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Introduction

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1.1 A Brief Look at Cellular History

The history of mobile communications started with the work of the first pioneers in the area. The experiments of Hertz in the late 18th century inspired Marconi to search markets for the new commodity (to be). The communication needs in the First and Second World Wars were also supporting and accelerating the start of cellular radio, especially in terms of utilisation of ever higher frequencies. The first commercial systems were simplex, and the operator was required to place the call. In the case of mobile-originated calls the customer had to search for an idle channel manually [1]. Bell Laboratories first introduced the cellular concept as known today. In December 1971 they demonstrated how the cellular system could be designed [2].

The first cellular system in the world became operational in Tokyo, Japan, in 1979. The network was operated by NTT, known also as a strong driver for cellular systems based on Wideband Code Division Multiple Access (WCDMA). The system utilised 600 duplex channels in the 800 MHz band with a channel separation of 25 kHz. Another analogue system in Japan was the Japanese Total Access Communication System (JTACS). During the 1980s it was realised that, from the user's point of view, a single air interface was required to provide roaming capabilities. A development study was initiated in 1989 by the Japanese government, and a new digital system, Pacific Digital Cellular (PDC), was introduced in 1991.

In 1981, 2 years later than in Japan, the cellular era also reached Europe. Nordic Mobile Telephone started operations in the 450 MHz band (the NMT450 system) in Scandinavia. The Total Access Communication System (TACS) was launched in the United Kingdom in 1982 and Extended TACS was deployed in 1985. Subsequently in Germany the C450 cellular system was introduced in September 1985. Thus, at the end of the 1980s Europe was equipped with several different cellular systems that were unable to inter-operate. By then it was clear that first-generation cellular systems were becoming obsolete, since integrated circuit technology had made digital communications not only practical but also more economical than analogue technology. In the early 1990s second-generation (2G) (digital) cellular systems began to be deployed

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throughout the world. Europe led the way by introducing the Global System for Mobile communications (GSM). The purpose of GSM was to provide a single, unified standard in Europe. This would enable seamless speech services throughout Europe in terms of international roaming.

The situation in the United States was somewhat different than in Europe. Analogue first-generation systems were supported by the Advanced Mobile Phone System (AMPS) standard, available for public use since 1983. There were three main lines of development of digital cellular systems in the US. The first digital system, launched in 1991, was the IS-54 (North American TDMA Digital Cellular), of which a new version supporting additional services (IS-136) was introduced in 1996. Meanwhile, IS-95 (cdmaOne) was deployed in 1993. Both of these standards operate in the same band as AMPS. At the same time, the US Federal Communications Commission (FCC) auctioned a new block of spectrum in the 1900 MHz band. This allowed GSM1900 (PCS) to enter the US market. An interesting overview of the GSM and its evolution towards 3G can be found in [3].

During the past decade the world of telecommunications changed drastically for various technical and political reasons. The widespread use of digital technology has brought radical changes in services and networks. Furthermore, as time has passed, the world has become smaller: roaming in Japan, in Europe or in the US alone is no longer enough. Globalisation has its impact also in the cellular world. In addition, a strong drive towards wireless Internet access through mobile terminals has generated a need for a universal standard, which became known as the Universal Mobile Telecommunication System (UMTS) ([4]–[6]). These new third-generation (3G) networks are being developed by integrating the features of telecommunications- and Internet Protocol (IP)-based networks. Networks based on IP, initially designed to support data communication, have begun to carry streaming traffic like voice/sound, though with limited voice quality and delays that are hard to control. Commentaries and predictions regarding wireless broadband communications and wireless Internet access are cultivating visions of unlimited services and applications that will be available to consumers ‘anywhere, anytime’. They expect to surf the Web, check their emails, download files, make real time videoconference calls and perform a variety of other tasks through wireless communication links. They expect a uniform user interface that will provide access to wireless links whether they are shopping at the mall, waiting at the airport, walking around the town, working at the office or driving on the highway. The new generation of mobile communications is revolutionary not only in terms of radio access technology, and equally the drive for new technical solutions is not the only motivation for UMTS. Requirements also come from expanded customer demands, new business visions and new priorities in life.

1.2 Evolution of Radio Network Planning

There is very little published on the Radio Network Planning (RNP) process itself. An integral approach is proposed in [7], but this is more related to the functionalities of an RNP tool than to the overall planning process. This paper challenged the existing practises in RNP by listing the following weaknesses:

- planning was based on hexagonal network layout;
- traffic density was assumed to be uniform;
- radio wave propagation was considered independent from the environment;
- base station locations were chosen arbitrarily, while in practice fixed sites were used;
- traffic region boundaries usually were not taken into account.

The discussion continued in [8], which for the first time accounted for the impacts of quality requirements in radio network planning. This paper starts to have a process approach, and capacity enhancement with base station sectorisation to support network evolution is investigated. The challenges of non-uniform traffic conditions are identified, and cell splitting as one solution is proposed.

It can be noted that radio network planning and its development through time can be easily mapped to the development of the access technologies and the requirements set by those. The first analog networks were planned based on low capacity requirements. Radio network planning was purely designed to provide coverage. Omnidirectional antennas were used and positioned high in order to keep the site density low. The Okumura–Hata model was and still is widely used for coverage calculation in macro-cell network planning ([9] and [10]). Certain enhancements and tailoring by the COST231 project have finally resulted in the still widely used COST231 Hata model, also applicable to third-generation radio networks [11]. The latest COST developments of this area can be found in [12]. Walfisch–Ikegami is another model often referred to. This model is based on the assumption that the transmitted wave propagates over the rooftops by a process of multiple diffractions ([15] and [16]). Although the Walfisch–Ikegami model is considered to be a micro-cell model, it should be used very carefully when the antenna of the transmitter is below the rooftops of the surrounding buildings. More about propagation models can be found in Section 3.2.2.2 and conclusions about their applicability in [17] and [18].

During the course of time, together with the evolution of 2G systems, the site density got higher due to increasing capacity requirements. Furthermore, the initial assumption that cellular customers would mostly be vehicular turned out to be incorrect. Thus the maximum transmit power levels of the user equipment were reduced by at least a factor of 10, causing a need to rebalance the radio link budgets. All this forced the cellular networks to omit the omnidirectional site structure and lead to the introduction of cell splitting – i.e., one site consisted of typically three sectors instead of just one ([8] and [13]). Owing to increased spectral efficiency requirements, the interference control mechanism became more important. In addition to the sectorisation antenna tilting was also introduced as a mechanism for co-channel interference reduction [14]. Furthermore, the macro-cellular propagation model was no longer accurate enough; new models were needed to support micro-cellular planning. Sectorisation, antenna tilting and link budgets are discussed later in Chapter 3.

Higher site densities also necessitated a more careful management of the scarce frequency resources. As the frequency planning and allocation methods were widely based on predicted propagation data, the propagation models had to undergo a further refinement. Examples of such more accurate models are the ones based on ray tracing. Some ray-tracing models can be found, for example, in [19] and [20].

In addition to the propagation model development it was noticed that the increasing capacity demands could only be met with more accurate frequency planning. The frequency assignment together with neighbour cell list (for handover purposes) planning and optimisation were the main issues when planning GSM networks. In the case of GSM, frequency hopping was introduced to further improve the spectrum efficiency. Advanced frequency allocation methods can be found in the literature, one example based on simulated annealing is in [23]. In [24] a method for automatic frequency planning for D-AMPS is studied. In [25] advanced features for Frequency Division Multiple Access/Time Division Multiple Access (FDMA/TDMA) systems are introduced. These features include improving the frequency reuse by applying:

- frequency hopping;
- adaptive antennas;
- fractional loading;
- hierarchical cell structures.

It can be concluded based on several papers (for example, [26]–[28]) that the prediction of propagation is of limited accuracy due to the fact that the propagation environment is very difficult to model and thus generating a generic model, which is applicable in multiple cells, is by nature accuracy-limited. This is especially applicable when the fading characteristics (both fast and slow) need to be considered. The latest radio network control activities concentrate on the closed-loop optimisation of the plan. The initial planned configuration is (semi-) automatically tuned based on statistics collected from the live network. Proposals for handover performance improvement in terms of correct neighbour cell lists can be found in [26] and [27]. The important aspect with this method is that neighbour relations that are initially based on propagation prediction are autotuned based on real measurements. Thus inaccuracies can be compensated in the optimisation phase. A similar measurement-based concept can be utilised also for WCDMA intra- and inter-system neighbour relations; this is discussed in more detail in Chapter 7.

Recently, methods for GSM frequency planning based on mobile station measurement reports have been introduced and implemented, see [21] and [22]. The possibilities offered by these reports in GSM and WCDMA should be more utilised in the network control process (planning, optimisation and integration of those two).

Another new trend in radio network planning research is plan synthesis, meaning automatic generation of base station site locations depending on a cost function output. This is briefly discussed in Section 7.3.1.1.

In cellular networks network utilisation control requires such functionality that can utilise the measured feedback information from the network and react correctly based on that. Therefore, it is crucial that the planning phase is tightly integrated into other network control functions and the network management system. This is especially important in the case of WCDMA, owing to the fact that there will be a multitude of services; that is, customer differentiation will set a multi-dimensional matrix of Quality of Service (QoS) requirements. Planning such a network very accurately is not feasible due to limited accuracy of the input data (propagation, traffic amount, traffic distribution etc.). An example of the integration of a network management system and planning for 2G systems can be found in [29].

Integrating the network management system and advanced analysis and optimisation methods for effective configuration parameter provisioning and 'pre-launch network performance' estimation are the next challenges in the radio network development and optimisation area. An example of the effective integration of the planning tools' functionalities into the Network Management System (NMS) is, for example, visualisation of statistical performance data on cell dominance areas. Furthermore, the adjacency relations can be directly generated in the NMS based on the base station coordinates and simple distance-based rules. These initial lists can be later autotuned based on statistics collected from the live network. Also WCDMA scrambling code allocation can be done in the NMS without interfacing to external planning tools by utilising the mobile station measurement reports required by both the GSM and WCDMA standards. These reports contain information that can be used to complement the information generated traditionally by the planning tool (propagation, traffic density, etc.). When mobile station positioning methods are fully in use, another huge new dimension to optimisation tasks will be opened.

Together with the introduction of the all-IP mobile world, QoS provisioning becomes very important for the operators. This directs the network control increasingly away from radio access network control to service control. In practice this means an increased abstraction level for the operator and a new era for network management.

This book concentrates on the challenges with WCDMA networks. Furthermore, one of the main motivations is to move away from the 'analytical' control of the network, and enhance the modelling and tools to give a picture as realistic as possible of the actual network performance. Network functionalities can no longer be considered as individual entities, but their interactions must be accounted for. In the analytical, ideal world this has no relevance, but in the true cellular world the understanding of these interactions and network element algorithms and their limitations is essential.

It can be stated that radio access evolution towards third generation is the first big evolutionary step after the birth of cellular systems. The large step in radio access development, the great interest in applications and services also forces the radio network planning and optimisation process to improve to fully support the offered possibilities.

1.3 Introduction to Radio Network Planning and Optimisation for UMTS

The mobile communications industry throughout the world is currently shifting its focus from 2G to third-generation (3G) UMTS technology; that is, it is investing in the design and manufacturing of advanced mobile Internet/multimedia-capable wireless networks based on the Wideband Code Division Multiple Access (WCDMA) radio access platform. While current 2G wireless networks, in particular the extremely successful and widespread global GSM-based cellular systems, will continue to evolve and to bring such facilities as new Internet packet data services onto the market, more and more radio network planners and other wireless communication professionals are becoming familiar with WCDMA radio technology and are preparing to build and launch high-quality 3G networks. This book has been written in particular for those RF (Radio Frequency) engineering professionals who need to thoroughly understand the key principles in planning and optimising WCDMA radio networks, though it should also prove useful to others in the industry.

Radio network planners, particularly, face a number of new challenges when moving from the familiar 2G to the new 3G networks, many of them related to the design and the planning of true multi-service radio networks, and some to particular aspects of the underlying WCDMA radio access method. In this introductory chapter we provide a brief outline of these challenges, which will then be discussed in much greater detail in the following chapters of this book.

Before considering in detail what actually will be new (and different) in WCDMA compared with GSM, for example, we summarise here some of the defining characteristics of 3G multi-service radio networks in an abstract setting, regardless of the particular incarnation of the underlying 3G radio access protocol, such as WCDMA or EDGE. Hence, one could attempt to characterise 3G radio access with the following attributes:

- Highly sophisticated radio interface, aiming at great *flexibility* in carrying and multiplexing a large set of voice and, in particular, data services with constant as well as variable throughput ranging from low to very high data rates, ultimately up to 2 Mbps.
- Efficient support for carrying traffic under IP.
- Cell coverage and service design for *multiple services* with largely different bit rates and QoS requirements. Due to the great differences in the resulting radio link budgets, uniform coverage and capacity designs – as implemented in today's voice-only radio networks – could no longer be obtained economically for high bit rate services. Consequently, traffic requirements and QoS targets will have to distinguish between the different services.
- A large set of sophisticated features and well-designed radio link layer 'modes' to ensure very *high spectral efficiency* in a wide range of operating environments, from large macro-cells to small pico-cells or indoor cells. Examples of such features are various radio link coding/throughput adaptation schemes; support for advanced performance-enhancing antenna concepts, such as BS transmission diversity for the downlink; and the enabling of interference cancellation schemes.
- Efficient *interference-averaging mechanisms* and robustness to enable operation in a strongly interference limited environment in order to support very *low frequency reuse* schemes, with the goal of achieving high spectral efficiency. This will require good *dominance* of, and striving for maximum *isolation* between the cells through the proper choice of site locations, antenna beamwidths, tilts, orientation and so on. Tight frequency reuse in conjunction with interference limited operation, on the other hand, means that *cell breathing* effects will necessarily occur.
- Extensive use of 'best effort' provision of packet data capacity. Temporarily unused radio resource capacity will be made available to the packet data connections in a flexible and fair manner so as to improve the commonly perceived QoS. This will

result in networks operating at a *higher spectral loading* compared with today's voice-dominated networks. This higher load on the RF spectrum will result in higher interference levels, thus requiring ever-better RF planning to achieve high throughput. This trend is amplified by the significant spectrum-licensing costs which some service providers, especially in Europe, are having to bear for providing their 3G services.
- IP packet services, with their possibly 'unlimited' demand for radio capacity together with network-based best effort packet data allocation and strong interference limitations, will place a higher than ever burden on *pre- and post-deployment optimisation* of the cell sites, if satisfactory cell throughput and QoS targets are to be met. As a consequence, the effort and cost of the radio network optimisation phase will exceed that of today's 2G networks, in which the primary burden is on initial frequency planning. Furthermore, the current practice of using the ample available 2G spectrum to circumvent interference problems by appropriate frequency planning will no longer be viable for the high-throughput services relying on high spectral efficiency and tight reuse of the available spectrum.
- In order to provide ultimately high radio capacity, 3G networks must offer efficient means for multi-layered network operation, supporting micro- and pico-cellular layers, for example, and ways of moving the traffic efficiently between these layers as appropriate. This will require efficient *inter-layer handover* mechanisms, together with appropriate dimensioning and RF planning of the cell layers.
- Introduction and rollout of 3G networks will be costly and will happen within a very competitive environment, with mature 2G (e.g., GSM) networks guiding end-users' expectations of service availability and quality. Therefore, service providers will utilise their existing GSM networks to the fullest possible extent. The most obvious way to do this is to use the comprehensive GSM footprint as a coverage extension of 3G, providing 3G services initially only in limited, typically urban, areas, thus relying on *3G to GSM inter-system handover* to provide coverage continuity for basic services. Therefore, it will be important for 3G service providers to implement 3G handover to GSM cells, in order to accelerate 3G rollout and minimise upfront deployment costs. This will require RF planning methods that allow for joint 2G–3G coverage and capacity planning – i.e., some degree of integration of the tools and practices used.
- Another very important aspect is the possibility of *co-siting 3G sites with existing 2G sites*, reducing costs and overheads during site acquisition and maintenance. However, such co-siting raises a number of issues for the radio network planner to consider. Should shared antenna solutions be used? Would the RF quality of the underlying 2G network meet acceptable standards for the 3G quality targets, or would there have to be a prior optimisation phase for the 2G sites? Might there exist other constraints on site reuse, such as shelter space? Are there any potential interference-related problems in co-siting? And so forth. Again, an integrated approach, recognising the operation of 3G jointly with 2G from a *multi-radio* perspective with the goal of achieving a good cost/performance ratio for *both* systems operating concurrently, will be required.

Any generic radio access method (TDMA, FDMA, CDMA, OFDM, etc.), designed for high spectral efficiency operation and to meet the above 3G service requirements, would face the listed issues, which suggests that most of the challenges faced by network planners in moving towards 3G actually stem from dealing with an integrated multi-service, multi-data-rate system providing end-users with capacity and bit rates on demand, rather than predominantly from the radio protocol, WCDMA.

What, therefore, are the radio network planning challenges *specific to WCDMA*? Obviously there are many differences in detail between WCDMA and GSM – in the radio network parameters, for example – but let's look at the more fundamental differences:

- Planning of soft(er) handover overhead. Soft handover is a feature specific to CDMA systems, such as IS-95-based systems, or as in our case WCDMA. However, a closer look reveals that minimising soft handover overhead is closely correlated with establishing proper *cell dominance*, which we have already identified as generically desirable for maturing 2G systems as well. Thus, planning for low soft handover overheads does not require any new skills and tools, but rather adherence of good radio network planning practices known from today's systems.
- Cell dominance and isolation. These will become relatively more important in WCDMA than in 2G, due to the frequency reuse in WCDMA being 1 and the resulting *closer coupling* of mutually interfering, nearby cells. WCDMA will 'see' different and, of course, more sites/cells than GSM does. This is particularly relevant when 2G–3G co-siting and antenna sharing is attempted.
- Vulnerability to 'external' interference – e.g., interference leaking from adjacent carriers used in other systems or similar interference between different WCDMA cell layers. Again, this issue is not so much specific to WCDMA, but its importance has been dramatically increased: with an operating bandwidth of 5 MHz, a single WCDMA carrier can consume as much as 25–50% of the service provider's available spectrum. Any residual interference leaking into a WCDMA carrier and desensitising the receivers will have a much more dramatic impact on service quality than for today's 2G narrowband systems.

In this section we have taken a 'bird's eye' view of WCDMA. Summarising, we can see some new challenges and certainly much new detail for the designer to consider when planning WCDMA networks, yet in a way there is very little new about planning WCDMA: it merely requires good planning practices from today's wireless systems to be recognised and implemented in a consequent and disciplined fashion.

But exactly where do radio network planning and optimisation fit into the whole UMTS mobile network business concept? In terms of technological expertise, mobile networks represent a heavy investment in human resources. This will be even more true for 3G networks. However, not only are mobile networks technologically advanced, but the technology has to be fine-tuned to meet demanding coverage, quality, traffic and economic requirements. Operators naturally expect to maximise the economic returns from their investment in the network infrastructure – i.e., from Capital Expenditure (CAPEX). Here we should note two important aspects of network performance – planning and optimisation. Any network needs to be both planned and optimised. To what degree depends on the overall economic climate, but network optimisation is much easier and much more efficient if the network is already well-planned initially. A poorly laid out network will prove difficult to optimise to meet long-term business or technical expectations. Optimisation is a continuous process that is part of the operating costs of the network – i.e., its Operational Expenditure (OPEX). However, the concept of *autotuning* (see Section 9.3) offers new opportunities for performing the optimisation process quickly and efficiently, with minimal contribution from OPEX, in order to maximise network revenues.

Operators face the following challenges in the planning of 3G networks:

- Planning means not only meeting current standards and demands, but also complying with future requirements in the sense of an acceptable development path.
- There is much uncertainty about future traffic growth and the expected proportions of different kinds of traffic and different data rates.
- New and demanding high bit rate services require knowledge of coverage and capacity enhancement methods and advanced site solutions.
- Network planning faces real constraints. Operators with existing networks may have to co-locate future sites for either economic, technical or planning reasons. Greenfield operators are subject to more and more environmental and land use considerations in acquiring and developing new sites.
- In general, all 3G systems show a certain relation between capacity and coverage, so the network planning process itself depends not only on propagation but also on cell load. Thus, the results of network planning are sensitive to capacity requirements, which makes the process less straightforward. Ideally, sites should be selected based on network analysis with the planned load and traffic/service portfolio. This requires more analysis with the planning tools and immediate feedback from the operating network. The 3G revolution forces operators to abandon the 'coverage first, capacity later' philosophy. Furthermore, because of the potential for mutual interference, sites need to be selected in groups. This fact should be considered in planning and optimisation.

1.4 Future Trends

Even though 3G telecommunication systems are still under development and not yet in widespread operation throughout the world, it is not possible to stand still. In today's fast-moving information society, continuous improvement is essential. This applies equally to 3G systems themselves, which have already evolved a long way from the first such systems in terms of services and capacities. Although the detailed steps in their evolution since Third Generation Partnership Project (3GPP) Release '99 are still somewhat unclear, some long-term trends are already visible. One major change will be separating more or less completely the user plane from the control plane, changing more and more from circuit switched to packet switched connections, thus making the whole network ready to be based completely on IP technology. The technology for accessing a network and transporting the information will become less important, but greater emphasis will be put on the services and the quality thereof. Users will no longer even know which access technology they are using – they will just request a service and the network will decide at the time the optimum technology (GSM/EDGE, cdma2000, WCDMA, WLAN, DVB, etc.) to provide it.

1.4.1 Towards a Service-driven Network Management

After the deployment of 3G networks new challenges are ahead: even higher bit rates shall be supported, with some possible average around 2 Mbps, some peaks at 20 Mbps and in the extreme up to 200 Mbps. As a first step towards this achievement can be mentioned the introduction of the High-speed Downlink Packet Access (HSDPA) in Release 5 of the 3GPP standardisation and its counterpart the High-speed Uplink Packet Access (HSUPA), which is one of the main topics of the coming Release 6. HSDPA is also one of the major additions to this edition and will be described – e.g., in Chapters 2 and 4 – where applicable.

In general the need for higher data rates will lead to even smaller cells, self-planning dynamic topologies, full integration of IP, more flexible use of spectrum and other resources and utilisation of precise user position. However, if the radio network control and management processes are carefully designed to support 3G, the step to a wider variety of cell types and new set of services will be smooth and less revolutionary than what we face now when moving from 2G speech-oriented networks to the 3G applications- and service-driven cellular world.

Until recent years, the development of the telecommunication industry has been very technology-driven. The technical solution and its implementation paved the way, and service-handling capabilities were evaluated in a later phase. The right types of services were created in the last phase. Today, the approach is different. Services and content are the driving force, the same service type can in certain cases be delivered by several different access technologies. With Voice over IP (VoIP) the voice services will become a commodity; the mobile services and mobile content are the business drivers. The evolution of network services is depicted in Figure 1.1. The transition from voice

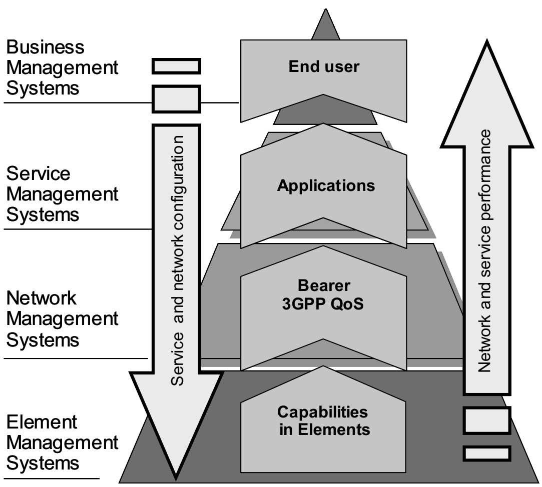

Figure 1.1 Service layers from the network point of view. Service provisioning and deployment is an evolutionary process – from best effort support to full utilisation of 3GPP Quality of Service mechanisms. The requirement for guaranteeing quality necessitates good integration between network configuration, service configuration and service assurance.

service only to QoS differentiation and Guaranteed Bit rate (GB) and non-GB separation/requirements provides possibilities, but at the same time sets new challenges for vendors and operators.

The forecast is that the Operations Support System (OSS) and especially the value adding components of the NMS are the areas to expand the business in IT as well as in telecommunications. This new trend evolves partly because the vision of the new service-driven future is becoming clearer. Further, the convergence of different technical solutions will set requirements also to OSS business.

Moreover, it is important to understand that 3G is not about technologies, but it is about services. The same service can be offered in several access technologies (GPRS, EDGE, WCDMA and the emerging WLANs, for example). Therefore, the evolution of the OSS in the service management area ought to be technology transparent and provide service management support independent of the access technology. Furthermore, the level of abstraction of service management should allow the operator to focus on service configuration rather than network element configuration. This is achieved by adding intelligence to perform automatic transitions from network layer to service layer in network management systems.

1.4.2 Wireless Local Area Networks (WLANs)

Wireless Local Area Networks (WLANs) are a strongly emerging complement to cellular communication. WLAN is a short-range, high bit rate and easy-to-use radio access technology. It is, as the name says, a wireless LAN, and is used to replace wired LAN when freedom from wires is desired. Practically, a synonym to WLAN is the standard IEEE 802.11 (this is the 'full' standard name, sometimes the 'IEEE' is dropped), although there are some other technologies that could serve the same purpose. The original 802.11 was developed during 1991–1997. The first release of the standard, '802.11' – without any specifying letters – was accepted in June 1997 and consisted of a specification for the Medium Access Control (MAC) layer and three different physical layers (PHYs), frequency hopping, Direct Sequence Spread Spectrum (DS-SS) and infrared. Radio PHYs operate in the 2.4 GHz unlicensed ISM (Industrial, Scientific, Medical) band, which is available globally, and give up to 2 Mbps bit rate. Over time the DS-SS variant gained the most popularity. The MAC layer is robust and elegant, is easy to take into use and works reliably even in interfered environments. No frequency planning or other radio-related parameters are necessary to be set before use, although larger areas with a number of access points operate more efficiently when some engineering effort is spent. These characteristics are achieved at the expense of spectrum efficiency but, because spectrum is free, it is of no big concern.

Overview of the 'WLAN Standard's Alphabet'

Since wired LANs developed meanwhile from 10 to 100 Mbps, there was a need to also increase the WLAN bit rate. Therefore, enhancements to the physical layers were developed in the late 1990s, leading to a family of 802.11 standards, distinguished by an appended letter. Table 1.1 presents a summary of the 'WLAN standard's alphabet' and their main enhancements. The 802.11b, delivering up to 11 Mbps, was introduced

Table 1.1 Overview of the 802.11 standard family (for current status the reader is referred to *http://grouper.ieee.org/groups/802/11/*).

802.11 Working Group	Brief description
802.11-1997, 802.11-1999	Base standard
802.11a-1999	5 GHz extension, up to 54 Mbps
802.11b-1999	Data rate extension in 2.4 GHz IMS band up to 11 Mbps
802.11c	ID bridge addition
802.11d-2001	Regulatory domains
802.11e	QoS enhancements
802.11f-2003	Recommended practices for interaccess point communication
802.11g-2003	11a-like high-speed extension for 2.4 GHz IMS band
802.11h-2003	Dynamic channel allocation and power control extensions for European requirements
802.11i-2004	Security enhancements to MAC
802.11j-2004	Support for 4.9 GHz bands for Japan
802.11k	Radio resource measurements
802.11m	Standard maintenance, technical and editorial corrections
802.11n	High throughput >100 Mbps extension
802.11p	Wireless access in vehicular environments
802.11r	Fast BSS transition – i.e., fast handover
802.11s	Mesh networks
802.11t	Wireless performance prediction
802.11u	Inter-working with external networks
802.11v	Wireless network management

Note: If no year is indicated with the standard, then it is ongoing in 802.11 standardisation at the time of writing.

in September 1999, and 802.11a, up to 54 Mbps, in December 1999. The bit rate figures mentioned here are the 'instantaneous' PHY rates, the actual user data throughputs are 1/3 ... 2/3 of those values. The 11a operates at a higher RF band, at the 5 GHz U-NII (Unlicensed National Information Infrastructure) band, which makes the equipment slightly more expensive. The exploding popularity of WLAN began with the 11b standard around 2000–2001, while the 11a has seen quite poor success in the marketplace. Although 11a is technically superior – at least regarding bit rates – the 11b was a better fit to the market, was 'good enough', had compatibility with previous 802.11 DS-SS installations and was a bit cheaper. Later on (November 2001), the higher speed 11a modulations were added to the 2.4 GHz band, producing the 11g variant, which runs up to 54 Mbps. Today the 11g is the most common in the marketplace. The volume of tens of millions of 11b devices causes considerable inertia to the market, and hence most 11g equipment also includes the 11b radio interface.

802.11e MAC Enhancement

The above-described enhancements deal with the PHY layer, the original 802.11 MAC has been untouched. Practically all the 802.11 equipment has the standard Distributed Control Function (DCF) MAC, which operates in a non-connection-oriented best effort way. This supports no QoS guarantees. In the original 1997 standard there is a Point Coordination Function (PCF) option that could facilitate QoS in theory, but it has not been implemented due to some difficulties with it. So in late 1999, Task Group 11e started to reconsider the QoS issue, and finally in October 2004 the task group achieved a positive vote in the sponsor ballot. The long process is an indication of how difficult the introduction of QoS is if it is not there in the beginning. So possibly we can soon add a new 'clump into the alphabet soup'. The role of 11e is somewhat different in different environments. There are three main application environments of WLAN – enterprise, home and public – which can also be seen as different markets. The role of 11e will be slightly different at these environments. Company premises are controlled environments, so there already have been internal wireless telephone systems utilising the 802.11 WLAN. Homes are relatively low load environments so it can be expected that QoS applications might run there quite satisfactorily even without 11e, although successful application of 11e would enhance reliability. The public environment is the most difficult; until now service providers have been reluctant to sell any applications requiring QoS over WLAN in this environment. At the time of writing it remains to be seen if 11e will change this. Possibly the most obvious effect of the absence of QoS has been experienced at conference premises where a large crowd of WLAN users may collect in a single space. The best effort MAC has a bell-shaped throughput curve as a function of load – meaning that when there are too many contenders for air time, nobody no longer gets anything, the total throughput of the access point goes to a very low value. This situation may be the first to see the benefits of 11e when it gets implemented.

802.11g and the Tug of War of Market Share

The Shannon law states that low path loss – i.e., small range (typical of the WLAN usage situation) – makes very high bit rates possible, whereas the opposite, high path loss – i.e., long range (typical of the cellular usage situation) – restricts the bit rate to lower values. Today the 11g WLAN reaches 54 Mbps, with some proprietary implementation even more than 100 Mbps, whereas the fastest cellular-based radio systems reach a few 100 kbps; newer technologies are expected to operate up to a few Mbps. Considering also the low price of WLAN access points compared with a cellular base station, this obviously makes the cost of delivering data over WLAN a lot cheaper per megabyte than over cellular radio. Given that the number of public access WLAN hotspots increase rapidly, this creates an obvious tug of war between the radio technologies about the share of business of 'wireless data' for each. Both technologies have their obvious benefits in their 'home base', where they don't compete; cellular has higher coverage and more QoS mechanisms, at least for the time being, while WLAN has advantages in the indoor environment and a higher bit rate. The distinction of the technologies is deep-rooted; by natural laws, by quite separate equipment vendor companies and by different companies implementing the physical access networks. The only thing that we can conclude is that the outcome is very difficult to predict. The 'chaotic boundary area' of the technologies will potentially see dynamic behaviour in the years to come. The mechanism – be it some automatic one or the human user – that chooses the radio system over which the applications run will attract interest and be an arena of competition.

Integration of WLAN with 3G

Although many analysts and marketing departments have positioned WLAN as complementary to cellular data access both technologies obviously compete for wireless data services and revenues while having application areas where 3G is strong, and where WLAN is strong. Realising that, the cellular community has launched an effort to integrate WLAN access into cellular systems. The results are WLAN-cellular inter-working standards produced by 3GPP and 3GPP2. Inter-working was spearheaded by 3GPP in Release 6, which envisioned loose inter-working with no inter-working at the Radio Access Network (RAN) level but rather at the Core Network (CN) level. Inter-working has been introduced in so-called scenarios, which are functionally built on top of each other starting from the lowest one – no other inter-working but common customer care and billing, using authentication based on, e.g., username and password. In this scenario a user accesses the Internet over the WLAN access network and bypasses the cellular CN completely. The next inter-working scenario uses Subscriber Identity Module/UMTS SIM (SIM/USIM)-based access control and charging functionalities from the cellular CN. This is then augmented with another scenario, specifying a standardised way of diverting user traffic to the CN. Here, the user may consume all the spectrum of offered cellular services, including Internet access. There are higher scenarios being considered for the Release 7 of 3GPP standards leading up to the support of full mobility and QoS between the WLAN and cellular accesses.

Unlicensed Mobile Access (UMA) – Integration with 2G

Coverage limitation in some areas and the possibility to complement them with wireless access to 2G cellular services over home WLAN and residential broadband connection was a strong motivation to integrate the WLAN and legacy 2G services provided by cellular operators. Similarly, fixed–mobile convergence made it very attractive to offer cellular-like services from fixed network and Mobile Virtual Network Operator (MVNO) services over wide area network for fixed operators with wireless ambitions. Shared interest resulted in the Unlicensed Mobile Access (UMA) standard specifying the transport of 2G circuit switched voice and data bearers over generic IP access to cellular terminals. Although being access-technology-agnostic, UMA names WLAN and Bluetooth™ as access technologies.

802.16 and WiMAX (Worldwide Inter-operability for Microwave Access)

As the popularity of WLAN rose, the coverage limitations of the technology were soon recognised. The attention of the wireless IT community has turned to a new fledgling IT standard, IEEE 802.16, which is specified for broadband wireless access. A lot of effort is being spent on specifying mobility extensions in 802.16 enabling its use as Mobile Broadband Wireless Access. Going further, the 802.16 certification body, WiMAX, is starting efforts to specify system architecture and thus one can expect that a new standardised vendor-inter-operable wide-area wireless packet switched network will be available in the near future. Still in its inception stage it is already being recognised as yet another technology competing with the cellular technologies for the wireless data access market and it is very likely that the cellular community will try to coopt this technology by integrating a WiMAX inter-working standard into its system.

802.20
The perceived demand for high-speed wide-area wireless data networks for highly mobile users has led to the creation of IEEE 802.20. The standardisation is at a virtual standstill and may not produce the expected results but it is widely referenced.

Looking to the Future
In homes the 802.11 WLAN easily carries over the air what a broadband Internet connection delivers today and probably will do so as long as homes are connected by copper-based wires. Within the home it is able to carry several video streams or one HDTV (High Definition Television) stream. So it can be expected that the current 802.11 WLAN may serve the home environment quite well in the foreseeable future. At company premises the useful bit rate is clearly less than what wired LANs have, but the highest rates of wired LAN are not needed by the average user, except for special cases like server input/output or when the Information Management (IM) service wants to make a backup of a disk. So we don't even expect the WLAN to be needed at those points. As access connection to most users the 802.11 can be expected to serve well for quite some time. A very interesting factor for the future is the performance of 11e in the public environment. If it fulfils the expectations then we can expect the 802.11 WLAN to serve our needs for a number of years.

1.4.3 Next-generation Mobile Communication

The current 3G and 3.5G mobile communication and the variants thereof will surely not be the end of the development, even though with HSDPA and HSUPA the 3GPP radio access will be highly competitive for quite some years. The drivers behind the development can be seen basically in the WLAN and Digital Subscriber Line (DSL) technologies, both of which are capable even now to deliver high bit rates in a very cost-efficient manner. Next-generation systems denoted as fourth generation (4G) are around the corner and will ensure competitiveness even in the longer run.

The main additional requirements compared with the current 3G systems can be seen in particular in that these new systems will be developed for an optimised, pure packet switched data access with a much more distributed radio resource and network management (fully IP-based) and a multi-carrier radio access (allowing more flexible carrier bandwidths than the current 5 MHz). Furthermore, being fully IP-based, mobility management could be replaced by IP mobility as known today, improving coverage and capacity at lower costs for the operator.

As an early version of such systems can be considered an approach initiated from NTT DoCoMo, which is an adaptation of the technologies originally studied for 4G deployments onto 3G bands, internally called Enhanced 3G (E3G). With carrier bandwidths up to 20 MHz air interface peak bit rates are expected to raise up to the order of 100 Mbps, allowing practical bit rates of around 20 Mbps. For real 4G systems, carrier bandwidths are envisaged to be around 100 MHz, pushing the theoretical air interface bit rate towards the 1 Gbps border and having a spectral efficiency of roughly double that of current Release 6 plans.

However, much is still speculative and the requirements are only being formulated at the moment, but clear trends as described above can be seen.

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