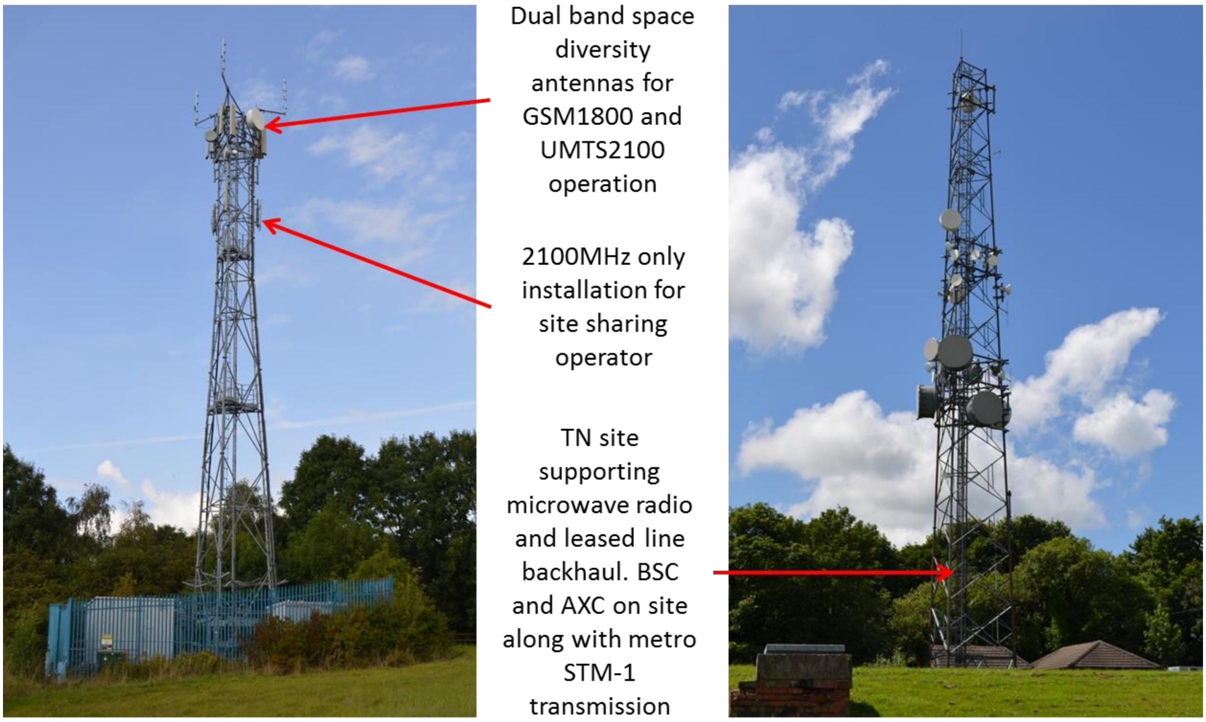


Figure 55: GSM only and GSM + UMTS network synchronisation architecture

The GSM only synchronisation solution made use of the end to end E1 connectivity; an E1 signal is synchronous by design as timeslots are accurately aligned in time behind a frame alignment signal. The GSM and UMTS solution uses a 2 Mbps output from the GPS as its primary reference signal, this is connected to port 21 of the MS card in slot 9 of the PSAX 2300 chassis. A backup synchronisation signal is available from the STM-1 aggregate line rate via the STM-1 MSP cards in slots 1 or 2, depending on which SDH transmission path is in use, normally path 1. A primary and secondary synchronisation signal is passed to the BSC via the primary and secondary Ater connections. The HDB3 line code of the E1 signal is used across the access backhaul transmission circuits between BSC and BTS and AXC and NodeB, providing a suitable reference for the local oscillators within the radio base stations. This solution provided a +/-16ppb reference on the transmission link which ensured the radio interface operates within the +/-50ppb limits set by the GSM and UMTS radio standards.

The GPS solution is the Datum GPS-LC product, the antenna is mounted outdoors, either on the TN cabin or the radio tower while the indoor module is fitted to a 2U panel which is installed below the PSAX 2300.

The complete solution described enabled Orange to rollout a UMTS network while realising maximum technical and commercial synergies with the existing GSM/GPRS network. Figure 56 shows a macro-cell cell site with Orange GSM1800 and UMTS2100 supported via the dual band cellular panel antennas on the head-frame, backhaul transmission is provided via a point to point microwave radio link. This site also acts as a line of sight repeater to connect a sub-tended microwave radio connected site back to the TN. The tower on the right is a TN site with approx. 120 connected cell sites, supporting GSM and UMTS.



Dual band space diversity antennas for GSM1800 and UMTS2100 operation

2100MHz only installation for site sharing operator

TN site supporting microwave radio and leased line backhaul. BSC and AXC on site along with metro STM-1 transmission

Figure 56: GSM/UMTS macro cell site (left) and TN site (right) (2014)

Initial UMTS network rollout was focused on macro-cells as they provided the greatest coverage and therefore ensured the maximum geographical coverage was available as the service was deployed across urban centres and major transport routes. As rollout continued the UMST network would be deployed to more rural areas and also as upgrades to micro-cells which were deployed for either in-fill coverage or GSM capacity reasons. It was proven that areas with high GSM/GPRS traffic demands also became hot-spots for UMTS, therefore upgrading the micro-cells to support UMTS was beneficial.

4.7 UMTS micro-cells

The Nokia WCDMA product portfolio included the MetroSite base station; this is a small form factor UMTS base station which supported 2 x 5 MHz WCDMA FDD carriers (with version 2 hardware). Nokia had also released a GSM version of the MetroSite BTS which enabled an upgrade from the maximum 1 TRX supported on the PrimeSite, or 2 TRX supported on the Mini-BTS products to a maximum of 4 TRX configuration. To add a UMTS microcell to an existing GSM micro-cell often involved a cabin swap, to a larger cabin, unless the installation was wall mounted within a building. As previously explained in section 3.8 the GSM micro-cell site had n x 64 kbps of backhaul which was aggregated with other micro-cells to an aggregate bearer for termination to the BSC. The UMTS micro-cell backhaul requirement would be of a higher capacity than GSM, therefore a dedicated E1 would be provided in parallel with the existing n x 64kbps circuit (Appendix 1, PLAN599).

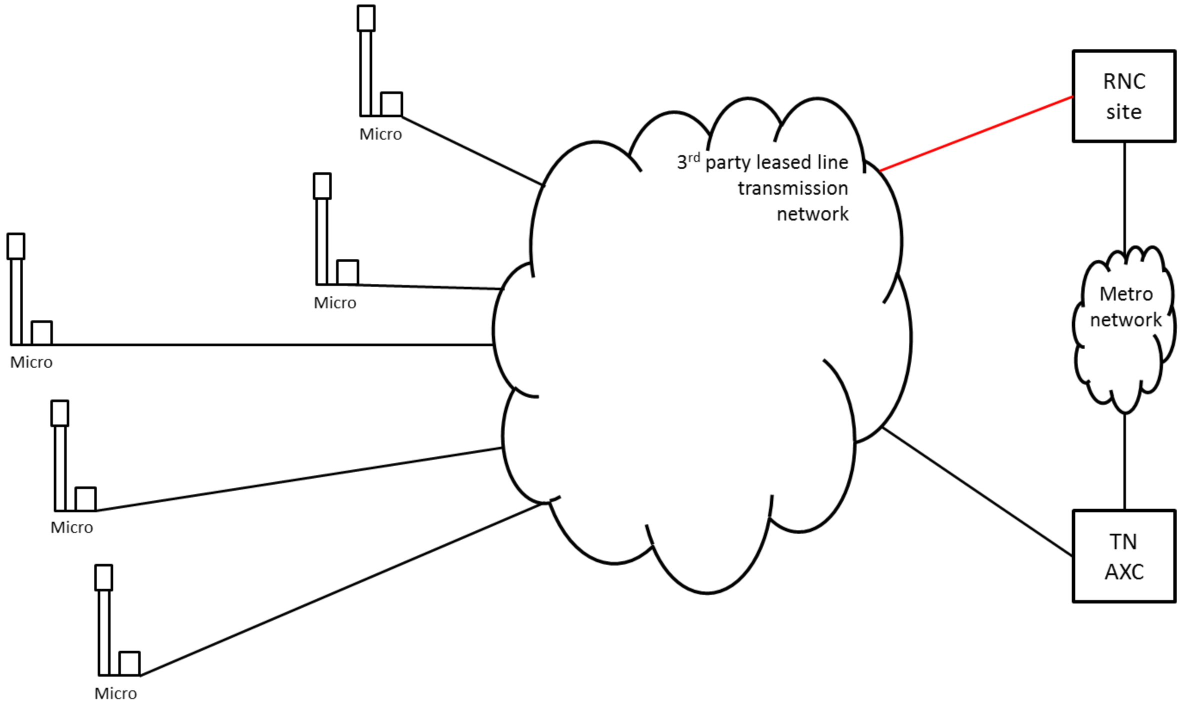


Figure 57: UMTS micro-cell NodeB backhaul

GSM backhaul had to be delivered to the local TN site (or switch site if local BSC was located at a logical TN on a core network site) however UMTS traffic does not necessarily have to go to the TN site, as the RNC is located on the core network site. The reason for most UMTS traffic terminating at a TN site is the shared use of microwave radio links with GSM traffic, the TN does provide an aggregation and optimisation function for UMTS Iub interface traffic due to the use of rt-VBR on the metro transport network. Whether to terminate the micro-cell Iub interface at a TN site or take it directly to the RNC locations at the core network site is based purely on economic considerations, to terminate at the TN incurs costs for the leased line (it is unlikely that a micro-cell will support microwave backhaul, as explained previously) along with costs of ports on the AXC and capacity on the metro STM-1 backhaul. Avoiding the latter two costs is a benefit of taking a leased line directly back to the core site however leased line charging was based on distance bounds and the core network site was likely a longer distance from the micro-cell location, hence the due-diligence during the network planning process. In most cases it proved cheaper to take the Iub interface circuit from the micro-cell directly back to the RNC location, as illustrated by the red connection in Figure 57.

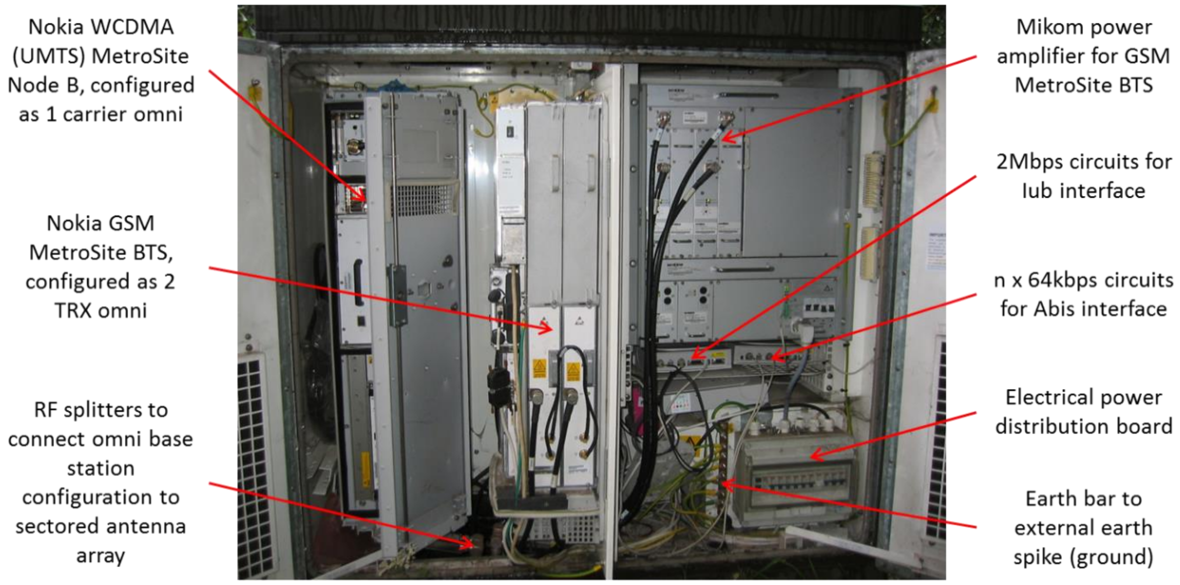


Figure 58: GSM/UMTS micro-cell street cabinet with Nokia BTS/NodeB equipment (2007)

Figure 58 illustrates a combined GSM and UMTS micro-cell street cabinet installation, both radio base stations are Nokia MetroSite products, UMTS NodeB on the left and GSM BTS on the right in the left segment of the cab. The right of the cab contains a power amplifier for the GSM BTS as the output power was limited to 5W, insufficient for this particular deployment scenario hence the need for an external power amplifier to increase the output power to 20W. An external power amplifier wasn’t required for the UMTS NodeB. The backhaul transmission was delivered as two circuits, an n x 64kbps circuit for GSM Abis, terminated as an sub-equipped E1 interface to the BTS, and a full E1 terminated to the NodeB.

Figure 59: Micro-cell installations examples, street-works (left) (2014) and building mounted (right) (2017)

4.8 UMTS traffic growth

As UMTS adoption took off, network operators noticed a steady rise in data communications. This growth in data traffic was initially driven by business users with PCMCIA data cards in laptops however it wasn’t long before advanced feature phones came to market with a form factor and feature set which made them very attractive in comparison with the relatively limited data capability of GSM/GPRS devices. It is fair to say that at this stage UMTS had failed to deliver on its promise with regard to mobile data rates. Initial hype had suggested a user data rate of 2 Mbps however in reality this was the total capacity of a 5 MHz carrier, because of the use of WCDMA as the air interface technology, the actual peak user data rate was limited to 384 kbps in the downlink and 64 kbps in the uplink. To manage data growth it was possible to add more carriers to the NodeB, in the case of Orange UK this would be the second and final carrier, increasing the overall cell radio capacity to 2 x 5 MHz FDD carriers. This did increase area network capacity however it didn't increase user data rates. The addition of a second carrier also increased backhaul capacity requirements and therefore all of the considerations reviewed previously with regard to microwave radio capacity, AXC ports and cards, metro backhaul and RNC capacity had to be revisited and scaled accordingly. This was managed as part of a business as usual capacity management and network planning process. To further increase user data rates and significantly scale network capacity would require enhanced technical capability, this would be delivered as part of 3GPP release 5, ratified in 2002 which included a feature focused on mobile broadband, this feature is known as High Speed Downlink Packet Access.

4.9 Summary

Chapter 4 has discussed the development of a converged mobile backhaul network to support GSM, GPRS and UMTS traffic. The segmentation of the traditional mobile backhaul network into two domains; access and metro, has enabled specific designs and optimisations to be applied where most appropriate. The research and development process involved theoretical network modelling along with test-lab experimentation, equipment validation, development of target network architecture, technical designs and practical field trials. The outcome became the technical solution implemented by Orange to support the deployment of UMTS across the UK while enabling GSM and GPRS coverage to expand and capacity to scale as necessary.

5. Evolving the 3G backhaul network for mobile broadband

5.1 Introduction

Whilst 3G adoption was steady in the early years it wasn't long before new and innovative handsets and data optimised devices such as PCMCIA based radio modules, commonly known as 'dongles', started to generate significant volumes of data traffic. Fixed line broadband penetration had increased significantly and subscribers wanted the Internet on their mobile devices and laptops when out and about. The technological landscape was evolving at a rapid pace and Internet technologies fully integrated with mobile systems and associated network interfaces. Networks were evolving from traditional TDM based transmission systems with lots of bespoke overlays such as ATM and Frame Relay to IP based technologies, including IP/MPLS, which would be transported over a unifying transmission layer based on Carrier Ethernet. 3GPP responded to the rapid growth in mobile data demand with HSDPA, this coupled with the transport network developments resulted in a second research question; How is it possible to ensure scalability of the converged backhaul network given the introduction of HSDPA and associated mobile broadband data growth? This chapter presents the next phase of research undertaken by the author and explains how suitable network scalability was achieved whilst maintaining the principle of a converged mobile backhaul network.

5.2 Background

HSDPA was a first step towards what was known as 'WCDMA Evolved', an evolution from the base 3GPP release 99 radio interface towards a true mobile broadband experience. HSDPA introduced significant changes to the UMTS system, on the radio interface it would ultimately enable peak data rates of 14.4 Mbps, albeit there would be several steps on the road to this data rate. It resulted in a new functional split between the RNC and NodeB along with a new protocol architecture on the Iub interface. The extra capacity it supported resulted in much greater volumes of traffic through the UMTS core network and therefore platforms and transmission/transport networks had to be upgraded accordingly.

Release 99 used the concept of dedicated channels for downlink and uplink transmission whereas HSDPA introduced the concept of a shared channel for downlink transmission, known as the High Speed - Downlink Shared Channel or HS-DSCH. HS-DSCH is shared amongst all users that are accessing HSDPA for their background and interactive class radio access bearers. Shared channels can be mapped to one or more physical channels, known as codes, using a fixed spreading factor of 16. HSDPA also introduced a shorter transmission time interval (TTI) of 2ms, compared with the 10, 20, 40 and 80ms transmission time intervals specified in R99. This shorter TTI enabled a more optimised Internet browsing experience as the lower end to end network latency enabled optimisation of TCP and more interactive services, such as on-line gaming from mobile phones or laptops via mobile connections. Each code (physical channel) is known as a High Speed - Physical Downlink Shared Channel, the higher data rates are possible through the introduction of 16 QAM and aggregation of multiple channels. A maximum of 15 codes is available from the fixed spreading factor of 16, one being reserved for control channels, further down the spreading factor code tree.

UMTS has a channel symbol rate of 240 ksps and with HSDPA has QPSK and 16QAM available with different levels of coding making up a new set of modulation and coding schemes. The theoretical maximum data rate of 14.4 Mbps is achieved as follows:

$$240\ (symbol\ rate) x\ 4\ (bits\ per\ symbol\ with\ 16\ QAM) =\ 960$$

$$960\ x\ 15\ (codes/channels)\ =\ 14.4\ Mbps$$

Equation 2: Maximum throughput of HSDPA

Due to complexity within devices the actual journey to 14.4 Mbps came via a number of steps. Firstly HSDPA devices supporting 1.8 Mbps were introduced, followed by 3.6 Mbps, 7.2 Mbps, 10.8 Mbps and eventually; 14.4 Mbps. The new HS-DSCH was added to the radio network layer user plane as illustrated in Figure 27 (the vertical plane on the right of the diagram). The alternative functional decomposition of the UTRAN resulted in part of the MAC layer concerned with HSDPA moving from the RNC to the NodeB, this new MAC-hs entity enabled fast scheduling in the NodeB and fast retransmissions with incremental redundancy. The HSDPA protocol architecture is illustrated in Figure 60. For comparison, release 99 UMTS protocol architecture is illustrated in Figure 38, the difference being the changes to MAC functions and the distribution of MAC entities.

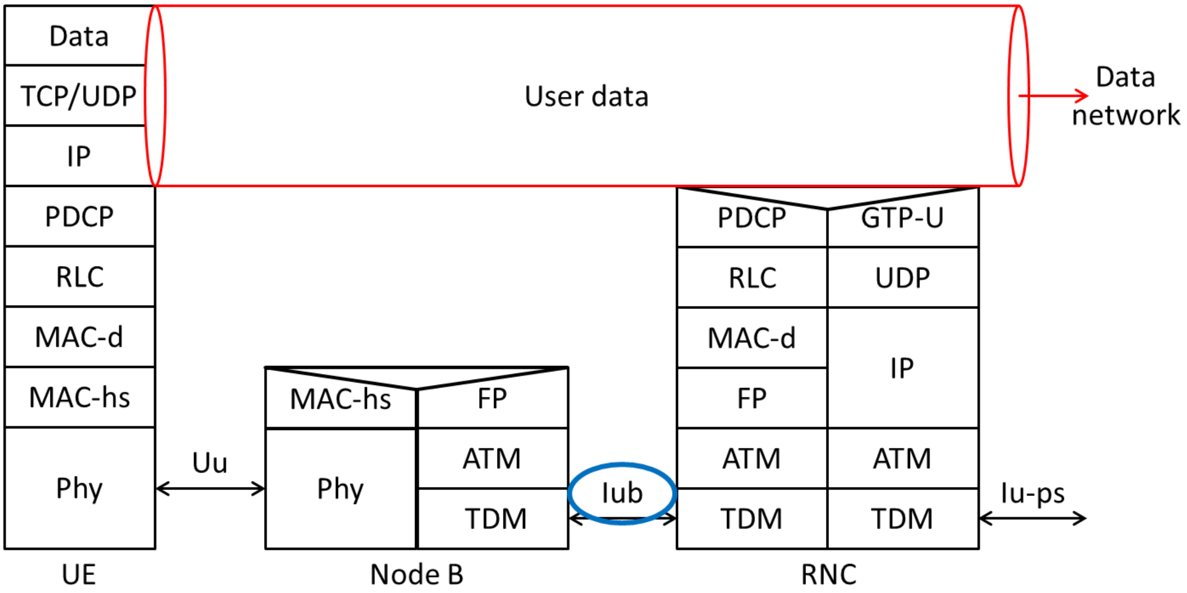


Figure 60: **HSDPA protocol architecture**

Some limited scale HSDPA rollout took place on the Orange network during late 2006 and 2007 (Orange launched HSDPA in February 2007) however the pace of rollout increased considerably during 2008, there was also a number of step changes in peak data rate too.

5.3 UMTS network status

The first Orange UK UMTS NodeBs were commissioned and integrated in 2002, rollout continued to a level considered suitable for commercial launch in July 2004. Post commercial launch the rollout continued at a pace and by August 2008 almost 7,000 UMTS sites were live in the network, for comparison, at this point in time the GSM/GPRS network consisted of almost 13,000 sites (many with n x E1 Abis). Many of the UMTS sites had been upgraded to n x E1 IMA backhaul and therefore the population of E1s in the network had grown considerably.

Description	Count
2G sites (macro & micro)	12,985
3G sites (macro & micro)	6,845
Macro sites (2G and/or 3G)	9,414
Micro sites (2G and/or 3G)	3,970
BSC equipment	284
TN sites	183
TN sites with PSAX 2300	150
MSC equipment	46
RNC equipment	38
Core network sites	22
Core sites with PSAX 4500	21
Core sites with RNC	18
SGSN equipment	16
Core sites with SGSN	15

Table 11: Orange network status as of August 2008

Table 11 provides an insight into the scale of the network and the pace of UMST rollout. A total of 150 TN sites had a PSAX 2300 deployed while 21 core network sites had a minimum of 2 x PSAX 4500 deployed, there were a total of 64 PSAX 4500s deployed across these 21 core sites, the maximum on any one core site was 4 x PSAX 4500.

The scale of growth in mobile backhaul capacity is illustrated in Figure 61, which shows the increase in the number of E1 circuits available on the microwave radio estate and how this increased over the period from 1993, the start of GSM network rollout, to August 2008. The graph is the sum of microwave radio based E1 circuits so doesn't include sites connected by E1 leased lines, these are additional circuits. The microwave E1 count gives an indication of traffic growth and also site rollout as each GSM macro-cell site had a minimum of 1 x E1 and likewise for UMTS. A site at the end of two microwave radio hops will utilise twice the number of microwave radio based E1 circuits than a site supported by a single hop, therefore network topology is also a consideration when interrupting these figures. The average microwave radio chain length across the national network was 2.2. When considered with the site details in Table 11, the growth in E1 circuits attributed to capacity is considerable.

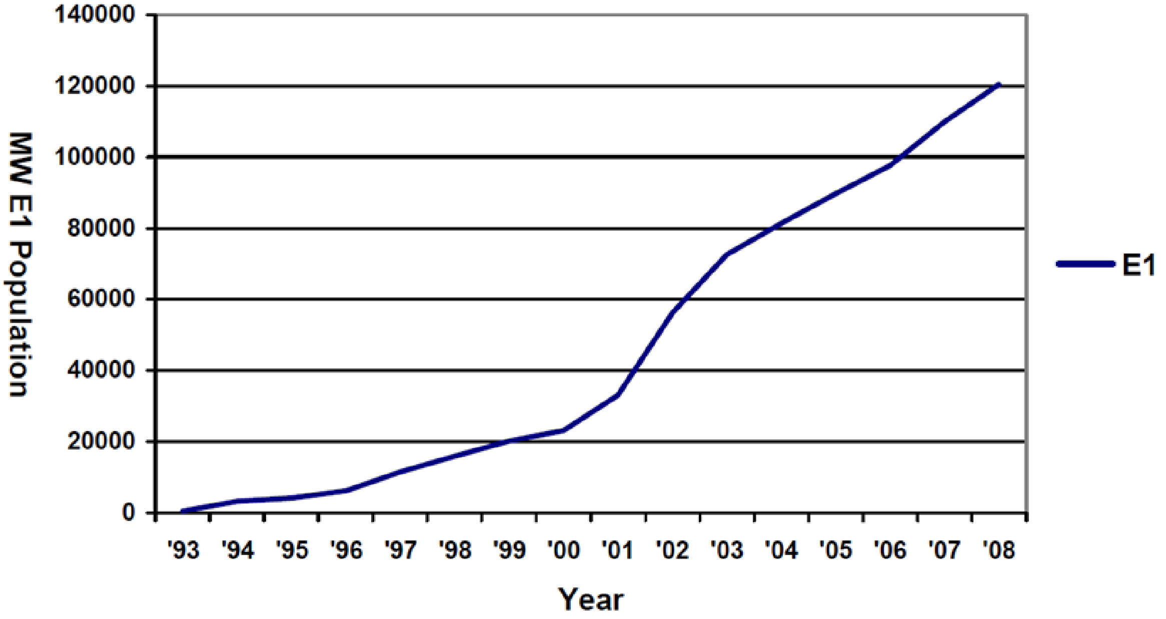


Figure 61: Microwave radio E1 count due to rollout and capacity upgrades

As HSDPA evolved and ever higher data rates arrived for UMTS, the management of such a large number of E1s was becoming a real technical and commercial challenge. Busy NodeBs were scaling to 4 x E1s with very busy sites requiring 8 x E1, the maximum supported by the IFUD interface card on the WCDMA UltraSite BTS product. Despite the fact that E1s had served the industry well for many years, an alternative solution had to be found to enable cost-effective scalability of mobile backhaul networks in support of mobile broadband. The original research question was, how is it possible to evolve a GSM/GPRS mobile backhaul network to support a converged GSM/GPRS and UMTS cellular mobile service? This had been answered however it now needed to be revisited as many of the original inputs had changed, hence the second research question which asked, how is it possible to ensure scalability of the converged backhaul network given the introduction of HSDPA and associated mobile broadband data growth?

The metro network had evolved from E1 to ATM based STM-1 however many circuits still had to be managed as E1 circuits; at the cell site, intermediate site for microwave repeaters, at the TN and within the core network site. The capacity limitations of E1 interface cards on NodeBs and other network elements had to be addressed to allow for scalability within the mobile broadband era and overall total cost of ownership had to be reduced as the volume of data within a subscribers tariff was increasing significantly however the average revenue per user was remaining flat. Work within the Metro Ethernet Forum and other industry bodies had started to explore the use of carrier grade Ethernet as a wide area networking technology while 3GPP has defined an IP TNL as an alternative to ATM. The challenge was to develop a target architecture and migration strategy to enable a cost effective evolution from ATM and TDM to IP and Carrier Ethernet, while maintaining and scaling a live operational mobile communications network. Figure 62 illustrates a large DDF in a core network site, these frames were expensive to install and maintain and simply didn't offer the scalability needs for the mobile broadband era.

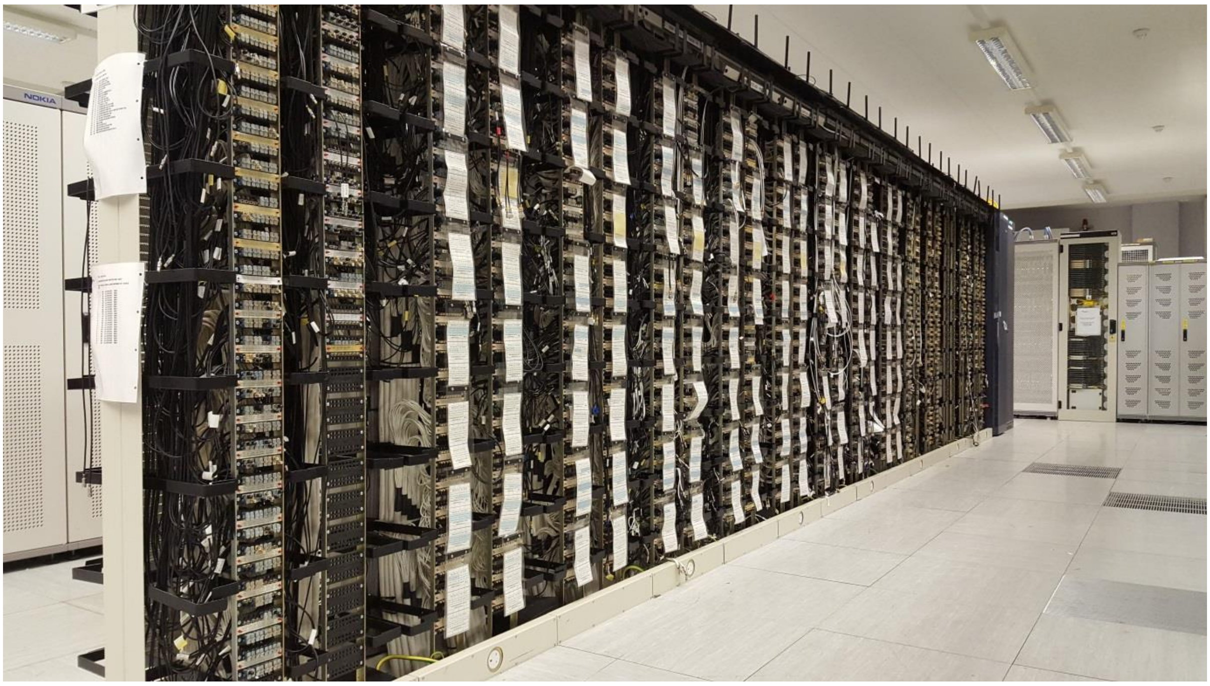


Figure 62: DDF in a core network site, this is one of several per site, taking up significant floor space (2010)

5.4 Backhaul for the mobile broadband era

The problem with scaling the access backhaul domain with E1s is illustrated in Figure 63. The chain of four microwave links is used as a model to consider the implications of scaling UMTS/HSDPA while co-existing with GSM/GPRS, the latter having now been upgraded with EDGE technology. Each site in the chain of four links terminates all of the microwave radio based E1 circuits to a DDF, some E1 circuits are used for the Abis interface and Iub interface of the local cell site while the remainder are simply patched via the DDF to another microwave radio for onwards transmission to the sub-tended site. The final link to the TN carries the aggregate traffic from all four sites. The model is then scaled for between 20 and 80 cell sites to understand the impact on the TN site, in many cases a TN site would support more than 80 cell sites however by this stage the model had delivered the answer. It was not practical from a technical, commercial or implementation perspective to scale HSDPA mobile broadband networks with underlying transmission based on a granularity of 2.048 Mbps circuits.

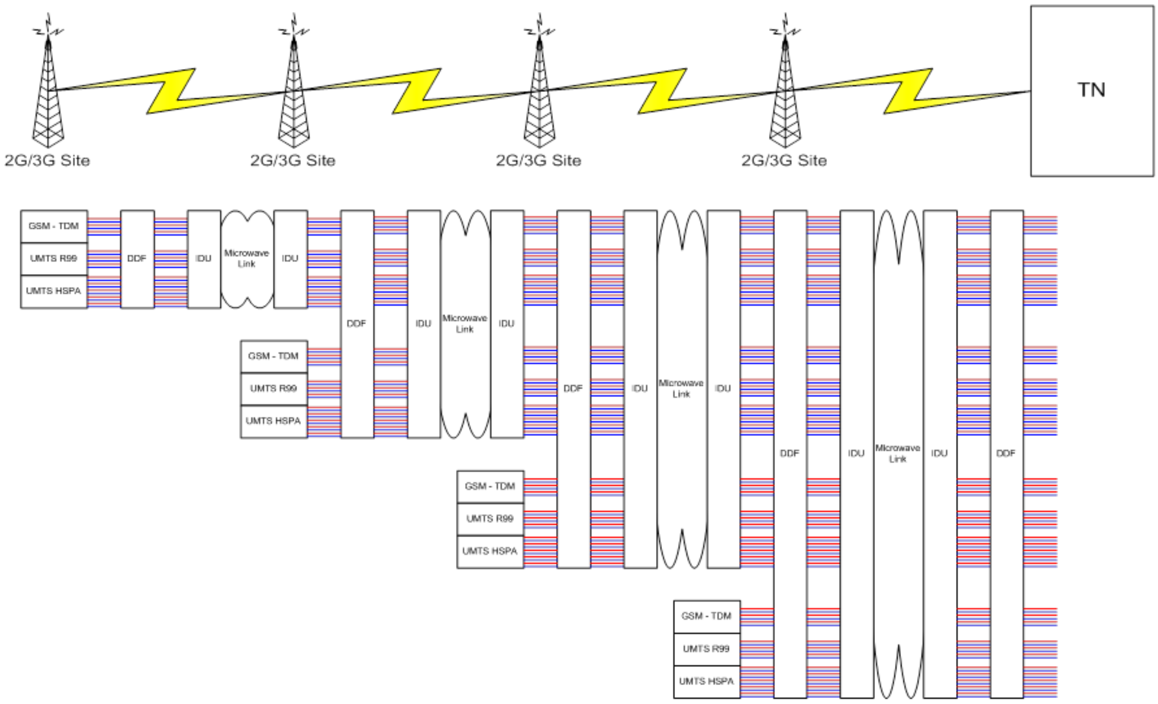


Figure 63: Increasing number of E1 circuits within the access backhaul domain

In this scenario each GSM BTS has 3 x E1 while each NodeB has 8 x E1, split logically to 3 x E1 for DCH traffic and 5 x E1 for HSDPA traffic. The model of 11 x E1 per cell site came from business forecasts for urban areas and therefore resulted in the following demand on TN sites:

- TN site with 20 sites = 220 x E1
- TN site with 30 sites = 330 x E1
- TN site with 40 sites = 440 x E1
- TN site with 50 sites = 550 x E1
- TN site with 60 sites = 660 x E1

- TN site with 70 sites = 770 x E1
- TN site with 80 sites = 880 x E1

Longer term forecasts and marketing plans predicted the need to support 14.4 Mbps (10 x E1 for HSDPA) and the new dual carrier WCDMA solution with peak data rates of 28.8 Mbps (20 x E1 for HSDPA), this would result in the following E1 demands at the TN site:

- TN with 20 sites for 14.4 Mbps radio = 320 x E1, for 28.8 Mbps radio = 520 x E1
- TN with 30 sites for 14.4 Mbps radio = 480 x E1, for 28.8 Mbps radio = 780 x E1
- TN with 40 sites for 14.4 Mbps radio = 640 x E1, for 28.8 Mbps radio = 1040 x E1
- TN with 50 sites for 14.4 Mbps radio = 800 x E1, for 28.8 Mbps radio = 1300 x E1
- TN with 60 sites for 14.4 Mbps radio = 960 x E1, for 28.8 Mbps radio = 1560 x E1
- TN with 70 sites for 14.4 Mbps radio = 1120 x E1, for 28.8 Mbps radio = 1820 x E1
- TN with 80 sites for 14.4 Mbps radio = 1280 x E1, for 28.8 Mbps radio = 2080 x E1

Considering the typical TN was a 7.2m x 3m cabin, the reality of fitting enough physical DDF in was not possible as scalability headed towards the upper bounds. Each E1 circuit had to be installed and terminated to the DDF, jumper cables applied between connecting equipment and labels applied to enable identification of circuits, this is above and beyond the costs of network planning. When a single E1 supported over 100 subscribers, the economics worked, when a single user could consume the capacity of multiple E1 circuits, the economics simply didn’t work. Even with volume the cost of supplying materials and installing 252 x E1 circuits in 2008 was £6,380. This was for E1 coaxial cables between an equipment and the DDF in a single site.

5.2.1 Evolving access and metro transport domains

The evolution of the GSM access transmission network to a combined GSM and UMTS access and metro network enabled the deployment and launch of the Orange 3G service, it also reduced the overall costs significantly when compared with an up-scaling of the previous TDM based solution. The rapid adoption of mobile data services and the introduction of mobile broadband with HSDPA highlighted the need for further innovation to enable future cost and performance optimised mobile network scalability.

Regular reviewing and updating of mobile network strategy, architecture and design is very common as technologies evolve and new use cases are identified. Typically the network is reviewed on an annual basis and new requirements identified which leads to new projects being initiated and previous assumptions questioned in light of the new requirements. The review associated with this phase of the research considered the following aspects:

- Future MNO products and services
- Network traffic forecasts
- Introduction of nodal microwave radio systems
- Evolution from TDM to hybrid microwave radio systems
- Development of pseudo-wire technologies
- Opportunities for pushing IP/MPLS technology from the core towards network edge
- Standardisation of a 3GPP IP transport network layer in release 5
- Development of high-capacity L2/L3 platforms with high-speed interfaces
- Specifications for Carrier Ethernet as a WAN technology

5.4.1.1 Future products and services

Mobile network operators such as Orange were developing a wide range of new products and services to address the growing demand for mobile data and mobile broadband services. This demand was being driven by the adoption of HSDPA dongles for laptops which generated significantly more data traffic than the typical feature phone of the time. Figure 64 is an example of an early HSDPA dongle which was launched in 2008. It was essential that the engineering teams within network operators responded with new architectures and designs to enable the mobile broadband revolution. Network traffic forecasts based on market research identified a latent demand for mobile data, this demand would quickly drive aggregated peak demand from a few Mbps to daily peaks measured in Gbps.

Orange mobile broadband gives you a high-speed mobile broadband connection when you're on the move from just £15 a month.

Figure 64: Orange HSDPA mobile broadband dongle (Source: Orange UK)

5.4.1.2 Hybrid backhaul in the access domain

Given the new products and services, coupled with aggressive traffic growth forecasts within the business plan, a fundamental review of the end to end network was initiated. Within the backhaul domain it was essential to decouple the relationship between cost and capacity, in the same way as was achieved for the initial 3G network design, via the introduction of the metro network with ATM technology and PSAX equipment.

The evolution from pure TDM microwave radios, be that PDH or SDH, to hybrid microwave radio systems resulted in parallel connectivity options, TDM ports and Ethernet over the same link. Increasingly the Ethernet port and associated features would align with the MEF Carrier Ethernet services and therefore support a range of value added capabilities such as Ethernet OAM. The addition of an Ethernet port would enable an evolution to packet switched technologies such as IP or alternatively support the use of pseudo-wires to emulate existing transmission and transport technologies such as TDM and/or ATM circuits over a high-capacity Ethernet interface. Figure 65 illustrates the optional use of an Ethernet port on the UMTS NodeB for HSDPA along with E1 TDM interfaces for R99 DCH traffic (voice, video and data), GSM is connected by E1 circuits for the Abis interface. Splitting the Iub interface in this manner is known as hybrid backhaul. This solution was available as an option on many vendors NodeBs however often required a new interface card (in addition to the E1 card) to provide the physical Ethernet port.

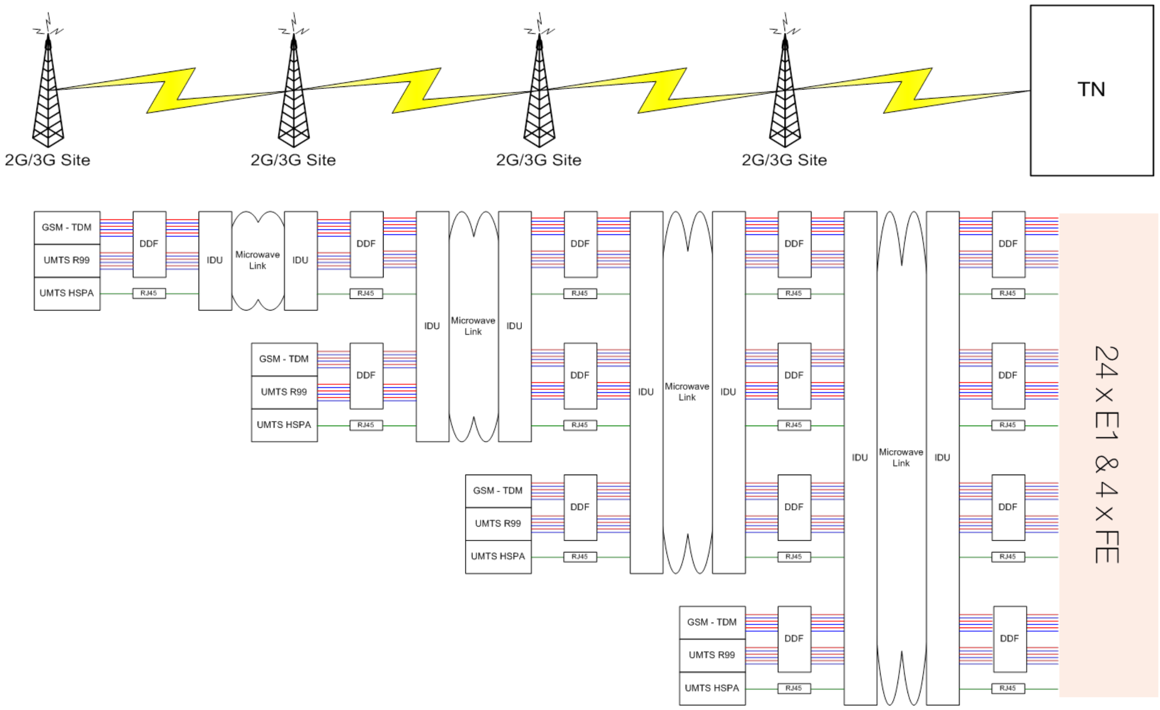


Figure 65: Hybrid backhaul of TDM E1 circuits and Ethernet

The option of adding a new Ethernet interface card to the NodeB was explored however ruled out at this stage due to costs and implementation complexity as all of the microwave radios were TDM. The network diagrams in this series are conceptual, further details of the actual solutions developed for implementation will be presented after the analysis of the options has been completed.

5.4.1.3 Nodal microwave radio

Microwave radio equipment vendors, with input from network operators, had started to develop nodal based microwave radio systems. These radios enabled multiple individual point to point links to share a single IDU, within which cross connections could be mapped via an internal TDM switch therefore removing the need to cable out all E1 circuit to a DDF, only local connectivity requirements needed to be cabled. This would save cost and enhance overall system reliability. The number of radio link supported would vary by vendor with 2, 4 and 10 being common maximum configurations.

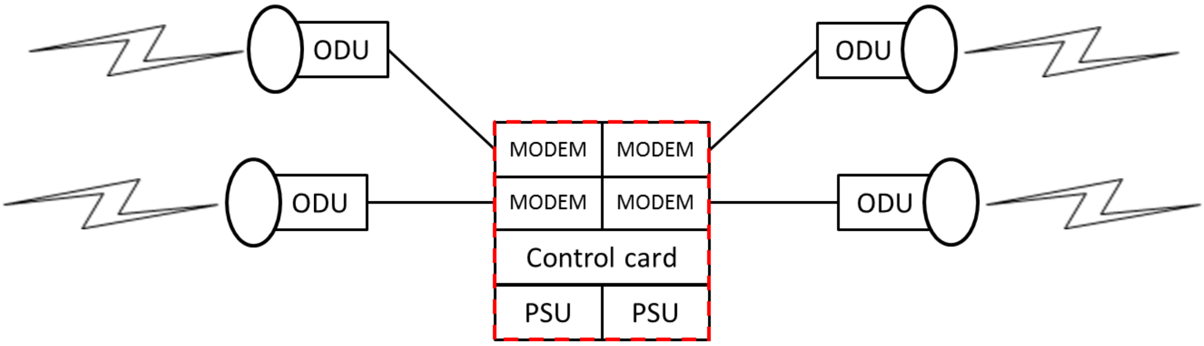


Figure 66: Nodal microwave radio concept

Figure 67 illustrates the concept of nodal microwave radios in a typical chain of 4 links. The internal cross-connect is represented by the blue interconnection between the two units marked 'IDU' on each site, unlike Figure 65 this concept has a single nodal microwave radio node at each cell site (acting as LoS relay for next site in chain) which only exposes the E1s and Ethernet circuit required for local connectivity, everything else is cross-connected within the unit, often on the control (and switching) card as illustrated in Figure 66.

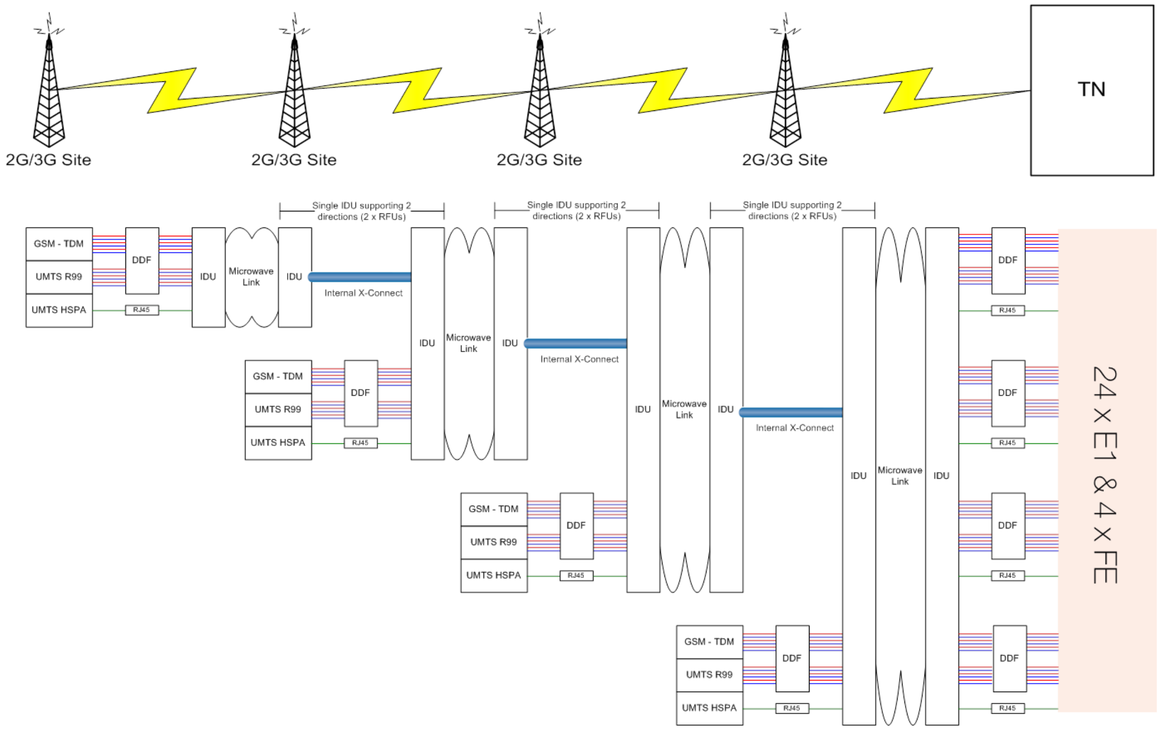


Figure 67: Nodal microwave radio systems with internal cross-connection capability

The Ethernet circuits are simply mapped to n x E1s worth of capacity within these early hybrid radio and cross-connected accordingly, hence no Ethernet aggregation as such, the original 4 x Ethernet interfaces are presented at the TN site in parallel with the E1s from the 4 cell sites.

5.4.1.4 Hybrid microwave radio

Hybrid microwave radio systems combine TDM and Ethernet capability and over time evolved to support more enhanced Ethernet capabilities such as VLAN switching.

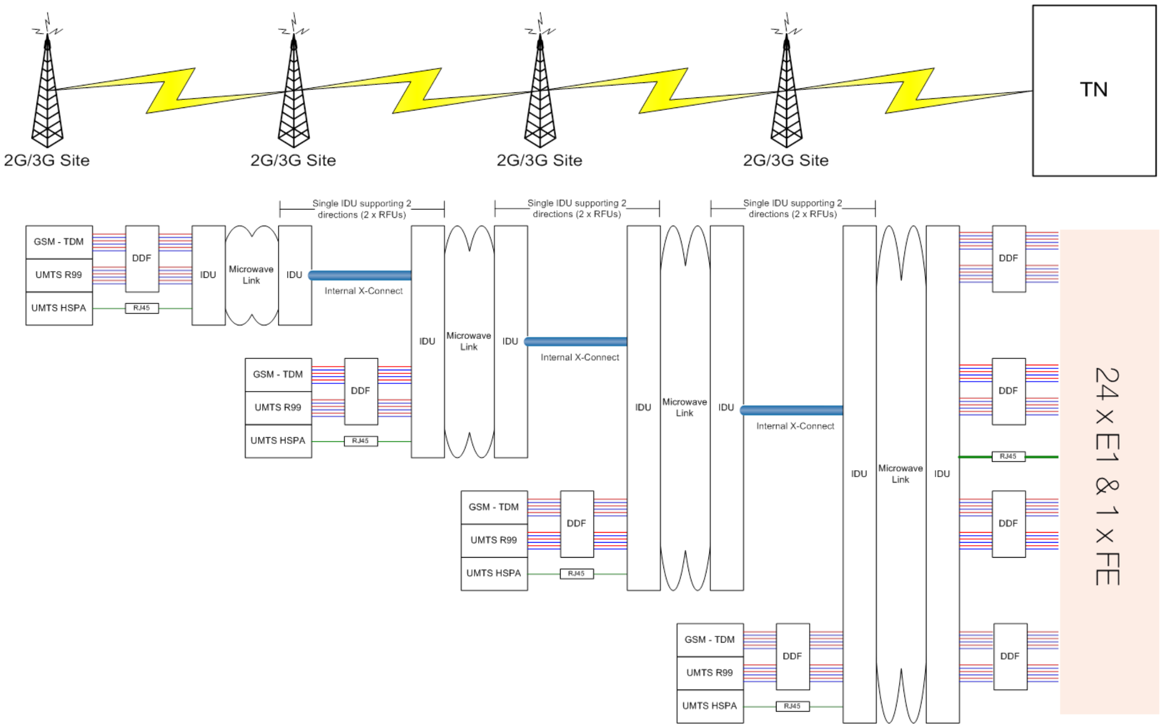


Figure 68: Ethernet VLAN switching within nodal radio unit

The addition of Ethernet switching and in particular VLAN switching, would enable the HSDPA traffic from the 4 cell sites to be aggregated on a single Ethernet connection between the TN IDU and patch panel, for onwards connectivity to the metro network. This would further reduce costs and installation time, it would also save precious physical space within the space constrained TN cabin. The complete Iub interface could be carried over an Ethernet interface, either as a pseudo-wire or alternatively, as a 3GPP IP transport network layer. This is illustrated in Figure 69. This approach would have resulted in a need for an alternative frequency synchronisation strategy as the deterministic 8 kHz clock from the E1

HDB3 line code would no longer be available, unless it was sub-tended from the GSM BTS to a suitable E1 port on the NodeB.

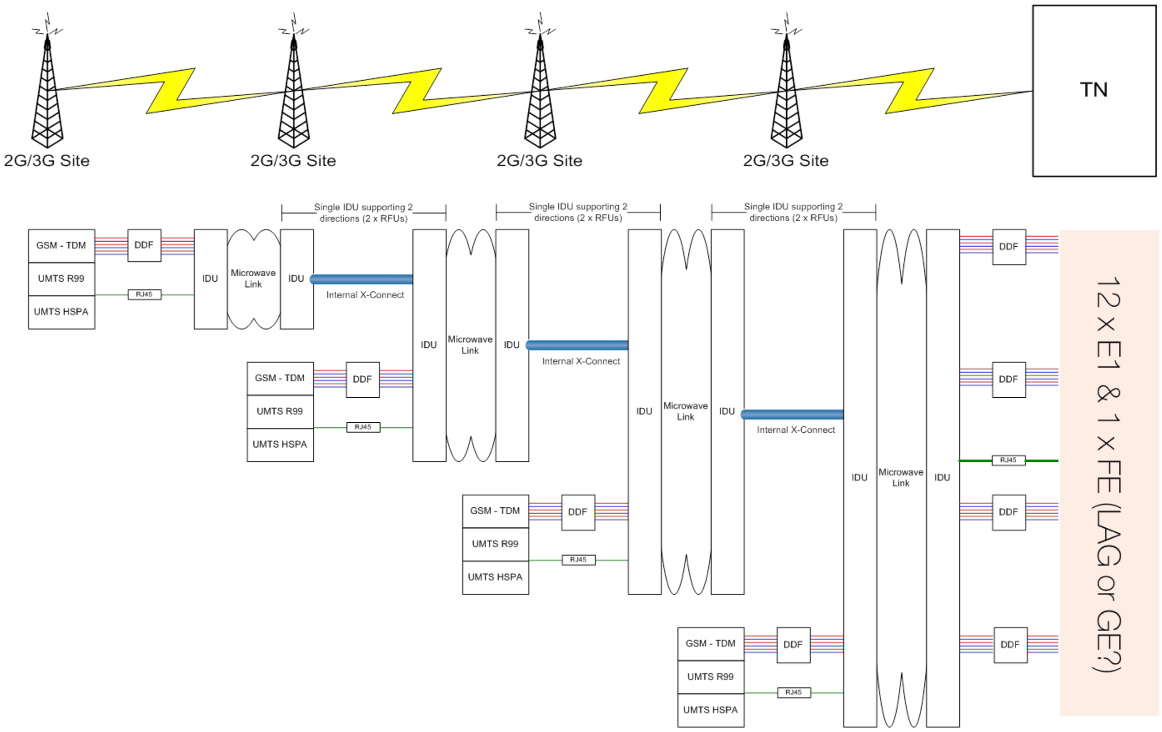


Figure 69: All 3G traffic, DCH and HSDPA, carried via single NodeB Ethernet interface

For capacity reasons it is highly likely that the chain of 4 sites would exceed the network planning traffic threshold for the single FE link towards the metro transport domain. To mitigate this a Gigabit Ethernet could be used or multiple FEs in a link aggregation group.

The final phase of the access transport domain evolution research considered the optimisation of handover from the access transport domain to the metro transport domain. To minimise the number of E1 circuits at the TN site, STM-1 circuits could be used between the IDU and metro terminating equipment, there would still be some E1s required at the TN for Abis (plus Ater and Gb to and from metro domain) however these could be de-multiplexed from the metro transport equipment and presented to a DDF for conventional connectivity to the BSC. Given the size of geographical coverage from the cell sites which could potentially be aggregated through the nodal microwave radio at the TN site, the node itself would require a high-level of resilience and the connection to the metro transport equipment would need to be protected with SDH MSP 1+1 protection in the case of TDM and two links with suitable convergence for the Ethernet traffic. The dual technology protected hand-off to the metro equipment is illustrated in Figure 70.

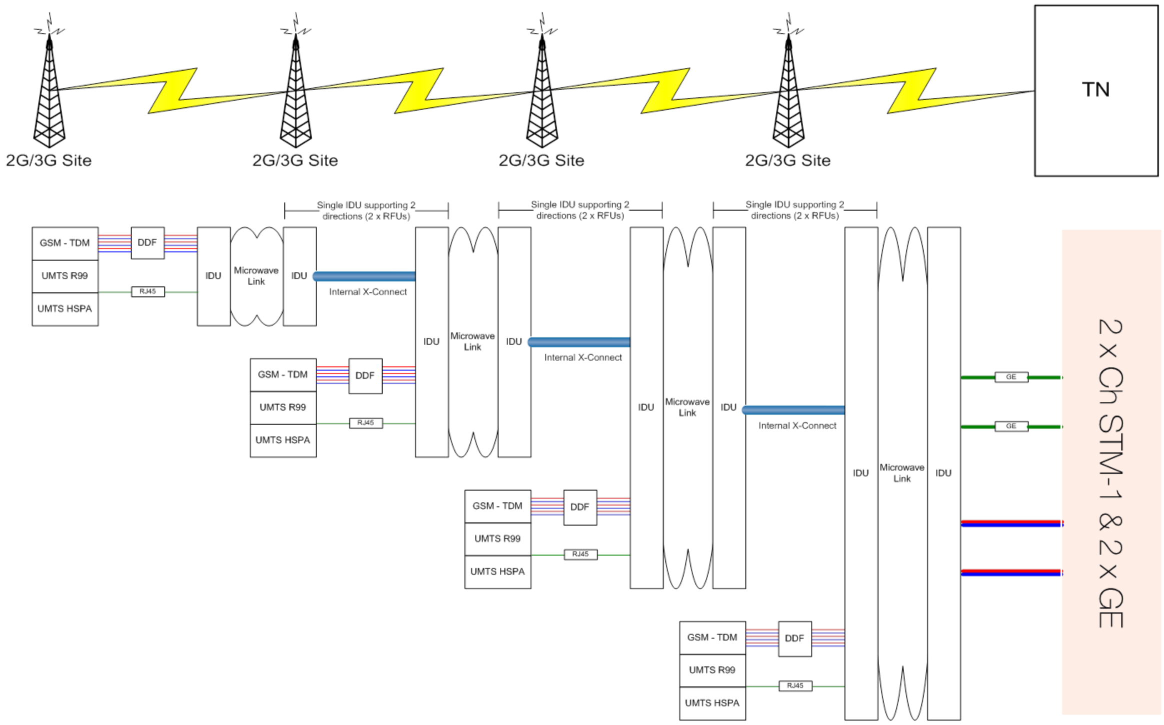


Figure 70: Aggregated traffic with high-order hand-off towards metro transport domain

5.4.1.5 Pseudo-wires

RFC 3985 describes an architecture for Pseudo Wire Emulation Edge-to-Edge (PWE3). It discusses the emulation of services such as Frame Relay, ATM, Ethernet, TDM, and SONET/SDH over packet switched networks (PSNs) using IP or MPLS. It presents the architectural framework for pseudo wires (PWs), defines terminology, and specifies the various protocol elements and their functions (Bryant & Pate, 2005).

Pseudo-wires are similar in concept to AAL1 CES in ATM however operate over an IP/MPLS network. By this time most MNOs had operational IP/MPLS core network to support packet data and also operated ATM core networks for UTRAN interfaces within the core transport domain, these comprise Iur, Iu-cs and Iu-ps. Orange was no different with a IP/MPLS network of routers provided by Juniper Networks and a now aging ATM network based on

Cisco MGX/BPX equipment. In addition to the need to evolve the access and metro transport domains, there was a need to refresh the ATM transport capability within the core transport domain.

Figure 71 illustrates the pseudo-wire emulation edge to edge concept in which the customer equipment (CE) provide the source traffic and termination point. In the case of a UMTS network, the CE to the left of the diagram is the NodeB while the CE to the right is the RNC. The CE attaches to a provider edge (PE) router via the attachment circuit, this carries the native service, i.e. E1 based ATM IMA for Iub interface. The pseudo-wire is then constructed within the PE router and transmitted over a packet switched network (PSN) tunnel, in the case of IP/MPLS this is a label switched path. Depending on the particulars of the IP/MPLS network there may be P routers between the two PE routers however these core routers simply switch LSPs and therefore don't interact in any way with the actual payload, in this case the pseudo-wire. The receiving PE router terminates the pseudo-wire and recreates the native service for onwards transmission to the CE via the attachment circuit. Pseudo-wires are unidirectional, therefore a transmit and receive pseudo-wire is configured to enable bi-directional communications. The connectivity from CE to CE, including the attachment circuits is known as the emulated service.

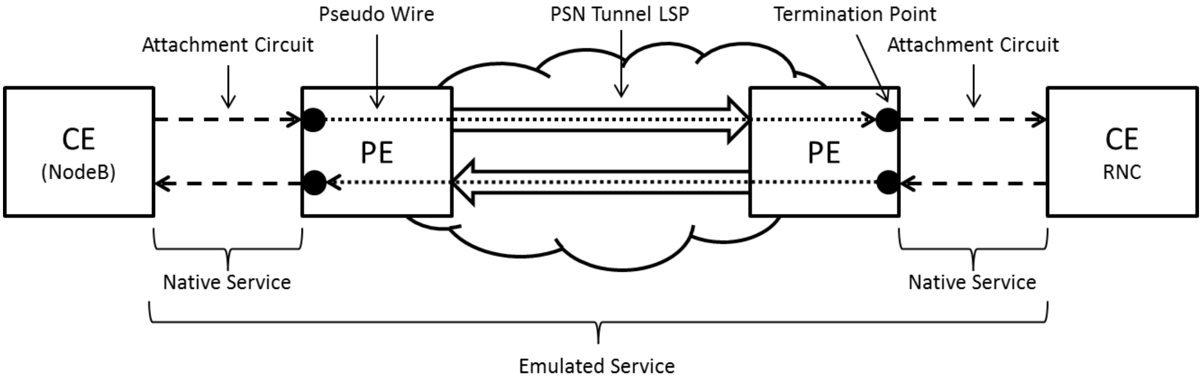


Figure 71: Pseudo-wire emulation edge to edge network architecture

A number of service specific RFCs followed RFC 3985 with details of how to implement pseudo wires for specific transmission and transport network technologies. Figure 72 illustrates the requirements of the Orange network if the technology was to be adopted in any of the transport network domains. Considering the core transport network briefly, there was a need to replace legacy ATM transport with a much higher capacity system to enable this domain to scale cost-effectively as mobile data traffic increased. The research presented in this thesis is focused on the mobile backhaul domains of the access and metro domains however the adoption of a new platform in the core offered an opportunity to align across multiple domains and realise economies of scale, not just in number of platforms but also in OSS, training and spares stock holdings.

Figure 72 details the mapping required for various traffic types to enable them to be carried across a packet switched network, in this case as MPLS based pseudo wires over an underlying Carrier Ethernet network. The biggest challenge to the backhaul network was cost-effective scalability of the metro transport domain, the PSAX had served the network well however the rise in data traffic meant that many NodeBs were scaling from 1 or 2 x E1 Iub to 4 to 8 x E1 Iub. As a result of this the PSAX simply couldn't support the number of E1 ports or the metro domain aggregate data rates which were forecast. TDM requirements from Ater and Gb could be accommodated as TDM PWE3, in theory the Gb interface could be implemented as a Frame Relay PWE3 however to keep things simple it was decided to continue to treat the Gb E1s as point to point TDM circuits (in this case as TDM PWE3), as per the implementation on the PSAX. ATM traffic from the Iub interface could map to an ATM PWE3 while the adoption of MPLS based pseudo wires offered a future proof solution for the introduction of a 3GPP R5 IP TNL. IP could be mapped over PWE3, carried natively over Ethernet or in a layer 3 IP VPN, all features which are available on the new platform.
In reality the pseudo wires would be carried over a mix of SDH and Carrier Ethernet based transmission which would be carried over a physical layer of optical and/or microwave radio systems.

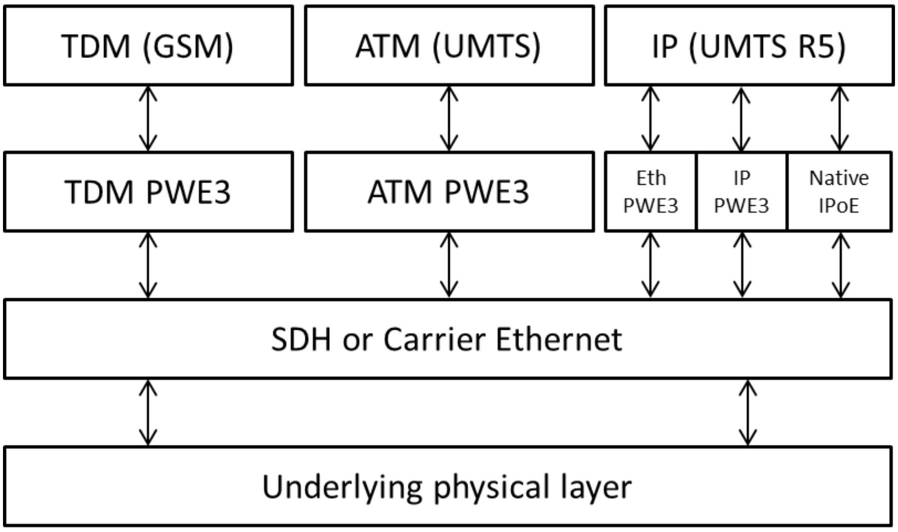


Figure 72: Transport options for mobile traffic types over PWE3 platform

5.4.1.6 Evaluation of options

A process of technical and commercial due-diligence was required to ensure that the adoption of PWE3 technology was the correct solution for the business. This analysis considered a range of options for supporting the evolution of the converged GSM/UMTS transport network, which included meeting the needs of the core ATM transport domain. ATM platforms simply didn't scale to meet the number of ports, throughput and aggregate line rates which would be necessary because ATM was specified to work at a maximum speed of 622.08 Mbps (STM-4). Therefore the requirements would involve deploying many PSAX 2300 chassis' at each TN site, neither a practical or cost-effective solution. Continuing with the ATM cross-connect approach would also be a challenge from a network planning perspective as IMA groups need to terminate to the same IMA card in the PSAX, a large number of cell sites with an 8 x E1 IMA requirement would result in just two sites per PSAX IMA card. IMA card supported up to 21 sites at 3G launch, most sites having just 1 x E1. In the early phase of addressing the second research question it was proven that ATM cross-connects and switches were no longer the most appropriate solution, those already installed would however remain and continue to play an important role in the evolving HSDPA network, more on this later.

Other options analysed included combining a multi-service switch/router with the ATM platform to support higher aggregate line rates in the metro transport domain however this was also an expensive option given the cost of more and more leased SDH metro transmission circuits.

The new range of multi-service provisioning platforms was investigated. These are next-generation SDH platforms with new features to make SDH more data-friendly. These new features include; Generic Framing Protocol which provides a mechanism to encapsulate Ethernet frames within an SDH payload. Virtual Concatenation which enables a logical higher-rate path through the SDH network by aggregating multiple lower speed virtual containers and assigning dedicated path overheads and pointers. Link Capacity Adjustment Scheme which allows the capacity of Ethernet transport to increase or decrease, based on demand via instructions from the network management system, the changes to capacity are hit-less and therefore don't impact the on-going service flow. These platforms did offer a reduced cost however SDH technology was not a strategic bet for the future and so the final solution for the evolution of the metro transport domain was a combination of the existing ATM cross-connect plus the addition of a new multi-service switch/router along with the introduction of Carrier Ethernet transmission for HSDPA traffic in parallel with the high-availability SDH transmission for GSM/GPRS and UMTS DCH traffic.

5.5 Evolution of Iub interface

There were a number of options for evolving the Iub interface, these are highlighted in Figure 73.

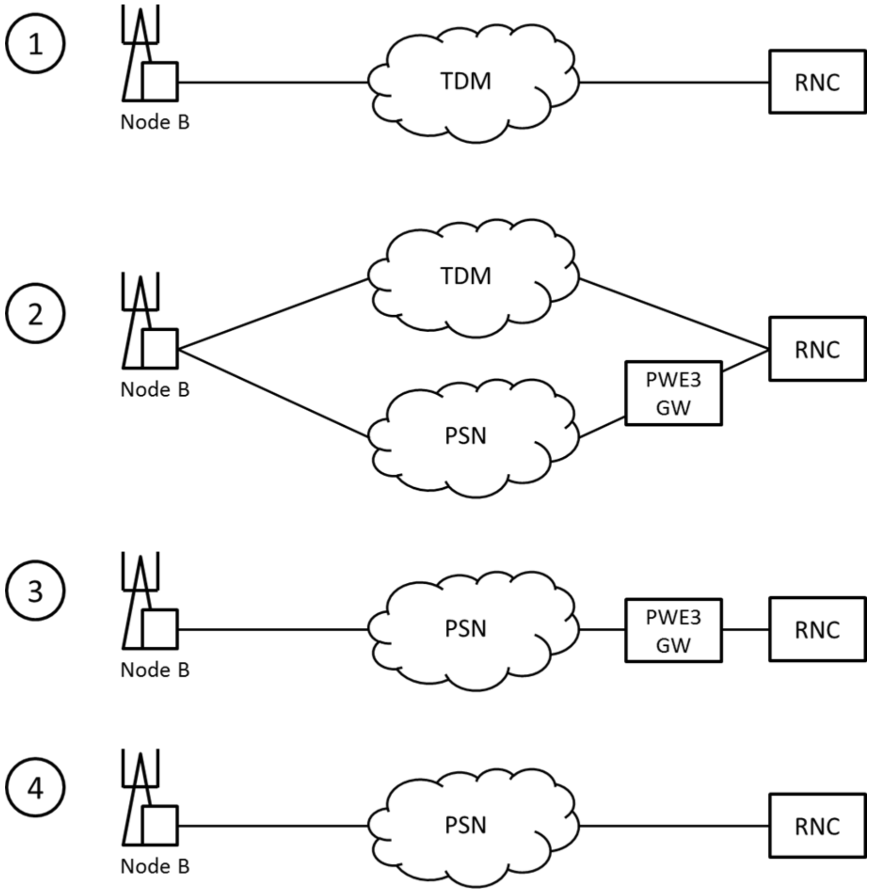


Figure 73: Iub interface evolution

Option 1 simply highlights the starting point from release 99, with all ATM based transport over TDM transmission. Option 2 illustrates the concept of hybrid backhaul in which the traffic between the NodeB and RNC is split over two independent transmission systems, one is TDM and the other is some form of PSN, likely MPLS based pseudo wires in most cases (as discussed previously with reference to hybrid microwave radio systems). The use of a PWE3 gateway (PWE3 GW) prior to the RNC confirms that the transport layer is still ATM and from these simple diagrams, assumes the corresponding PWE3 encapsulation/de-encapsulation process is within the NodeB, this was possible with some vendors however in reality generally required an external cell site router next to the NodeB. In the hybrid model the TDM path supports UMTS dedicated channels for voice, video and data traffic. Option 3 is a single route for all traffic via ATM pseudo-wire while option 4 is the end game with all UMTS traffic, DCH and HSDPA, being transported as an IP TNL as specified in 3GPP release 5. Whilst there's no PWE3 gateway in the path of option 4 there would be a router and this will likely be the same platform as the PWE3 GW, simply being used for IP transport, maybe as a MPLS PE router supporting a layer 3 VPN.

The MEF had an interest in all options which involved a PSN or, in their case a Metro Ethernet Network, the term Metro Ethernet has since changed to Carrier Ethernet however Carrier Ethernet is still defined by the organisation known as the Metro Ethernet Forum.

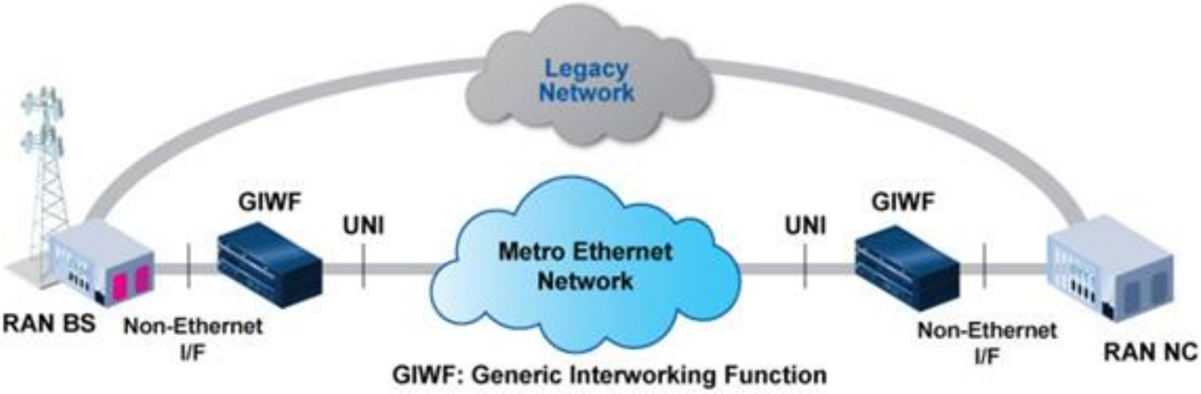


Figure 74: MEF architecture for hybrid backhaul (Source: MEF)

The MEF produced a series of recommended architectures which mapped closely to options 2, 3 and 4 in Figure 73. The solution which was implemented to address the HSDPA rollout within the Orange network was based on option 2, hybrid backhaul. The RAN BS in this case is the UMTS NodeB while the RAN NC is the RNC, the GIWF refers to a Generic Inter-Working Function while UNI is the User to Network Interface. The actual realisation of the Metro Ethernet Network could differ however in the case of Orange, this was IP/MPLS based.

5.6 Metro transport domain evolution

The strategy and architecture which was developed for Orange, whilst based on option 2, was somewhat different to the diagrams in Figure 73 and Figure 74, the option 2 solution was implemented across the metro domain only and therefore looked like Figure 75.

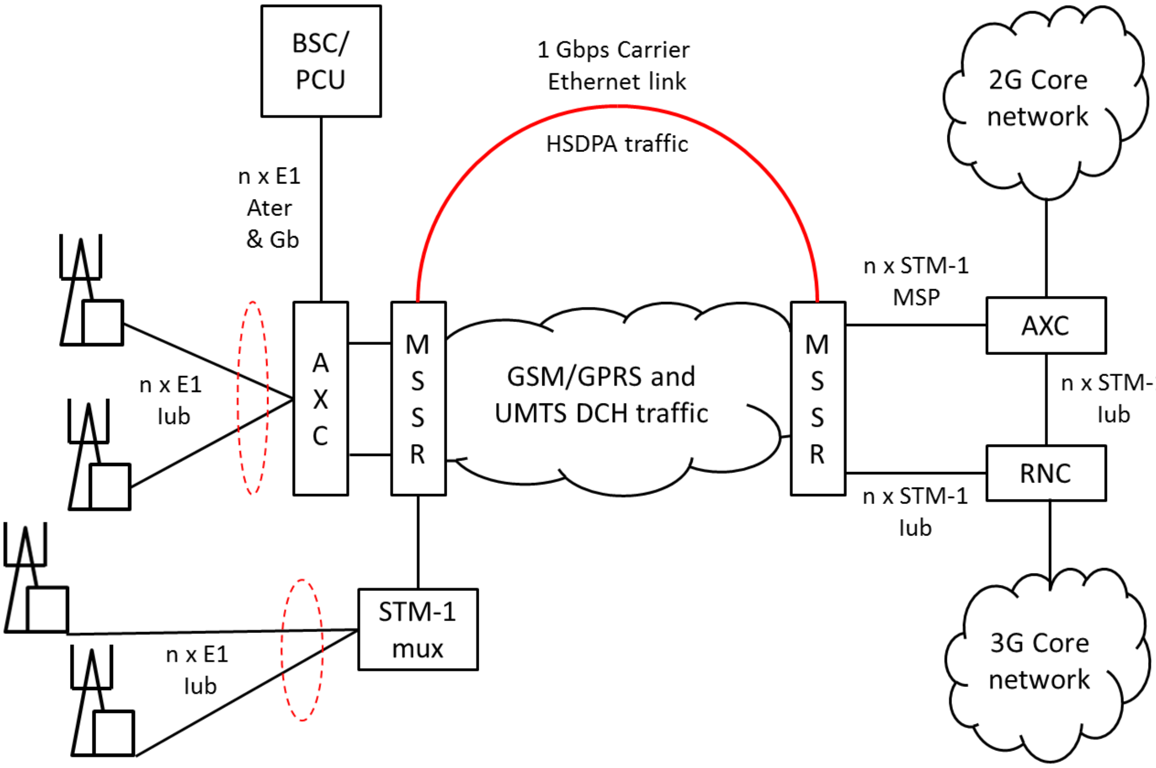


Figure 75: Hybrid backhaul implemented for the metro transport domain

Figure 75 illustrates the high-level target architecture for the evolved metro transport domain, GSM, GPRS and UMTS DCH traffic continues to transit the metro domain on the protected STM-1 circuits while HSDPA traffic is ATM VC switched within the MSSR to an alternative metro transmission circuit, an unprotected point to point 1 Gigabit Ethernet (1GE) path, this architecture was documented in Orange document Plan591 v2 (v1 being the original metro architecture). The 1GE is unprotected and therefore a fibre break or equipment failure would result in an outage, the probability of this is low and as the 1GE circuit was only carrying best-effort internet traffic, it was a reasonable compromise to enable a significant capacity uplift across the network in support of the growing quantity of mobile broadband data traffic. If a failure did occur, the UMTS/HSDPA UE would re-establish a session as a data DCH and therefore still have mobile communications albeit likely at a lower data rate for the duration of any outage on the 1GE circuit. The STM-1 link would continue to be fully protected with hit-less failover between primary and secondary paths (Appendix 1, PLAN591v2).

The detailed network strategy and architecture analysis and development delivered the target architecture just described along with a requirement to review the market for a suitable platform. This platform should be an MSSR capable of supporting large numbers of legacy interfaces from GSM and GPRS along with UMTS, it should be IP/MPLS based and support the necessary pseudo-wire capabilities. The platform must also support SDH and Carrier Ethernet transmission at line rates up to STM-16 and 1GE respectively. After a detailed market analysis and procurement process, the Tellabs 8600 product family was selected.

5.6.1 MSSR

The Tellabs 8600 (described as MSSR in design descriptions) product family includes the following platform variants:

- 8605
- 8620
- 8630
- 8660

The 8605 is the smallest unit, designed as a cell site gateway. The 8620 is dimensioned for a small access sites or customer premises installation. The 8630 is a more compact version of the larger 8660, both have the same architecture and offer fully redundant configurations. Orange selected the 8660 for core network sites, to terminate traffic from the metro transport domain and also provide inter-core site ATM transport. The 8630 was originally selected for TN sites however due to the rapid growth in mobile broadband, fuelled by HSDPA and new advanced feature phones/early smart-phones, the larger 8660 was also an option for TN sites. In practice the 8660 became the default deployment for TN sites due to its significantly higher port capacity.

Tellabs 8660 access switch subrack can be installed into a standard 19 inch rack. The forced cooling modules (fans) and air filter are located in the bottom of the subrack (Tellabs, 2007).

There are 14 slots of which 12 are available for the line cards with user traffic interfaces, and 2 for Control and DC Power Cards (CDC). The slots are positioned vertically. Interface Module Concentrator (IFC) slot numbers run from 1 to 12. The CDC slots are numbered 1 and 14.

The control and DC power functionality has been combined into a single card in order to have as many slots as possible for line cards. CDC in the slot 14 is mandatory in all configurations. Equipping slot 1 with another CDC depends on protection requirements, however, it is highly recommended. All cards are hot-removable and hot-insertable. To change or install an interface module, the line card needs to be removed from the subrack.

Figure 76: Tellabs 8660 MSSR

The line card in the Tellabs 8600 system consists of an IFC and up to two Interface Modules (IFMs). The line card contains the following functional features:

- Point-to-point high speed data links with other line cards
- Local power supply
- Hot insertion and removal
- One IFC

- Two interface modules

The following interface modules are supported:

- 2 x 1000BASE-X
- 8 x 1000BASE-X
- 8 x Fast Ethernet
- 8 x Combo Card (2 x GE and 6 x FE)
- 8 x STM-1 POS (Packet over SDH)
- 4 x STM-4 POS
- 1 x STM-16 POS
- 4 x STM-1 ATM
- 1 x chSTM-1 Multiservice
- 4 x chSTM-1 Multiservice
- CDC

5.6.1.1 Core site MSSR

The generic Core site build comprises of two 8660 chassis including fans, each chassis has 14 slots available, with CDC in each of slots 1 and 14, leaving slots 2 to 13 available for interfaces. Slot 1 is the left-most. The diagram below is an example of a core site build. As the MSSR provided many services to the core transport domain in addition to terminating the metro transport domain towards the TN, the actual core site configurations varied considerably. All had the necessary ports to terminate connectivity from the metro domain and connect as necessary to PSAX ATM cross-connects. Figure 77 shows an example of an 8660 Chassis configuration for a core network site.

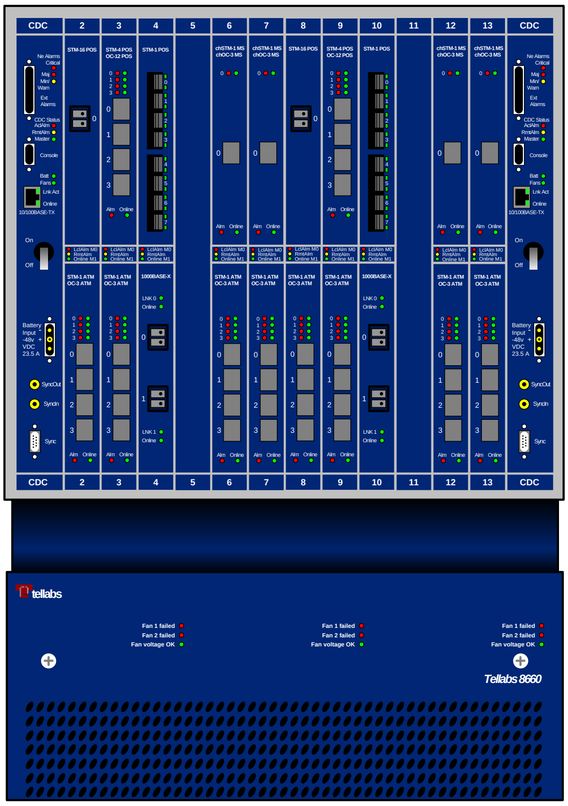


Figure 77: Core network MSSR

The high population of higher-order interfaces such as STM-1, STM-4, STM-16 and Gigabit Ethernet on a core site MSSR resulted in a huge amount of optical fibre cabling. Any local E1s would connect to the MSSR via STM-1 ADMs, these ADMs were supplied by Siae and were deployed to address a range of E1 to STM-1 connectivity requirements, including; core site E1 to MSSR STM-1 circuits. Figure 78 illustrates a rack of Siae ADMs and the associated Tellabs 8660 MSSR on a typical core network site. The MSSR is terminating incoming metro transport domain circuits, STM-1 (1+1) and STM-4/1GE (1+0) from TNs, providing local connectivity within the core site and inter-core site pseudo-wires, mainly for ATM traffic in support of Iur, Iu-cs and Iu-ps traffic.

Figure 78: Siae STM-1 ADMs (left) and core site Tellabs MSSR (right) (2016)

5.6.1.2 TN site MSSR

Two 2 chassis configurations were developed for use in the Orange network, one for Core sites and one for TN sites. The actual platform is identical, both being 8660s however the actual configuration differs based on their placement within the network. The situation with PSAX was different as a PSAX 4500 was deployed to the core while a PSAX 2300 was deployed to the TN. Each 8660 chassis uses IFCs that comprise of upper and lower IFMs. The 2 Modules are installed as a single IFC, and are supplied in a range of pre-determined combinations. The TN nodes are populated from the middle by design choice, this ensures the same base configuration in the rare cases that an 8630 is required for a TN, this is only the case if there’s a lack of physical accommodation and is used by exception.

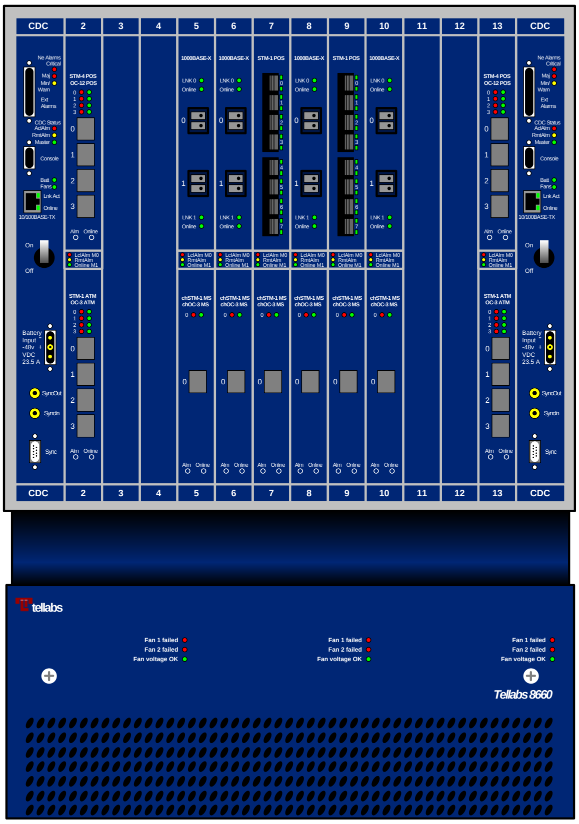


Figure 79: TN site MSSR

Whilst the unprotected leg of the hybrid backhaul solution was specified as 1GE, due to product availability from the fixed network provider, the first batch were actually STM-4 links, this was ok from a capacity perspective at the time and an upgrade path did exist to 1GE if necessary. This explains the inclusion of STM-4 POS cards in the TN build illustrated in Figure 79, once these links were being delivered as 1GE, the STM-4 interfaces were removed from the base build to reduce overall cost.

The addition of the MSSR to the TN enabled a significantly larger number of E1 Iub circuits to be supported and therefore served as an enabler for wider HSDPA rollout to the radio network and upgrading of HSDPA data rates on those sites already operating. The access transport domain would continue to scale with E1s due to the scale of investment which would be required to implement Ethernet interfaces on all NodeBs and upgrade all microwave radio links to hybrid configurations. By this time there was significant E1 capacity within the access microwave radio network and were required, additional upgrades were implemented with hybrid radio systems, which whilst initially being used for E1s only, would enable future upgrades to Ethernet in support of an IP TNL.

5.6.1.3 TN site evolution

The increase in E1s arriving at the TN sites resulted in new DDF installations and the introduction of a new node to act as a pre-aggregation device for the MSSR. This new device is a SDH STM-1 multiplexer which is key to the overall design as it enables the MSSR to accommodate so much traffic. Fitting E1 cards to the MSSR would effectively create the same scalability problem that's being experienced on the PSAX 2300s, to avoid this the MSSR will be equipped with channelized STM-1 cards, each of which can support 63 x E1 mapped into a structured VC-4 as 63 x VC-12 via the multiplexer. The detail of the TN build is illustrated in Figure 80.

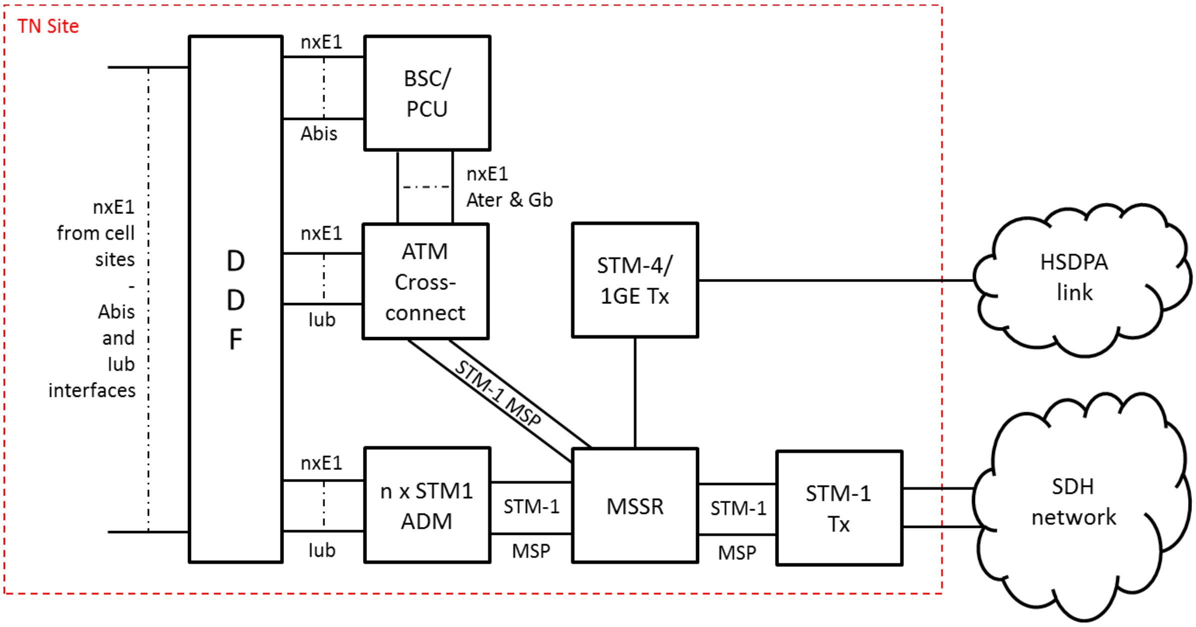


Figure 80: TN site configuration with MSSR

Once a MSSR was installed at the TN site, the protected STM-1 connections between the AXC and third party SDH network were swung to connect between the AXC and MSSR, the MSSR would then provide the connectivity to the third party SDH network for the STM-1 1+1 metro transport domain, this would terminate to a core network MSSR on the core site, any circuits destined for the PSAX 4500 would be connected within the core site. The hybrid backhaul solution was realised as an unprotected (1+0) STM-4 initially and then as a 1GE circuit once this option was available from the third-party metro transmission provider. The metro transmission provider was the same for both the protected and unprotected circuit so in reality these would likely share the same SDH network however they're drawn as two separate networks (clouds) in Figure 80 for clarity.

TN sites with direct connectivity to the Orange WTN had more capacity to use prior to needing an upgrade to an MSSR, as described earlier the WTN sites had 63 x E1 which was used for Ater and Gb and some early Iub while a PSAX 2300 was added to a second STM-1 which was used mainly for Iub interface traffic. When a MSSR was required on a WTN connected site, additional capacity was provisioned on the Orange SDH network to provide metro transmission back to the core network site.

The addition of the MSSR with hybrid backhaul to the metro transport domain enabled the evolution of the 3G network and supported the large scale rollout and upgrading of HSDPA and its evolutions. Figure 81 illustrates a MSSR installation in a TN site in Warrington, Cheshire, while Figure 82 shows the author explaining the MSSR to a number of industry press journalists during an Orange network open-day to mark the launch of the iPhone (3GS) on the Orange network in 2009.

Figure 81: Tellabs 8660 MSSR at TN site

Figure 82: The author explains the MSSR to industry journalists (ComputerWeekly.com, 2009)

5.5 HSDPA network status

The rapid growth in backhaul capacity can be seen from the graph in Figure 83. In a 2 year period between the end of 2007 and end of 2009 approximately 40,000 additional E1 circuits were added to microwave radio network within the access transport domain (approximately 3 additional E1 circuits per NodeB whereas the majority of GSM base stations had typically had 1 or 2 x E1 since the 1990s), these are in addition to any additional E1 leased lines (non-microwave fed macros and micro-cells). While not all of the microwave E1s would have been used however the vast majority would, many of them terminating to the TN based MSSR via STM-1 ADMs due to the local PSAX IMA cards being full to maximum capacity. Once an MSSR was deployed to a TN site, future E1 IMA growth was managed via the MSSR, effectively capping investment in the PSAX 2300 platform. Ater and Gb interface growth continued via the PSAX (now sub-tended from the MSSR) as 2 x 21 port MS cards provided a large amount of capacity for GSM and GPRS.

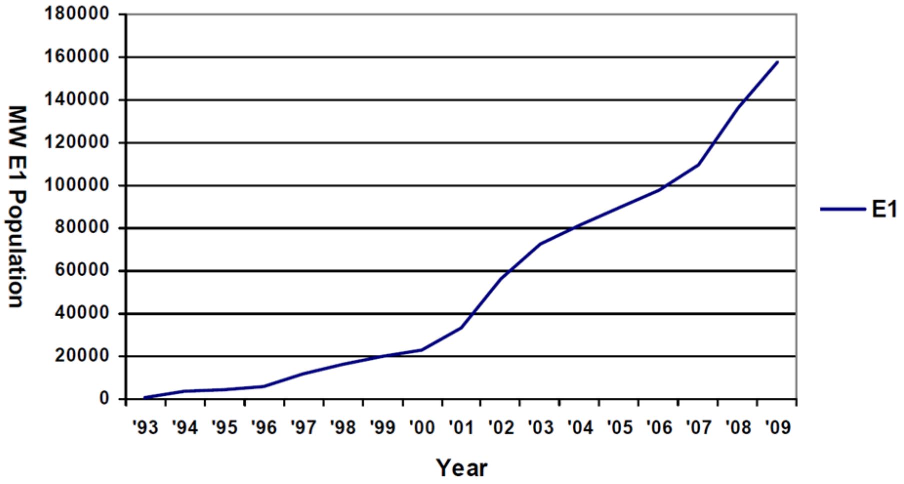


Figure 83: Microwave radio E1 count due to rollout and HSDPA capacity upgrades

By February 2010 Orange had rolled out 61 x Tellabs 8660 MSSR platforms to TN sites and a further 54 MSSR platforms across the 22 core network sites. An additional 598 3G sites had been added to the network between August 2008 and February 2010, bringing the total 3G site count to 7,443. All of these 3G sites had been upgraded to support HSDPA.

Description	02/2010	08/2008
2G sites (macro & micro)	13,198	12,985
3G sites (macro & micro)	7,443	6,845
Macro sites (2G and/or 3G)	9,453	9,414
Micro sites (2G and/or 3G)	4,059	3,970
BSC equipment	285	284
TN sites	182	183
TN sites with PSAX 2300	154	150
TN sites with MSSR	61	0
RNC equipment	44	38
Core network sites	22	22
Core sites with MSSR	22 (54)	0
Core sites with RNC	19	18

Table 12: Orange network status as of 02/2010, compared with 08/2008

Table 12 provides a comparison of network status between August 2010, post HSDPA upgrades, and August 2008, during the early days of HSDPA rollout and prior to the MSSR deployment programme. In addition to 3G rollout the 2G network continues to expand, new 2G cell sites and a new BSC had been added to the network. There was one less TN site in 2010 than there was in 2008, this was likely due to site churn. Site churn is not uncommon and is often triggered as a result of the demolition of a tall building or the end of a site lease for which a renewal could not be negotiated. In this case the sites would have been re-networked into surrounding TN sites.

It is very likely that the pace of 3G rollout during the period August 2008 and February 2010 wasn’t as fast as originally planned because the merger of Orange UK and T-Mobile UK was announced in September 2009. That merger completed on the 1st April 2010 resulted in the need for a new network plan to enable technical integration of the two networks.

5.7 Summary

This chapter has reviewed the impact of the mass adoption of mobile data services based on 3GPP HSDPA technology and the consequences for the mobile backhaul network. The issues with scaling huge numbers of E1 circuits was investigated and modelled along with requirements to scale the metro transport domain to support the different requirements of best-effort mobile data and critical real-time communications such as voice and video telephony. Network statistics have been presented to show the scale of the Orange network and how the author’s research directly influenced the network architecture and design. The concept of hybrid backhaul was introduced in the metro domain whilst practical and financial considerations were factored in to the overall end to end solution. New Internet based technologies were researched and where appropriate utilised in the evolved mobile backhaul network, including the deployment of new hardware to implement pseudo-wires.

6. Conclusion

The research documented within this thesis highlights the approach necessary to review, develop and implement a significant network architecture and design evolution programme. The specific example being the evolution of the Orange UK mobile backhaul network from 2G GSM and GPRS technologies to 3G UMTS and HSDPA technologies, while continuing to support and evolve the former. The need to fully understand the starting point cannot be stressed enough as this is the existing network baseline from which the architecture and design will be developed. A detailed technical review of the new technology is an important early phase, firstly this was UMTS and then, as the network evolved and mobile data growth started to accelerate, this was HSDPA. Once the network baseline and new technology is understood the detailed network strategy, architecture and design phase can commence. This was followed by an equipment procurement process which was necessary as a direct result of this research. The fixed input was the selection of Nokia as the UTRAN equipment provider, this was the output of a standalone procurement activity, the procurement activities triggered by this research included; ATM cross-connects/switches, GPS based synchronisation system and fixed STM-1 transmission services followed by STM-1 microwave radio systems, STM-1 ADMs, STM-4/1GE transmission services and multi-service switch router platform.

The successful outcome of the research and delivery of a new mobile backhaul target architecture and associated technical designs enabled Orange UK to deploy a national 3G network and launch commercial service in 2004. The designs to support this became industry best practice due to the technical and commercial advantages of this approach over a TDM like approach with CBR traffic. Other network operators and equipment provider's adopted this design, in the UK the Hutchison 3G network was upgraded to operate in the same way as the Orange network did, albeit with equipment from a different vendor. The use of rt-VBR resulted in significantly lower costs wherever it was implemented. Due to the second phase of research it was then possible to augment the Orange UMTS capability with HSDPA in 2007. Tens of thousands of new E1 circuits were added to the backhaul network while the following key transport platforms had been added to the metro transport domain by February 2010 (Table 13). Note, not all core site MSSRs terminated metro transport, some were purely core transport domain however all came from the same overall network architecture and design activity.

Platform	Quantity deployed
TN site AXC (Lucent PSAX 2300)	154
Core site AXC (Lucent PSAX 4500)	68
TN site MSSR (Tellabs 8660)	61
Core site MSSR (Tellabs 8660)	54

Table 13: Metro deployments by February 2010

By February 2010 a total of 7,443 UMTS sites were live on the Orange network, all enabled by the outcome of the research presented in this thesis. A total of 44 RNCs had been installed and scaled appropriately with designs and dimensioning rules developed within this research. A total of 13,198 GSM/GPRS sites were also supported by the architecture and designs via 285 BSCs installed across 182 TN sites and 21 core network sites.

The innovative network architecture and designs developed by the author and presented in this thesis resulted in a much lower total cost of ownership when compared with simply scaling the existing mobile backhaul solution, it also enabled a highly scalable 3G network while catering for continued 2G traffic growth. The key innovation in the first phase (ATM AXC) was the use of rt-VBR over the protected STM-1 transmission circuit which completely decoupled the fixed relationship between number of Iub E1 circuits and the capacity of the SDH VC-4, the relationship between the two became the actual traffic load and therefore more closely aligned with revenue rather than network configuration. The principles from this phase of the research would underpin all future thinking in this field and have become industry best practice nowadays. The key innovation in the second phase (MSSR) was the introduction of hybrid backhaul via ATM VC switching of HSDPA traffic to a lower cost backhaul circuit, to better match the revenue from mass market mobile broadband which at the time was considered best-effort Internet access. The use of pseudo-wire technologies, expansion of IP/MPLS from the core to metro, and introduction of Carrier Ethernet all provided significant learnings and paved the way for the future introduction of IP as an alternative transport network layer for 3G. This acted as an enabler for a future all IP network for 2G and 3G supported by Carrier Ethernet based mobile backhaul, therefore removing the expensive and now inefficient TDM E1 circuits.

Given the multi-disciplinary approach to this research, it is intended that this thesis also acts as a historical record of the events described and provides documentary evidence of the network architecture and technology of the period from someone who was deeply involved in the process as the Principal Network Designer within Orange.

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Appendices

Appendix 1

This appendix provides an overview of the formal Orange UK network strategy, architecture and design documents which were produced by the author as a result of the research described within this thesis. These documents were the formal outputs, along with several journal articles and many conference presentations, from the research. These documents were used by technical engineering and project teams within Orange UK to develop detailed designs, network plans and rollout programmes to facilitate the deployment and activation of UMTS along with the implementation of a converged GSM/GPRS and UMTS mobile backhaul network. The introduction of HSDPA resulted in updates to a number of these document, one of which is included as version 1 and 2 to highlight this (Plan591). All documents were signed off at CTO level and suitably funded to enable network implementation. The main documents are briefly described here and screen shots included within this appendix. The screenshots of the front covers are included as evidence however the full documents haven't been included as they are still subject to commercial sensitivity.

PLAN141: Transmission Strategy for the 80% Population Area

This document details the access transport network domain strategy and architecture, the first version states 80% population area which is of historical significance as the initial focus for high-speed data services was the key population centres, it was thought that GSM/GPRS would be sufficient elsewhere, particularly once upgraded to EDGE. Subsequent versions of this document referred to the full network. The document details the microwave radio topology, link planning guidelines, capacity planning and rules for deploying third party leased lines within the access network.

SPEC616: Transmission Capacity Requirement - Abis and Iub interface

Specification document number 616 provides an overview of BTS and NodeB dimensioning along with a mapping to Abis and Iub interface capacity requirements. Business forecasts are then used to build a capacity requirement for different cell sites, depending on their traffic density region. Six traffic density regions were identified which mapped as High 1, 2 and 3 to urban areas, to provide a level of granularity within high traffic areas. Medium mapped to typical suburban while low mapped to rural and very low to sparse rural areas.

SPEC1000: Leased STM-1 Backhaul - Technical Specification

This document was written for third party leased line providers to specify the Orange requirements for STM-1 transmission within the metro transport domain, in support of the converged GSM/GPRS and UMTS mobile backhaul network. It specified key design aspects such as resilience, diverse fibre routing and use of SDH MSP for hand-off to Orange equipment. Additionally the document covered detailed requirements for optical transmit and receive power levels and requirements for conformance with ITU-T standards.

PLAN342: Iub Architecture

Plan 342 details the UMTS Iub interface architecture. The document lists the planned RNC capacity per core network site and specifies the configurations of RNC being deployed. A detailed architecture is presented for TN sites with WTN metro connectivity and those with leased STM-1 metro connectivity. Instructions on the use of PSAX ATM cross-connects is included along with specifications for managing Iub circuits which terminate directly to the core network site which accommodates the RNC.

PLAN591: Metro Transmission Architecture

Plan 591 was the document which introduced the concept of the metro transport domain which resulted in the network being split into the three transmission/transport network domains of access, metro and core. This document also describes the introduction of ATM cross-connects/switches, how access domain circuits will terminate to the AXC for GSM Ater, GPRS Gb and UMTS Iub interfaces and sets out the use of rt-VBR on the metro transport domain. The document provides a single point of reference for all metro network architectures, including microwave radio, E1 leased lines, STM-1 leased lines and WTN scenarios.

PLAN599: Interim 3G Microcell Transmission Strategy

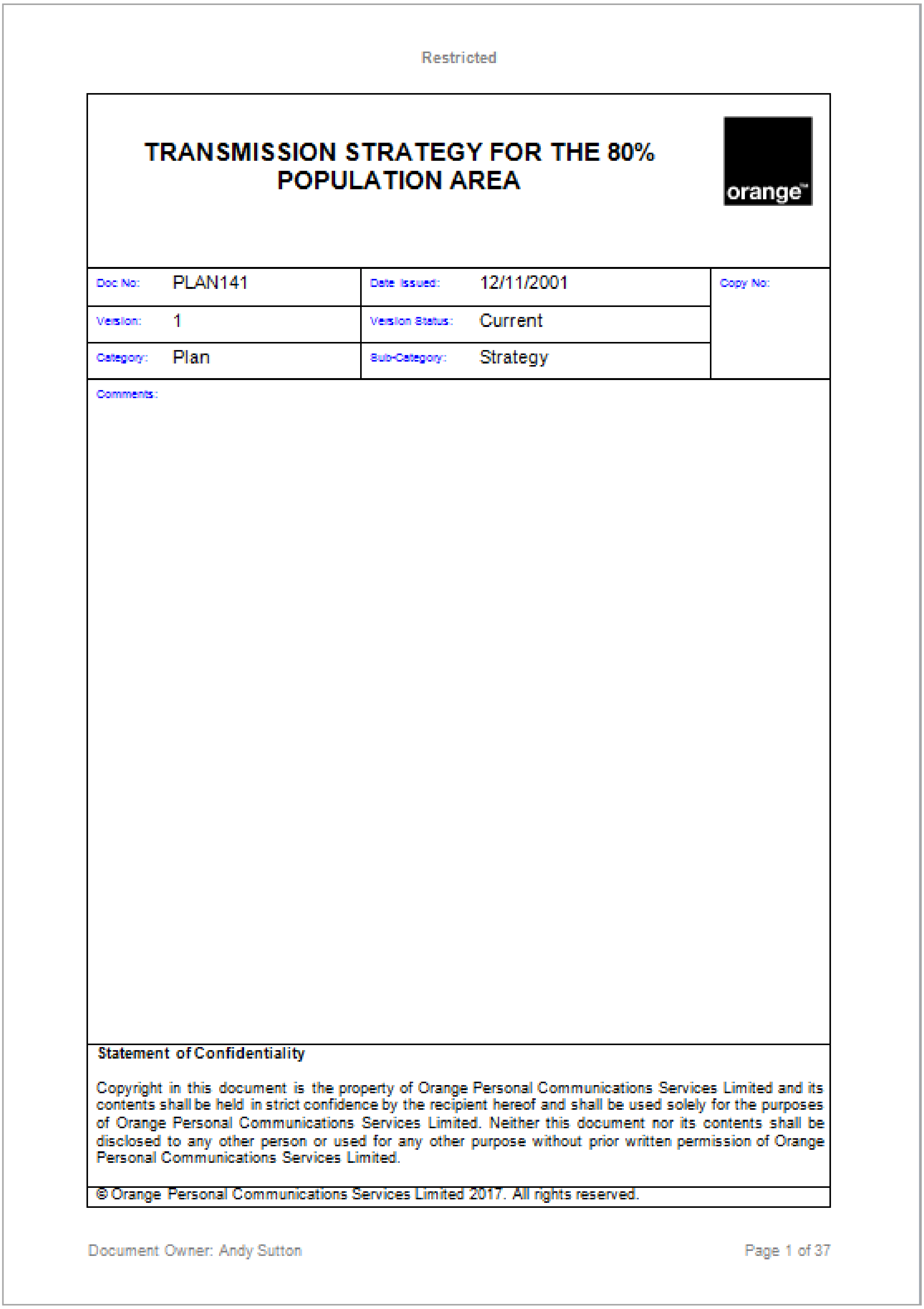
An interim 3G microcell transmission strategy was required to inform network planning engineers about the specific changes in microcell transmission, 3G (UMTS) requirements differed from 2G (GSM/GPRS) due to the centralised RNC architecture and minimum 3G microcell backhaul transmission requirement of 2Mbps. The strategy document explains the two architectural options; leased line back to TN site and leased line direct to RNC on core network site and the need for a commercial analysis as part of the decision process. In time the 3G microcell transmission strategy was absorbed within an update of PLAN141.

PLAN362: Network Synchronisation Architecture

Cellular radio base stations with FDD mode of operation require a frequency synchronisation reference to ensure they transmit on the correct frequency and don't drift, this is vital for mobile access, handover and regulatory compliance. This document specifies the network synchronisation architecture to support the access, metro and core transport domains.

PLAN591: Metro Transport Design Strategy (formerly Metro Transmission Architecture) - version 2

Version 2 of the metro transmission architecture, renamed to metro transport design strategy, provides the base information from plan591 v1 along with details of network scalability with the PSAX platform and the introduction of the Tellabs 8660 as an MSSR in support of HSDPA driven data growth. The document explains the use of pseudo-wire technology and Carrier Ethernet transmission along with introducing the concept of hybrid backhaul in support of HSDPA off-load within the metro transport domain. The sub-tending of the PSAX from the MSSR is instructed along with the use of ports and features of the MSSR platform. Deployment scenarios for TN sites with leased STM-1 metro transmission and those TN sites on WTN is described along with BSCs co-located on RNC core network sites. The document sets the overall strategy for the deployment of MSSR platforms to TN sites and how these connect to the core site MSSRs.



Restricted

TRANSMISSION STRATEGY FOR THE 80% POPULATION AREA

Doc No:	PLAN141	Date Issued:	12/11/2001	Copy No:
Version:	1	Version Status:	Current	
Category:	Plan	Sub-Category:	Strategy	

Comments:

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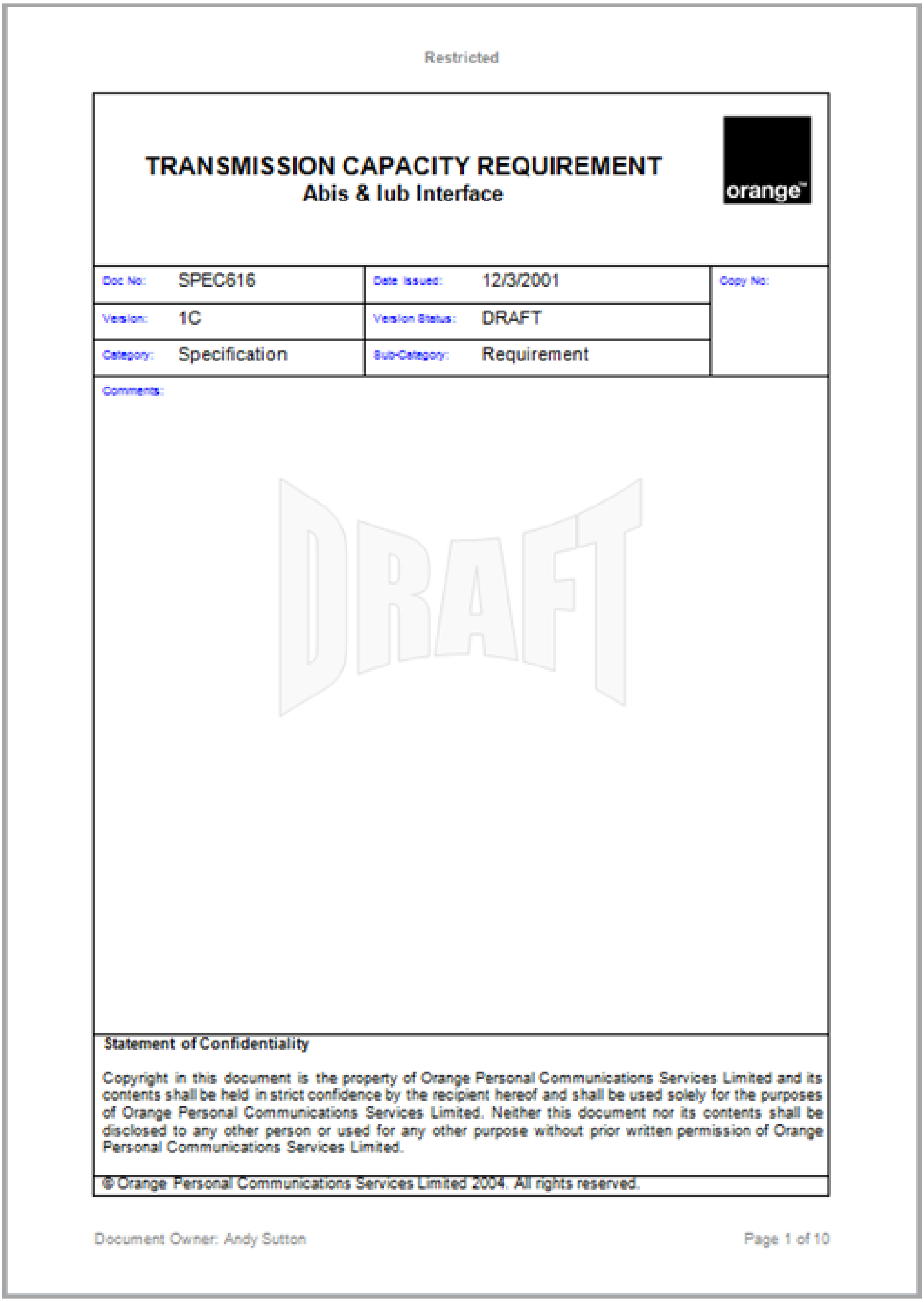
Appendix 1 figure 1: Plan141



Restricted

TRANSMISSION CAPACITY REQUIREMENT
Abis & Iub Interface

orange™

Doc No:	SPEC616	Date Issued:	12/3/2001	Copy No:
Version:	1C	Version Status:	DRAFT	
Category:	Specification	Sub-Category:	Requirement	

Comments:

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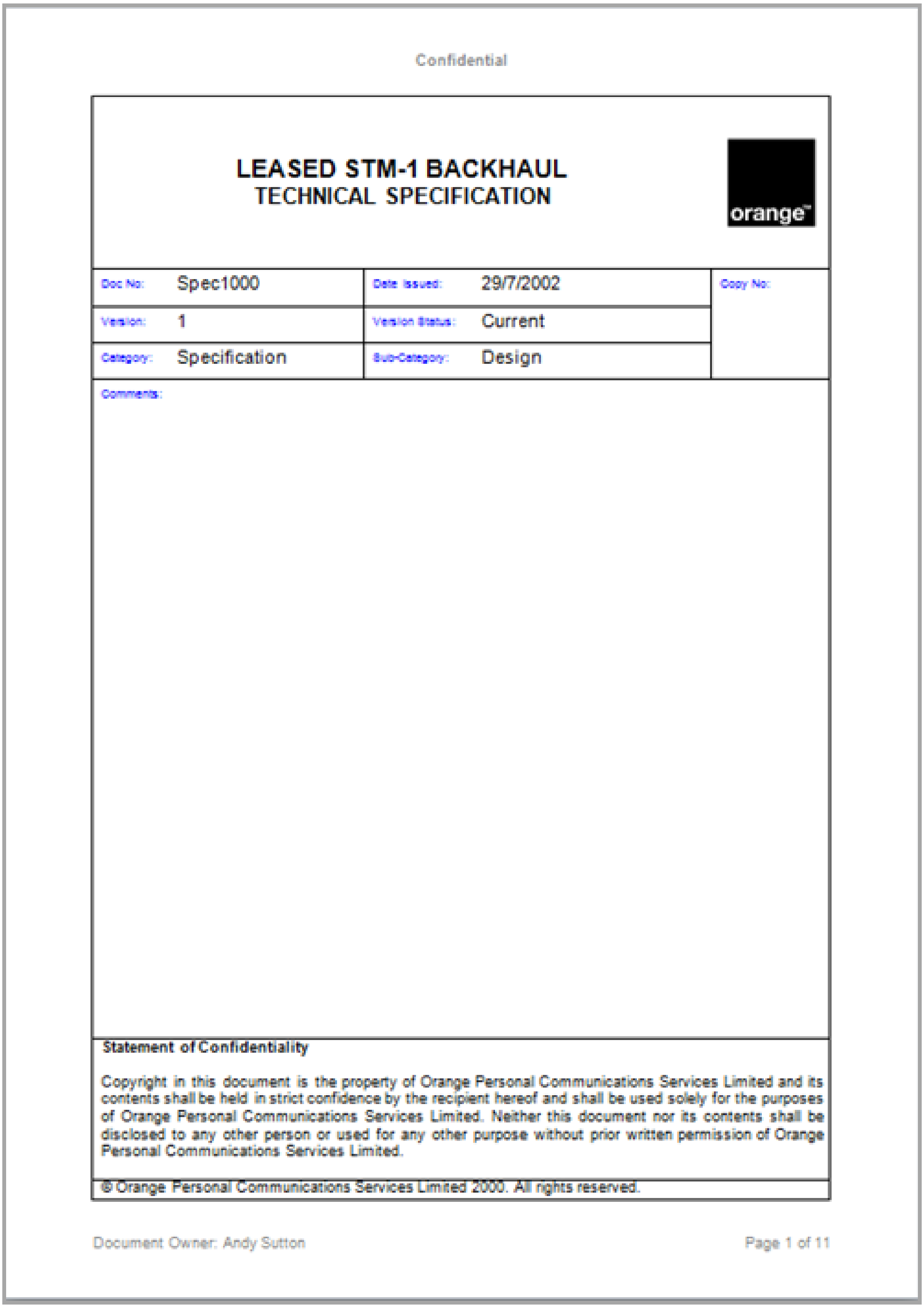
Appendix 1 figure 2: Spec616



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LEASED STM-1 BACKHAUL
TECHNICAL SPECIFICATION

Doc No:	Spec1000	Date Issued:	29/7/2002	Copy No:
Version:	1	Version Status:	Current	
Category:	Specification	Sub-Category:	Design	

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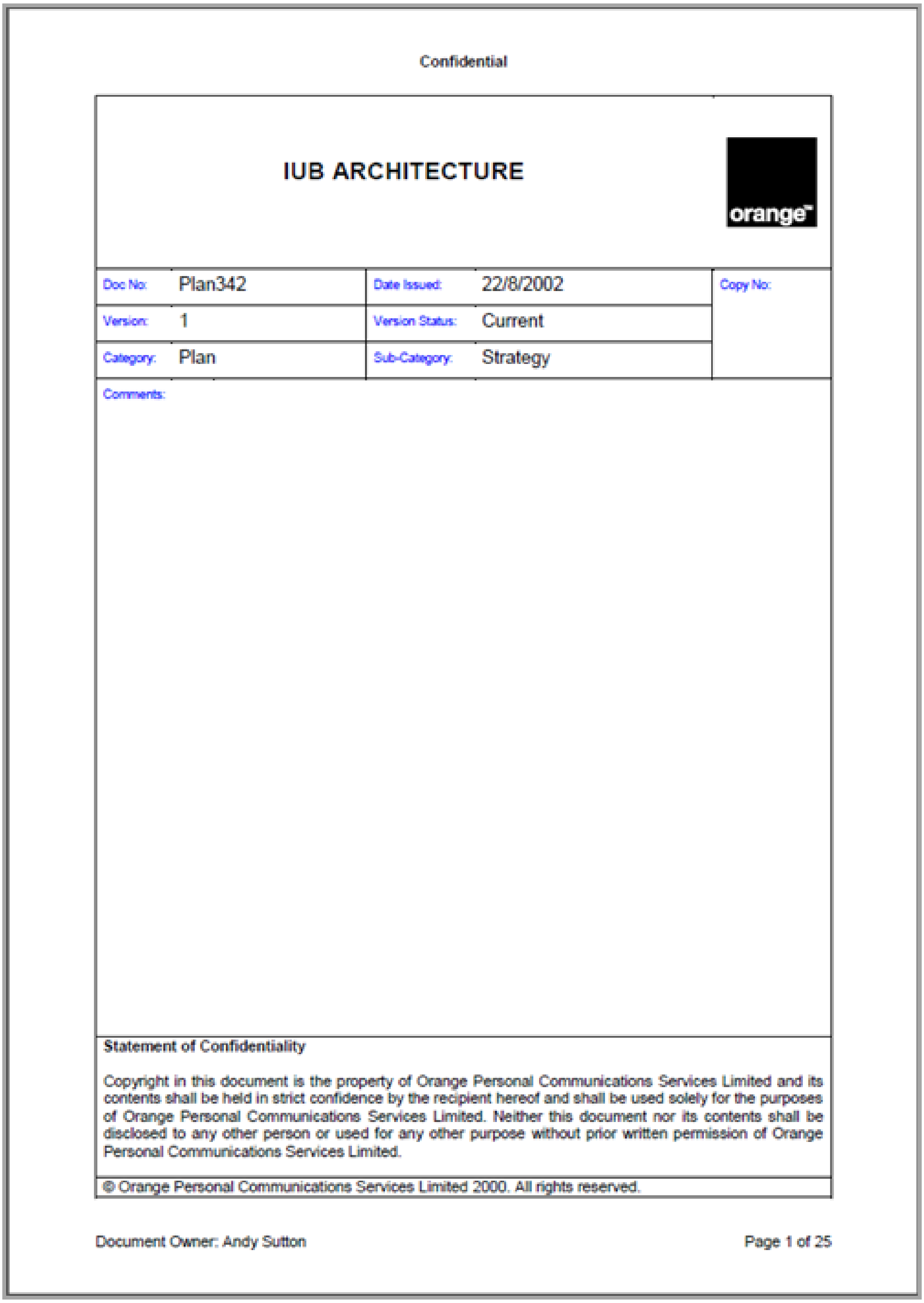
Appendix 1 figure 3: Spec1000



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IUB ARCHITECTURE

Doc No:	Plan342	Date Issued:	22/8/2002	Copy No:
Version:	1	Version Status:	Current	
Category:	Plan	Sub-Category:	Strategy	

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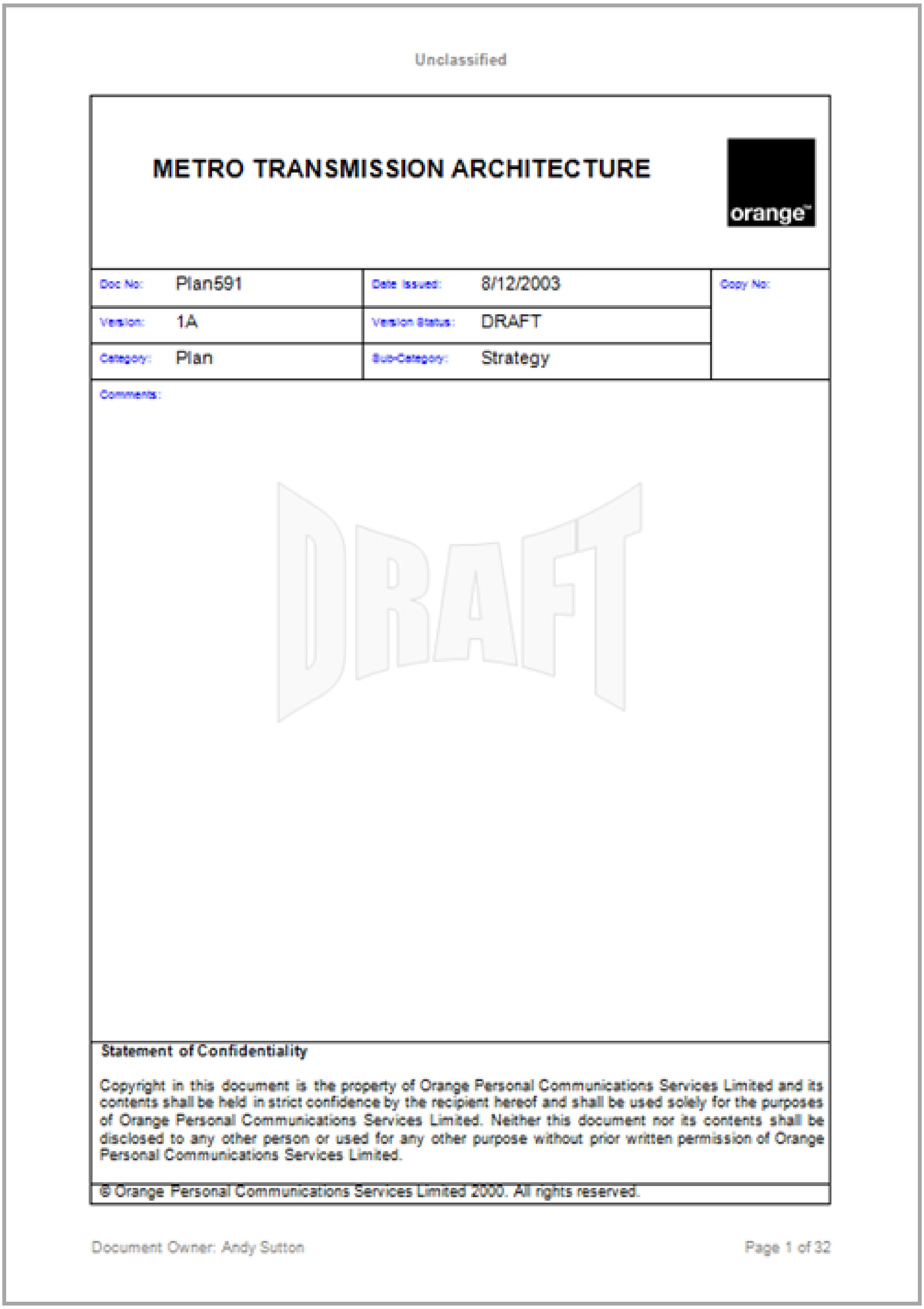
Appendix 1 figure 4: Plan342



Unclassified

METRO TRANSMISSION ARCHITECTURE

Doc No:	Plan591	Date Issued:	8/12/2003	Copy No:
Version:	1A	Version Status:	DRAFT	
Category:	Plan	Sub-Category:	Strategy	

Comments:

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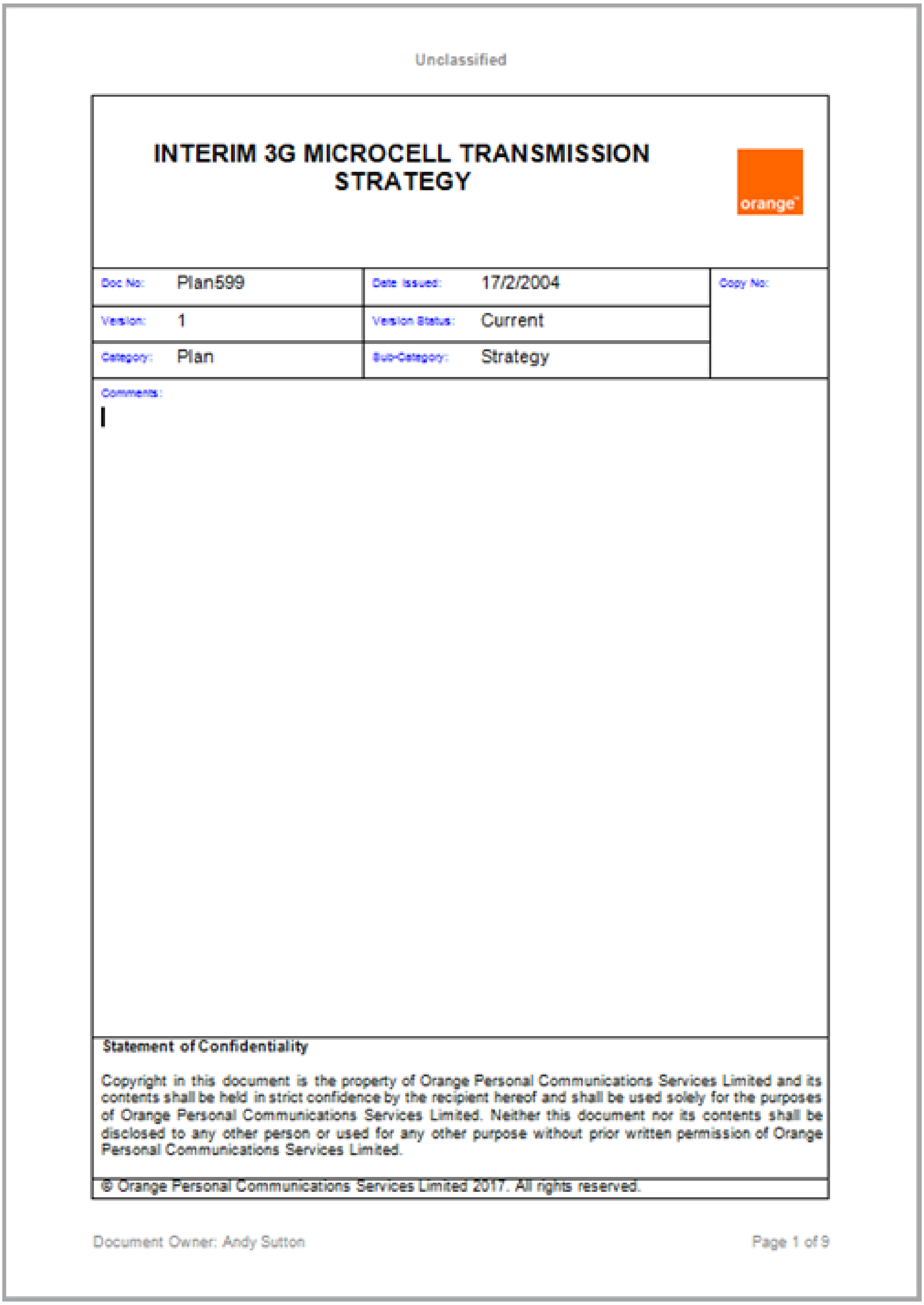
Appendix 1 figure 5: Plan591



Unclassified

INTERIM 3G MICROCELL TRANSMISSION STRATEGY

orange

Doc No:	Plan599	Date Issued:	17/2/2004	Copy No:
Version:	1	Version Status:	Current	
Category:	Plan	Sub-Category:	Strategy	

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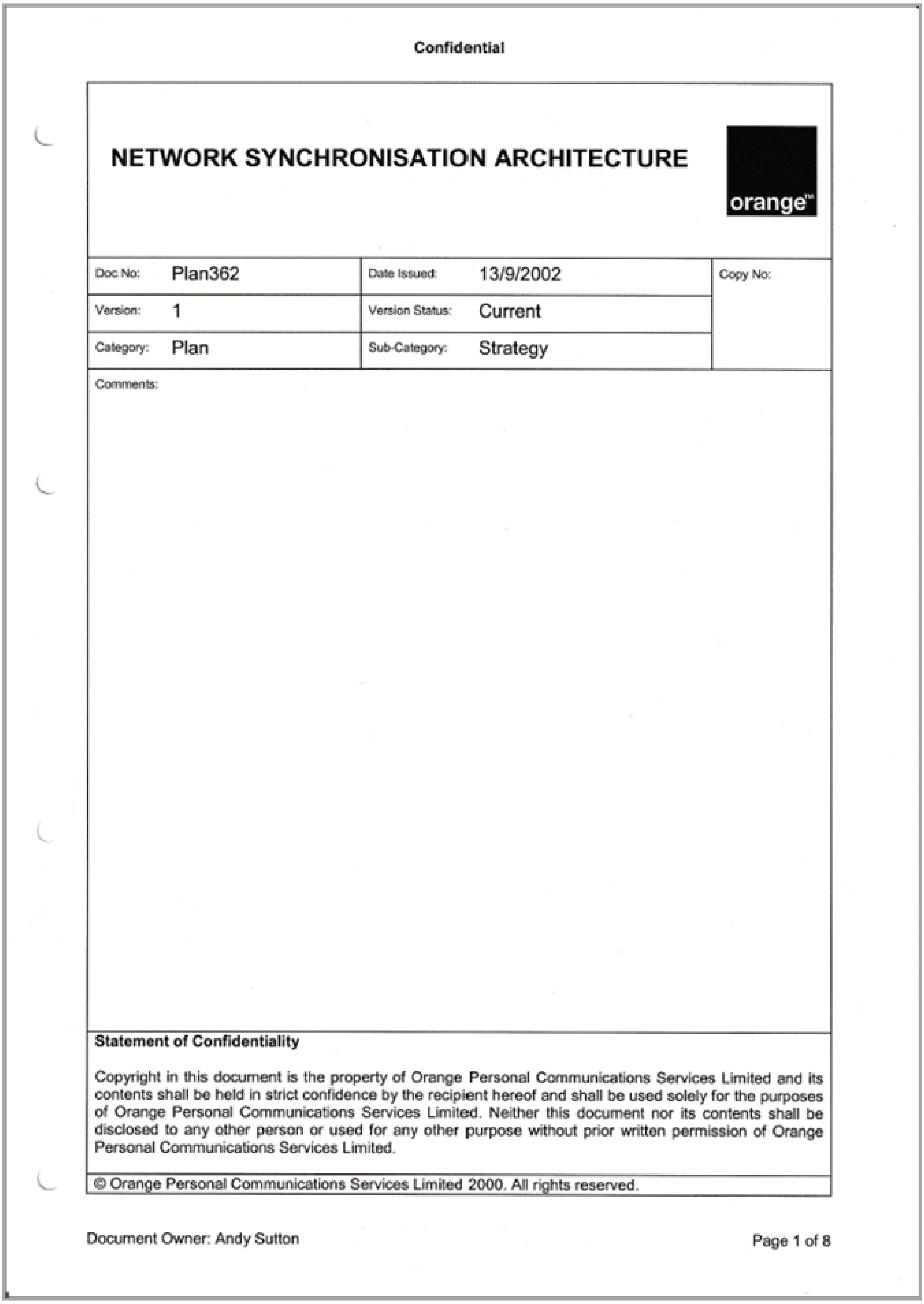
Appendix 1 figure 6: Plan599



Confidential

NETWORK SYNCHRONISATION ARCHITECTURE

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Doc No:	Plan362	Date Issued:	13/9/2002	Copy No:
Version:	1	Version Status:	Current	
Category:	Plan	Sub-Category:	Strategy	

Comments:

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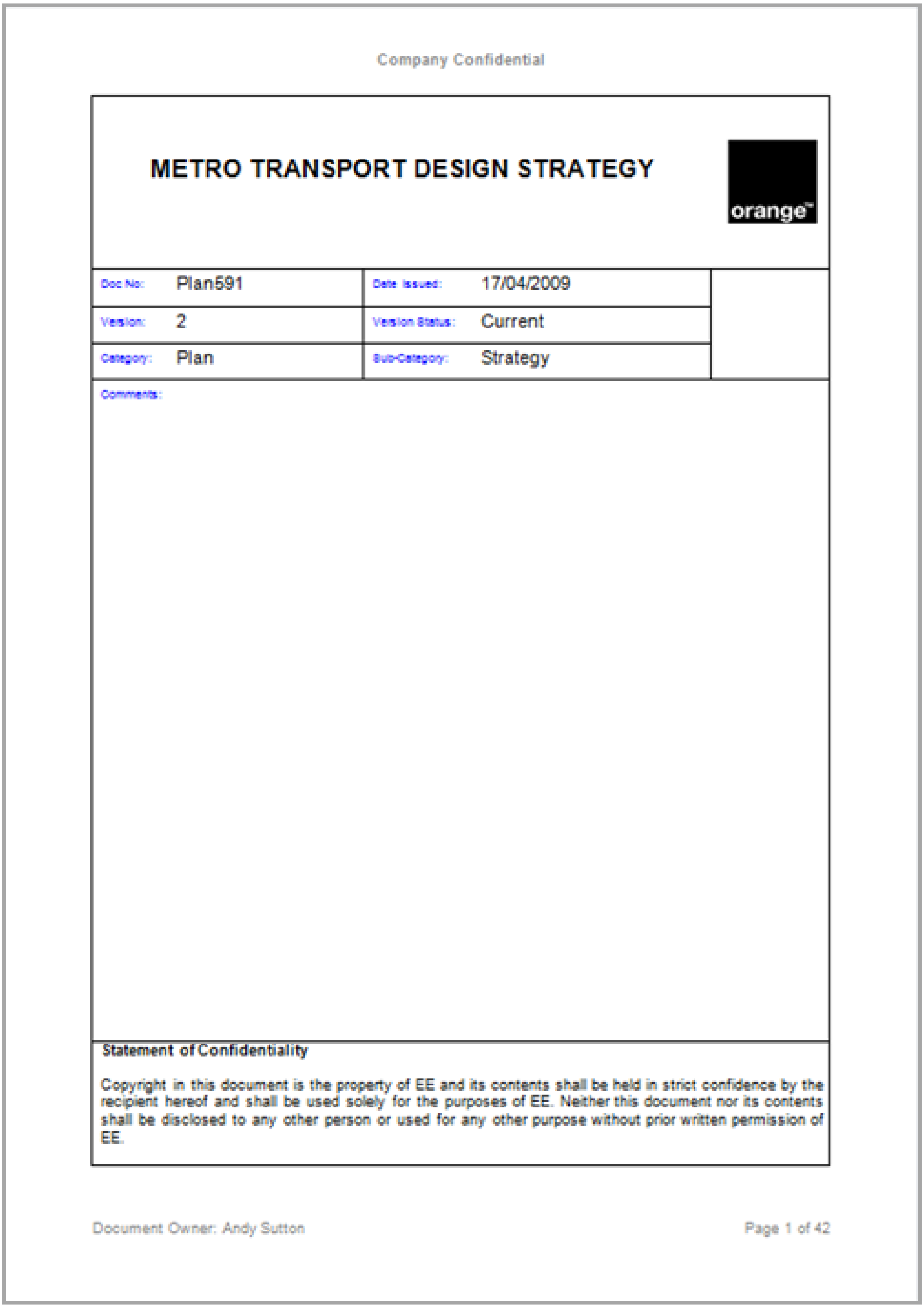
Appendix 1 figure 7: Plan362



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METRO TRANSPORT DESIGN STRATEGY

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Doc No:	Plan591	Date Issued:	17/04/2009
Version:	2	Version Status:	Current
Category:	Plan	Sub-Category:	Strategy

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Appendix 1 figure 8: Plan591 version 2

Appendix 2

Selected papers and publications by the author:

Jaber, M., Imran, MA., Sutton, A., Tukmanov, A., & Tafazolli, R. (2017). Modular Approach for Modelling the Hybrid Multi-Hop Backhaul Performance. *IEEE Wireless Communications Letters, 6*(2), 262-265.

Sutton, A. (2016). Small Cells and Heterogeneous Networks. *The Institute of Telecommunications Professionals Journal, 10*(2), 35-39.

Linge, N., & Sutton, A. (2016). The Heritage of 30 Years of Mobile Communications in the UK. *Industrial Archaeology Review Journal, 38*(1), 2-18.

Sutton, A., & Linge, N. (2015). Mobile Network Architecture Evolution - 1G to 4G. *The Institute of Telecommunications Professionals Journal, 9*(2), 10-16.

Sutton, A. (2015). Radio Systems, Microwave and Millimetre Wave. *The Institute of Telecommunications Professionals Journal, 9*(2), 38-43.

Linge, N., & Sutton, A. (2015). *30 years of mobile phones in the UK.* Stroud: Amberley Publishing.

Sutton, A., & Tafazolli, R. (2015). 5G - The Future of Mobile Communications. *The Institute of Telecommunications Professionals Journal, 9*(1), 10-16.

Sutton, A., & Linge, N. (2014). The Road to 4G. *The Institute of Telecommunications Professionals Journal, 8*(1), 10-16.

Sutton, A. (2013). Mobile Backhaul Evolution. *The Institute of Telecommunications Professionals Journal, 7*(3), 34-38.

Sutton, A. (2011). Building Better Backhaul. *IET E & T Magazine, 6*(5), pp. 72-75.

Appendix 3

Selected list of invited conference presentations by the author:

1. 2017 (London) - Informa, 5G World Congress

   5G Backhaul and X-haul

2. 2017 (London) - IET, Towards 5G Mobile Technology – Vision to Reality conference

   5G Network Architecture and Design

3. 2016 (London) - WWRF, 5G Huddle – Making the Vision a Reality

   Next Generation Internet Protocols: 5G & the Internet, finding the best path together

4. 2016 (London) Informa, Self-Organising Networks World

   SON for Ultra-Reliable Networks

5. 2016 (London) European Microwave Week

   Millimetre Wave Radio Systems - The Next Frontier

6. 2015 (London) IET, Towards 5G Mobile Technology – Vision to Reality conference

   5G: End to End and Top to Bottom Network Design

7. 2015 (Coventry) Electronics Design Show

   5G – The Future of Mobile Communications

8. 2014 (Dusseldorf) Layer123, Packet Microwave Forum

   The Role of Wireless Backhaul in Future Mobile Networks

9. 2014 (Budapest) ITSF, Time and Sync in Telecoms conference

   The Route to 5G

10. 2013 (London) Avren Events, Base Station Conference

Densification of the macro layer and the roadmap to heterogeneous network deployments

11. 2013 (Amsterdam) Informa, LTE World Congress

    Multi-RAT mobile backhaul for Het-Nets

12. 2013 (London) Informa, LTE Voice Summit

    Transport Network Design for Next Generation Voice Services

13. 2012 (Berlin) IIR, Transport Networks for Mobile Operators conference

    The Importance of Low Latency Mobile Backhaul Network Design

14. 2011 (London) Layer123, Packet Microwave Forum

    Microwave in future mobile networks

15. 2011 (London) IIR, Transport Networks for Mobile Operators conference

    The Impact of LTE on Mobile Backhaul

16. 2010 (London) Layer123, LTE/EPC & Converged Mobile Summit

    Mobile backhaul evolution

17. 2010 (Warsaw) IIR, Carrier Ethernet World Congress

    Managing the evolution from legacy to Ethernet backhaul

18. 2010 (London) IIR, Transport Networks for Mobile Operators conference

    Core transmission and transport network evolution

19. 2009 (Nice) IIR, WDM and Next Generation Optical Networking conference

    Infrastructure Fixed-Mobile Convergence at the Optical Layer

20. 2009 (Amsterdam) IIR, Transport Networks for Mobile Operators conference

    Defining a Transport Network Strategy for Next Generation Mobile Networks

21. 2008 (Berlin) IIR, Carrier Ethernet World Congress

Considering the Evolution to Packet Backhaul Over Microwave

22. 2008 (Amsterdam) IIR, Transport Networks for Mobile Operators conference

    Exploiting xDSL Applications to Support Mobile Backhaul Evolution

23. 2007 (Geneva) IIR, Carrier Ethernet World Congress

    Explaining Where Ethernet Fits into the Mobile Operator's Network Evolution Plans

24. 2007 (Budapest) IIR, Transport Networks for Mobile Operators conference

    Technology Choices and Timing of Network Evolution

25. 2007 (Barcelona) IIR, Transport Network Strategies conference

    Evolving UMTS backhaul to support HSDPA

Appendix 4

Specifications of Lucent PSAX 2300 and 4500 platforms

(Lucent Technologies, 2002) product literature describes the PSAX 2300 platform as follows:

System features - The PacketStar PSAX 2300 Multiservice Media Gateway provides high-capacity, universal connectivity over an asynchronous transfer mode (ATM) wide area network (WAN). The PSAX 2300 system is a carrier-grade, high-density ATM multiservice media gateway that provides network access for TDM voice, frame relay, and ATM data applications. The PSAX 2300 system I/O interfaces are supported by a sophisticated package of features, such as PNNI (private network-node interface), ILMI (integrated local management interface), 1+1 APS (automatic protection switching) and 1+1 MSP (multiplexer section protection), trunk conditioning, a connection gateway API, and redundant common equipment modules. Echo cancellation and silence suppression features make the PSAX 2300 a true multiservice platform. Featuring a 1.9 Gbps ATM cell bus capacity, carrier-class reliability, provisions for OC-12c interfaces and N:1 DS3/E3/STS-1e module protection-switching, the PSAX 2300 system solves demanding and diverse network design challenges.

System hardware components - The PacketStar® PSAX Multiservice Media Gateways base system includes the following hardware components:

- Chassis - 17.5 in. chassis with mounting brackets for 48.26 cm (19 in.) or 58.2 cm (23 in.) equipment racks
- -48 V dc Power Supply module - two each for redundant operation (includes cooling fan for power supply and chassis)
- Stratum 3–4 module - two each for redundant operation

The following items are ordered separately to complete the configuration of the PSAX 2300 system:

- Central processing unit (CPU2) module with the appropriately installed system software release

- Input/output (I/O) and server modules

- Blank faceplate modules - required for empty I/O and server slots

(Lucent Technologies, 2001) product literature describes the PSAX 4500 platform as follows:

System features - The PacketStar PSAX 4500 Multiservice Media Gateway is a carrier-grade, high-density asynchronous transfer mode (ATM) wide area network (WAN) access concentrator providing network access for TDM voice, frame relay, and ATM data applications. The PSAX 4500 system I/O interfaces are supported by a sophisticated package of features, such as private network node interface (PNNI), integrated local management interface (ILMI), 1+1 automatic protection switching (APS) and 1+1 multiplex section protection (MSP), trunk conditioning, a connection gateway API, and redundant common equipment modules. The chassis has the capacity of 120,000 CES DS0s (4 chassis) in a 7-foot rack. Echo cancellation and silence suppression features make the PSAX 4500 a true multiservice platform. Featuring a 9.6 Gbps ATM cell bus architecture, carrier-class reliability, provisions for OC- 12c interfaces, and N:1 DS3/E3/STS-1e module protection-switching, the PSAX 4500 Multiservice Media Gateway solves demanding and diverse network design challenges.

System hardware components - The PSAX 4500 Multiservice Media Gateway base system includes the

following hardware components:

- Chassis - 17.5 in. chassis with mounting brackets for 48.26 cm (19 in.) or 58.2 cm (23 in.) equipment racks

- -48 V dc Power Supply module - two each for redundant operation (includes cooling fan for power supply and chassis)

- Stratum 3–4 module - two each for redundant operation

The following items are ordered separately to complete the configuration of the PSAX 4500 system:

- Central processing unit (CPU2) module with the appropriately installed system software release
- Input/output (I/O) and server modules
- Blank faceplate modules - required for empty I/O and server slots

Appendix 5

Details of photographs.

Figure 5: Vodafone site reference: 5848. Hack Green Secret Nuclear Bunker, former cold war site which is now a museum. French Lane, Nantwich, Cheshire, CW5 8AP. Photo taken in 2014.

Figure 6: Vodafone site reference: 1324. Creamery Industrial Estate, Kenlis Rd, Barnacre, Preston PR3 1GD. Photo taken in 2014.

Figure 11: Left photo, Vodafone site reference: 116. Side of A5117 near Stanlow, Cheshire. Photo taken in 2015.

Figure 11: Right photo, Orange site reference: MER0063, now EE site reference: 18551 – Harefield farm, Warrington Road, Rainhill, Merseyside, L35 6PG. Photo taken in 2015

Figure 13: Mercury one2one site, later T-Mobile and now EE, site reference unknown – Rudge, Wiltshire. Photo taken in 1998. Source: http://www.prattfamily.demon.co.uk/mikep/phot19.html

Figure 14 : Site reference unknown – location unknown, possibly Bristol as many Orange engineering trials took place in and around Bristol. Photo taken in 1993.

Figure 15: Site reference number unknown. Former Warrington Collegiate building on Winwick Road, Warrington, Cheshire. Building was demolished in 2007 to make room for a new development, cell site was decommissioned and removed just prior to this. A new site was built nearby to provide the radio coverage which was lost due to the removal of this site. Photo taken in 1999.

Figure 21: Orange site reference: GMN0907, now EE site reference: 28324. Billinge Hill radio station, Crank Road, Billinge, Wigan, Greater Manchester, WN5 7EZ. Photo taken in 2014.

Figure 22: Left photo, Orange micro-cell installation in Liverpool, Merseyside. Exact location and site reference are unknown. Photo was taken in 1999.

Figure 22: Right photo, Orange site reference: CHS7037, now EE site reference: 11641. Grass verge north side of Herons Way, Chester business park, Chester, CH4 9QS. Photo taken in 2015.

Figure 31: Orange site reference: CHS0029M now EE site reference: 27386. Spark Hall, adjacent to Stretton Fox Pub, Stretton, Warrington, Cheshire, WA4 4NS. Photo taken in 2015.

Figure 40: Orange site reference: GMN0902, now EE site reference: 28323. Building 5, Exchange Quay, Salford, Greater Manchester, M5 3EQ. Photo taken in 2010.

Figure 54: Lucent PSAX2300 installation at Orange site reference: CHS0909, now EE site reference: 28224. Civil Defence Beacon Hill, Overton, Frodsham, Cheshire, WA6 6HD.

Figure 56: Left photo, Orange site reference: MER0063, now EE site reference: 18551 – Harefield farm, Warrington Road, Rainhill, Merseyside, L35 6PG. Photo taken in 2015

Figure 56: Right photo, : Orange site reference: GMN0907, now EE site reference: 28324. Billinge Hill radio station, Crank Road, Billinge, Wigan, Greater Manchester, WN5 7EZ. Photo taken in 2014.

Figure 59: Left photo, Orange site reference: CAM7036, now EE site reference: 11321. Opposite 89A, Barton Road, Cambridge, Cambridgeshire, CB3 9LL. Photo taken in 2014.

Figure 59: Right photo, Orange site reference: GLN7037, now EE site reference: 14489. Salisbury House, Bishopsgate, London, EC2M 7AB. Photo taken in 2017.

Figure 62: Digital Distribution Frame (DDF) in Orange site reference: GMN0901, then EE site reference: 15472. Manchester MSC site, Lapwing Centre, 1 Hagley Road, Salford, Greater Manchester, M5 3EY. Note: Site was decommissioned and closed down in 2017. Photo taken in 2010.

Figure 64: Orange HSDPA mobile broadband dongle from 2008.

Figure 78: Left photo, Siae STM-1 ADMs installed at Orange site reference: GN0901, then EE site reference: 15472. Manchester MSC site, Lapwing Centre, 1 Hagley Road, Salford,

Greater Manchester, M5 3EY. Note: Site was decommissioned and closed down in 2017. Photo taken in 2016.

Figure 78: Right photo, Tellabs MSSR installed at Orange site reference: GN0901, then EE site reference: 15472. Manchester MSC site, Lapwing Centre, 1 Hagley Road, Salford, Greater Manchester, M5 3EY. Note: Site was decommissioned and closed down in 2017. Photo taken in 2016.

Figure 82: MSSR installation at Orange site reference: AVN5074, now EE site reference: 10325. North Bristol BSC, Eagleswood, Almondsbury, Bristol, BS32 4EU. Photo taken in 2009 by Ian Grant for Computer Weekly: http://www.computerweekly.com/photostory/2240108774/What-goes-on-inside-Orange-UKs-network-management-centre/14/Andy-Sutton-describes-Tellabs-multi-service-switch-router