Foreword: Wireless Communication—History and Visions

HOW DID WE ARRIVE AT OUR CURRENT STATE OF THE ART?

Pre-Cellular Mobile Telephony

In order to understand where we’re going, we need to understand how we arrived at today’s state of the art. The notion of reliable mobile telephone service was first introduced in the 1950’s. The first widely deployed system was developed by AT&T Bell Laboratories in the United States and referred to as Mobile Telephone Service (MTS). MTS was fairly simple, comprising 1) a mobile analogue FM transceiver capable of operating on either 8 or 16 radio frequency channels in the vehicle, 2) a wide coverage FM base station transceiver and 3) an operator-assisted switching centre, by which calls were manually connected and disconnected to an outside party (Sarkar, Mailloux, Oliner, Salazar-Palma, & Sengupta, 2005). The mobile transceiver was extremely large, weighing 20 kilos or more and therefore was usually mounted in the trunk of the vehicle. A cable was run from the transceiver to the vehicle interior, where the user could operate the device using a control head and a telephone handset.

To place a call from the mobile, the user would first observe the “busy” light on the mobile control unit. If the system were available, the user would then lift the handset and press the “talk” switch to call the mobile operator and request that a number be dialled. The operator would then connect the audio lines from the Public Switched Telephone System (PSTN) to the mobile audio interface, and the call could proceed. Between 1964 and 1969, AT&T introduced the Improved Mobile Telephone Service (IMTS). The primary improvement was that automated switching replaced the need for manual involvement by a telephone operator. IMTS enabled users to place calls themselves using a dial installed on the mobile control head. Likewise, incoming calls were automatically routed to the mobile station, where the user was alerted by an alert tone (Gascoigne, 1974; Harte, 2006).

MTS and IMTS were fairly crude in contrast to the smart phones of today, but these systems were revolutionary for their time. They were truly technical substitutes for fixed-line telephony, and this is the way the consumer mobile communication industry remained for many years. Throughout the 1970’s, adoption of MTS and IMTS service in the United States was rapid, and in the mean time similar services were introduced in Europe. From a market segmentation viewpoint, the subscribers of mobile telephone services between the 1950’s and early 1980’s were primarily high-end business users. The cost of equipment and service were extremely high compared to the cost of fixed-line phone service, prohibiting adoption by the general population. Nevertheless, mobile subscribers were individuals for whom economic utility value was of primary importance – they could afford it, and didn’t mind paying the price one bit for mobile communication.

The rapid adoption of mobile telephony during the 1970’s was somewhat of a paradox to many fixed-line telephone company executives who saw the mobile telephone market as an extremely small niche market, deserving very little attention. After all, there was a huge network of coin phones across Europe
and the U.S. – if someone wanted to make a call, they could simply stop at a coin phone, drop in a relatively small amount of money and avoid the relatively large fixed cost of having mobile service. Of course, this was not how consumers viewed the situation. By 1980, there was a waiting list more than 5 years long for a mobile telephone number in every major city in Europe and the U.S. This was because the early systems had insufficient capacity. Each major city typically had either 8 or 16 FM voice frequencies, each of which could handle only one voice call at a time. To further compound the problem, the base stations were specifically designed to cover large geographical areas, typically a radius of 30 km or more, which limited the effectiveness of spatial frequency reuse. Indeed, the idea of aggressive frequency reuse and mobility control such as handover techniques were not even deployed until the advent of cellular technologies (Tabane, 2000).

Throughout the 1970’s communication companies were hard at work to develop a next generation to systems like MTS and IMTS. The concept being explored was that of cellular radio, as it was called. The idea behind cellular systems was that of small base station coverage, enabling aggressive frequency reuse, resulting in many more times the available system capacity of the existing services. In order to achieve this capacity increase, mobility control techniques were required so users could be handed over between base stations as they traversed the geography over which they used their devices.

1st Generation Cellular: Analogue Voice Service

In the MTS/IMTS world, if a user travelled outside the coverage area of a base station, any ongoing call dropped and would have to be re-established when the user re-entered system coverage area. In the cellular world, users had smooth and relatively seamless mobility over multiple cells. A major underlying success factor for cellular and its seamless mobility control technique was the availability of the microprocessor, which provided sophisticated, intelligent control at both the mobile and network. In 1983, the first commercial cellular system, the Advanced Mobile Phone Service (AMPS) was deployed in the Chicago area. AMPS is typically referred to as 1st Generation Cellular. In addition to aggressive spatial frequency reuse and instantaneous mobility management techniques, regulators in the United States provided AMPS with a substantial quantity of radio spectrum. Instead of 8 or 16 channels per metropolitan area, AMPS now had 666 channels available which provided a capacity increase of over a million times in large metropolitan areas. AMPS was still FM in the beginning, but now many more phone numbers were available and adoption was rapid throughout the 1980’s and early 1990’s. Similar technologies were developed and deployed
around the globe, e.g. the Nordic Mobile Telephone Service (NMT) in 1981, Total Access Communication System (TACS) and Extended TACS (ETACS) in Europe.

During the years 1983 through about 1986, cellular mobile equipment was still expensive. A typical automotive installation brought a fixed cost of $2,000 to $4000 US Dollars plus the monthly subscription fees to the mobile operator. Incremental costs of making and receiving calls was on top of the cost of equipment and service. Therefore, even after the introduction of the AMPS cellular system, the primary market segment for mobile telephony was still largely commercial users. But with the availability of equipment and phone numbers, there was an element of high-end personal users entering the cellular user community as well. Throughout the 1980’s and 1990’s, the learning curve brought down the cost of manufacturing equipment (Freeman, 1997). With lower costs came lower prices, and with lower prices came greater demand. By the early 1990’s, most middle class adults owned mobile telephone equipment of some kind.

The 2nd Generation: Digital Voice for Cellular

The first large global standard for digital mobile telecommunication was the result of work coordinated by the European Telecommunication Standards Institute (ETSI) in the standards body originally referred to as Groupe Speciale Mobile (GSM) during the late 1980’s and early 1990’s. The standard was referred to simply as GSM, but the acronym was later changed to the English phrase, “Global System for Mobile Communication” and later “Global System for Mobile Telecommunication” (GSM). GSM systems were deployed first in Europe during 1992. These first systems, referred to as GSM Phase 1, supported circuit-switched voice interchange and functioned much like their analogue cellular counterparts. In addition to the basic voice services, GSM offered some new functionality referred to collectively as “teleservices” which included extensible messaging features such as the Short Message Service (SMS) and Cell Broadcast (CB).

Work to extend the GSM feature base began in the mid-1990, as Phase 2 which included frequency hopping, support for global frequency bands and other enhancements. During the same period, other standards were deployed in the United States, e.g. Intermediate Standard 136 (IS-136) was a Time Division Multiple Access (TDMA) technique and Intermediate Standard 95 (IS-95) was a technique based on Code Division Multiple Access (CDMA) technology. These technologies were commonly referred to as “2nd Generation” or “2G” services. Other digital systems were deployed around the world during the same period, including the North American Digital Cellular (NADC) service in 1991 in the U.S., which was based on AMPS, and Personal Digital Cellular (PDC), which was deployed in Japan. Because GSM solved a very important business problem, i.e. the billing methods for users who “roam” among different
countries and network operators, these other systems eventually gave way to GSM’s dominance (Mouly & Pautet, 1992; Mehrotra, 1997).

2.5 and 2.75G: Cellular Data is Added to GSM

The first digital cellular systems like GSM, IS-136 and IS-95 were developed for circuit-switched voice service. This meant that calls were made on a point-to-point basis through a mobile switching centre (MSC) that was much like a fixed-line telephone switch. These technologies did support some means of user data interchange, but they relied on a circuit-switched, connection-oriented approach which consumed a fair amount of wireless and network resources in contrast to the actual amount of data being sent and received. In 1992, the idea for a packet-based subsystem was introduced into ETSI standards called General Packet Radio Service (GPRS), but some time was needed for the industry to see commercial applicability before widespread standards support was achieved. Initially, GPRS was created for the transmission of mobile telematics information, e.g. truck and bus location data, for which the GSM circuit-switched Mobile Switching Centre (MSC) was a choke point. Often, telematics data comprised only small amounts of information that could be sent within a time period of under a tenth of a second, but the fact that the MSC was involved in setting up a circuit-switched connection resulted in latencies of up to 60 seconds or more on early systems because of the time required for the wire line modem on the remote end to synchronize with the mobile through the network. It was speculated that a true packet-based technique would allow the transfer of information without making a circuit-switched call at all, i.e. to set up a temporary packet data channel over which a small amount of data would flow followed by the rapid teardown of the channel. In this manner, data transfers would be completed rapidly while radio resources on the network would be conserved for other traffic (GSM-02.03, 1996; GSM-03.41, 1996).

The introduction of the World Wide Web (WWW) in the early 1990’s created interest in extending the web to mobile users, and by the late 1990’s, the concept of GPRS had gained general acceptance by the industry as a vehicle for a “mobile Internet”. Because GPRS is packet-based, it creates the illusion of being “always on” by actually having both endpoints being “always off”, i.e. the endpoints are only aware of each other as entries in each others’ network-specific routing tables. Then, when there is a need to send data, i) a packet transfer is quickly set up, ii) data are transferred and iii) the transfer is torn down, returning resources to the network for subsequent use by other users or services.

*Figure 3. 1st generation analogue cellular equipment: fairly large and still expensive*
Although telematics data interchange was the initial motivation for the creation of GPRS, the growth of the Internet and World-Wide Web in the mid 1990’s generated far more interest and commercial intensity on the Standardisation Work Item. It was not until 1997 that Public Land Mobile Network (PLMN) operators began to take GPRS seriously as a means of generating additional revenues based on their excess capacity during non-peak usage period. The fact that GPRS had its first roots in telematics explains some of the technology decisions, e.g. the simplified method of mobility management during a packet transfer based on autonomous cell reselection by the mobile terminal. Some of these early technology decisions have introduced constraints on the system that remain today.

GPRS, and its superset, Enhanced Data for Global Evolution (EDGE), permit efficient use of radio and network resources when data transmission characteristics are i) packet based, ii) intermittent and non-periodic, iii) possibly frequent, with small transfers of data, e.g. less than 500 octets, or iv) possibly infrequent, with large transfers of data, e.g. more than several hundred kilobytes. User applications were originally envisioned to include Internet browsers, electronic mail, file transfers and other applications for which best efforts data transfer are appropriate. The first commercial release of GPRS specifications was Release 97, although the specifications were not complete until 1999 with a few corrections to Release 97 specifications noted as late as 2003 (GSM-04.06, 1996; GSM-02.60, 1996; GSM-03.60, 1996).

Enhanced Data for GSM Evolution (EDGE) was standardized as a parallel path to GSM evolution. EDGE is sometimes referred to in the 3GPP specifications as Enhanced General Packet Radio Service (EGPRS), and is a 3G superset of GPRS as defined by the International Telecommunications Union (ITU), although it is sometimes referred to as 2.75G because it was introduced early in the standardization cycle. EDGE enables higher data rates over the radio interface, but supports the same set of basic services as offered by GPRS. In order to support EDGE, the mobile terminal and network need to support GPRS. EDGE extends the existing capability of GPRS, by the addition of three underlying technologies: i) high order modulation, ii) radio link adaptation and iii) incremental redundancy. These techniques result in higher user data rates and greater system capacity than was possible with basic GSM and GPRS. In addition, simultaneous voice and data operation was added to GSM with the introduction of Dual Transfer Mode (DTM) (3GPP Work Plan, 2009; Pecen & Howell, 2001).

In the days of MTS, IMTS, 1st and 2nd Generation Cellular, mobile devices were viewed largely as something to be used as telephones. Except for the introduction of SMS on the GSM system for short text messaging.
messages, the basic user perception was that mobile devices were something to talk on. The notion of major services other than voice had not even entered the scope of discussion within the industry until the early 1990’s and the revenue produced by services like SMS was a tiny fragment of what revenues have become by the year 2009 for more sophisticated services such as email, browsing, enterprise applications, instant messaging, multimedia, social networking and others. So between the 1950’s and the end of the 1990’s the mobile device was primarily viewed, and utilized as a technical substitute for fixed-line voice telephone service.

3G: Evolution of 2G Architecture

Before GPRS standardization was complete, industry groups began work on the next generation of packet data systems, both for GSM and for a new standard referred to as Universal Mobile Telecommunication Service (UMTS) under the oversight of the 3rd Generation Partnership Project (3GPP), which was founded in 1997 by a number of mobile network operators and equipment manufacturers. The idea was to leverage the original 2G architecture of GSM and to extend the capabilities of the radio interface by moving to a Wideband Code Division Multiple Access (WCDMA). When 3GPP was created, the maintenance and evolution of the GSM standard was also placed under the management of 3GPP. UMTS was introduced as a completely new 3G standard with deployments beginning in 2001. Adoption of UMTS was slow, and by 2009, less than 6% of the total market had deployed UMTS (www.Informa.com, March 2009).

Simultaneously, it was recognized by the industry that some serious limitations to the user data interchange capabilities existed in UMTS, which prompted the development of an additional standard for High Speed Downlink Packet Access (HSDPA). HSDPA used similar techniques as did EDGE for increasing capacity and data rates, although within the framework of WCDMA. In 2005, participants in 3GPP began developing standards for the uplink equivalent to HSDPA, i.e. High Speed Uplink Packet Access (HSUPA) (3GPP FTP, 2009). By 2007, the combination of HSDPA/HSUPA was often referred to as High Speed Packet Access (HSPA) within the industry. By 2009, 90% of the global market for wide area wireless systems was occupied by the technologies standardized by 3GPP, 83% of which was GSM, GPRS and EDGE. In the first quarter of 2009, there were 3.9 billion GSM subscribers.

Other 3rd Generation systems were developed during the period between 1999 and 2007. 3rd Generation user data services were added to the IS-95 CDMA technology standards and introduced under the International Telecommunications Union (ITU) designator, IMT2000. This included such technologies
as Evolution for Data Only (EVDO), which technologically was fairly similar to HSDPA (3G Americas, 2009).

So how do we define 3G? It’s essentially an evolution of 2G technology to the next level – same basic functionality, but with a focus on user data support and higher data rates. The support for mobile user data by dominant mobile technology such as GPRS/EDGE, UMTS/HSPA and CDMA2000/EVDO is all important, because it is the foundation of what we think of in the year 2009 as the “age of the Smartphone” – a mobile device that not only support voice service, but messaging, email, browsing, enterprise services, cameras, multimedia and music players.

In 2004 standardization work on an item referred to as Long-Term Evolution (LTE) was launched in 3GPP. This work item represented a drastic departure from earlier 3GPP technology both in terms of architecture and wireless interface. Beginning in 2002, the Institute for Electrical and Electronic Engineers (IEEE) standards bodies were developing standards for the 802.16 and 802.20 wireless standards, commonly referred to as Wireless Microwave Access or WiMAX. These technologies were intended to be wider-area economic substitutes for the IEEE 802.11 Wireless Local Area Network (WLAN) technologies commonly known as Wireless Fidelity or WiFi.

Even the original GSM-based technology standards continue evolving. Between 2005 and 2008, 3GPP industry participants developed what is referred to as Evolved EDGE, which is a faster and more efficient data service based on the original EDGE work but featuring broadband data rates. Why extend GSM and EDGE? With almost 4 billion GSM/EDGE subscribers in 2009, the technology switching costs of moving to new systems are extremely high. Even with the next generation of wireless systems, GSM is going to be around for some years yet (3GPP TR 45.912, 2007; Fuertes, 2009). At the end of 2008, 3GPP technologies (GSM and WCDMA) dominated the global subscriber market.

**THE ROLE OF STANDARDS IN INTERNATIONAL TELECOMMUNICATION**

Wireless communication comprises a wide range of technologies, services and applications that have come into existence to meet the particular needs of different deployments and user environments. Different systems can be broadly characterized by:

- content and services offered,
- frequency bands of operation,
- standards defining the systems,
In today’s global society, it’s essential for different countries and regions to agree on common frequency bands, technologies, regulatory requirements and expectation of services to enable user mobility and roaming. These commonalities create powerful economies of scope, which in turn create large economies of scale. The platform for such discussions and agreements is the International Telecommunications Union (ITU). The ITU is an agency of the United Nations and a general oversight body for global telecommunications standards. International Mobile Telecommunications-2000 (IMT-2000) is the global standard for 3rd Generation wireless as defined by a set of interdependent recommendations of the ITU. These recommendations include standards for frequency spectrum usage, wireless system technical specifications, tariffs and billing, technical assistance and studies on regulatory and policy aspects.

Second generation systems were primarily designed to support voice service. IMT-2000 and enhanced IMT-2000 systems and systems beyond IMT-2000 were created to support multiple access technologies that compliment one another in an optimal way to provide a common, flexible platform for different services and applications.

A similarity of services and applications across the different systems is beneficial to users, and this has stimulated the current trend towards convergence. Furthermore, a broadly similar user experience across the different systems leads to a large-scale adoption of products and services, common applications and content. Access to a service or an application may be performed using one system or may be performed using multiple systems simultaneously. Such convergence should nevertheless impede any opportunities for competitive innovation. This is why it’s appropriate to standardize some system aspects but not others.

Relationship of IMT-2000 and IMT-Advanced

IMT-2000 systems are intended to provide access to a wide range of telecommunication services, supported by the fixed telecommunication networks (e.g. PSTN/ISDN/IP), and to other services which are specific to
mobile users. To meet the ever increasing demand for wireless communication (e.g. increased no. of users, higher data rates, video or gaming services which require increased quality of service, etc.), IMT-2000 has been, and continues to be, enhanced.

The diagram in Figure 9 is taken directly from Recommendation ITU-R M.1645 and reflects the terminology in use at the time of its adoption. Resolution ITU-R 56 defines the relationship between 1) IMT-2000, 2) the future development of IMT-2000 and 3) “systems beyond IMT-2000” for which it also provides the new identifier, IMT-Advanced. Resolution ITU-R 56 resolves that the term IMT-2000 encompasses also its enhancements and future developments. The term IMT-Advanced should be applied to those systems, system components, and related aspects that include any new radio interface(s) that support additional capabilities of systems beyond IMT-2000. The term “IMT” is the root name that encompasses both IMT-2000 and IMT-Advanced collectively.

IMT-Advanced systems support low to high mobility applications and a wide range of data rates in accordance with user and service requirements in multiple user environments. IMT-Advanced also defines capabilities for high quality multimedia applications within a wide range of services and platforms to provide a significant improvement in performance and quality of service.

The primary features of IMT-Advanced are:

- a high degree of commonality of functionality worldwide while retaining the flexibility to support a wide range of services and applications in a cost efficient manner,
- compatibility of services within IMT and with fixed networks,
- capability of interworking with other radio access systems,
- high quality mobile services,
- user equipment suitable for worldwide use,
- user-friendly applications, services and equipment,
- worldwide roaming capability; and
- enhanced peak data rates to support advanced services and applications (100 Mbit/s for high and 1 Gbit/s for low mobility were established as targets for research)

Consumer demands will shape the future development of IMT-2000 and IMT-Advanced. Recommendation ITU-R M.1645 describes these trends in detail, some of which include the growing demand for
mobile services, increasing user expectations, and the evolving nature of the services and applications that may become available. Report ITU-R M.2072 details the market analysis and forecast of the evolution of mobile products and services for the future development of IMT-2000, IMT-Advanced and other systems. This Report provides forecasts for the year 2015, and 2020 timeframes.

IMT-Advanced Development Process and Timeline

Resolution ITU-R 57 on the “Principles for the process of development of IMT-Advanced” outlines the essential criteria and principles that are used in the process of developing the Recommendations and Reports for IMT-Advanced, including Recommendation(s) for the radio interface specification. The detailed procedure is illustrated in Figure 12. The timeline shown in Figure 13 is directly from ITU-R M.1645, which was originally drafted in 2003 and makes the assumption that most of the innovation on next generation technology has already been completed. This is far from the case. In spring 2008, the ITU issued an invitation for submission of technologies that will meet the requirements of IMT-2000 Advance (David, 2008; IMT2000, 2009; ITU, 2008; ITU-R M.1645, 2008). During each phase of technology development, there are problems that require innovative solutions that include additional research, product development and insertion into the value chain. It’s extremely likely that we’ll see further advances and deployment of next generation systems well past 2015.

WHAT’S NEXT?

An Aggressive Industry Vision

The various wireless standards development organizations have set forth an extremely aggressive vision for next generation wireless networks (3GPP Rel. 8, 2009; 3GPP Rel. 9, 2009; 3GPP TR 21.902, 2008; IEEE, 2009). The requirements were designed to approach the performance levels of broadband fixed line service with the addition of full mobility control, subscriber roaming and the other features that allow users to perform useful tasks while mobile. Following are the primary criteria as set forth by 3GPP and IEEE:

1. High data rates: > 100 Mbits/sec – This represents the per-sector throughput of an entire base station carrier. Each user would receive proportionally lower data rates depending on signal quality and system congestion. These high data rates are indeed achievable, given the industry’s direction
for greater RF spectrum occupation and the use of Orthogonal Frequency Division Multiplexing (OFDM). OFDM has other strengths as well, including the simplicity of spectrum sensing in the frequency domain, ability to limit co-channel interference instantaneously by selectively turning off sub-carriers as needed and ease of interfacing with smart antennas. There are nevertheless challenges to achieving 100+ Mbits/sec data rates in the practical world. Adequate radio link margin becomes more of a challenge as data rates increase, and we’re seeing more technologies to address this issue such as advanced receivers and interference cancellation techniques.

2. Low latency: < 50 s – Depending on the application, latency is either totally unimportant or absolutely vital. An application for which low latency is vital is that of web browsing, and especially where web pages contain many pictures. Each picture downloaded by the browser must be acknowledged individually, and each individual acknowledgement is dependent on the latency of its turn-around time. Many systems such as GPRS have latencies of 600 ms or more, which severely cripples the transfer of web pages with several pictures. Imagine a web page having 10 pictures on a system with 600 ms of one way latency. Each picture requires 600 ms seconds to acknowledge and 600 ms begin sending the next one. If you have 10 pictures, latency would contribute 2 * 600 ms * 10 = 12 seconds, so the transfer could not be any quicker than 12 seconds. Contrast this to a system having 50 ms, where the same 10 pictures would require a minimum of 2 * 50 ms * 10 = 1 second to download – now latency becomes a less significant portion of the transmission time at 50 ms.

3. Mobility support: Mobility management controls and balances network resources incidental to the user’s geographical movement. The next generation would support both macro-mobility and micro-mobility at relatively high user speeds, such as might be encountered in moving vehicles or trains. The notion of micro-mobility is that of managing and handing over calls and/or ongoing data transfers among clusters of related base stations, referred to as eNodeB’s in 3GPP terminology. Macro-mobility is a higher-level abstraction whereby user mobility among un-related network components is achieved, e.g. from one Routing Area (RA) to another. Further to the mobility issue, the air-interface itself must be robust to Doppler shift and other fading channel effects. This is part of the basis for selecting Orthogonal Frequency Division Multiple Access (OFDMA) for the Long-Term Evolution (LTE) work item in 3GPP. OFDMA utilizes many relatively narrow band sub-carriers, which combined produce a broadband, high-speed channel, but may be individually treated as flat-fading channels thereby mitigating the impacts of broadband fading.

4. Scalable bandwidth: To produce the kinds of high data rates and trunking efficiency that are required for the next generation, network operators need a substantial amount of contiguous radio spectrum.
A potential issue is the immediate availability of spectrum for initial system rollout. An operator may not have e.g. 20 MHz of RF spectrum to immediately dedicate to the next generation system. Methods for incrementally adding RF bandwidth to a next generation system have been devised. These allow the operator to deploy their new systems in smaller segments of RF spectrum at first, and then gradually increase spectral occupation of the new system while reducing spectral occupation of their legacy systems. For example, a next-generation system may be first rolled out on 1.25 MHz of spectrum, and then gradually expanded to fill a full 20 MHz of RF bandwidth.

5. Optimized for data services: 1st, 2nd, and to some degree 3rd Generation wireless systems were optimized for voice traffic. This made complete sense at a time in history where mobile wireless was largely a technical and/or economic substitute for wired telephony. The use of data applications by both enterprise users and consumers is on a strong upward trend. Since approximately 2001, enterprise customers have led the consumption of user data capacity in cellular networks. This began to change in around 2005 as consumers brought non-voice mobile data applications into their life on a regular basis. In 2009, the top three user data applications were 1) email, 2) messaging and 3) browsing, with an exponential increase in browsing traffic between 2005 and 2009. Another strong trend since around 2007 is an ever increasing usage of streaming video, specifically YouTube videos over mobile terminals.

6. Backward compatibility with legacy systems, e.g. GSM and UMTS: With almost 4 billion subscribers in 2009, technology switching costs are a major force that the next generation wireless technology must mitigate in order to achieve substantial economic success. Compatibility between systems includes the ability to select among next generation and legacy systems as required based on coverage and available capacity. Looking back over the past 10 years, wireless systems have become more heterogeneous in general, with mobile devices now including such important auxiliary wireless interfaces as Bluetooth, WiFi and Near-Field Communication (NFC) techniques. As an industry, we’ve learned how these technologies can co-exist in a mobile terminal to a certain degree, and maybe how some of these vastly different wireless technologies can interwork, e.g. WiFi and cellular in the case of Unlicensed Mobile Access (UMA). An important issue for mobile terminal manufacturers as we move forward is how to cope with the number of new frequency bands and the required antennas, RF components and logic to manage their operation. We expect many more issues to be solved for
the next generation on both the radio access side as well as the core network side, such as billing and Quality of Service (QoS) control.

7. High spectral efficiency, 5 bits/symbol/Hz: Radio spectrum is the wireless highway over which your information travels. There exists a finite amount of spectrum in the range of wavelengths appropriate for cellular communication. For the most part, this means from about 700 MHz to around 3500 MHz. Spectral efficiency may be increased in three fundamental ways: 1) information theoretic innovations, such as higher order modulation and advanced receivers, 2) statistical gains, such as fat pipe techniques that improve trunking efficiency and 3) reducing the cell sizes, which requires more equipment and real estate. The industry direction is to constantly search for ways that higher and higher order modulation can be used over the wireless channel, which often goes hand-in-hand with
the use of an advanced receiver or interference cancellation technique on the receiving end. The industry trend toward use of OFDM also presents an opportunity to achieve statistical gains as well, as the bandwidth utilization increases with large amounts of contiguous spectrum. Such large spectral occupation means that there are no guard bands within the OFDM channel to consume spectrum. In addition, the network scheduler can quickly allocate capacity as-needed without incurring the overhead of a complex radio link setup procedure. Regulators around the globe also need to effectively coordinate the issuance and licensing of radio spectrum in such a way to help ensure that wide ranges of contiguous spectrum are in fact available. Reducing cell coverage increases spectral efficiency dramatically, but there are economic and basic physical limits. For more info regarding cell sizes, please see “About Wireless Capacity”.

### About Wireless Capacity

Between 1957 and 2008, wireless capacity has increased approximately 1,000,000 times (Chandrasekhar, Andrews, & Gatherer, 2008). This means that a given amount of radio spectrum over a given area of population will carry about 1,000,000 times more information than was possible in 1957. Let’s examine the sources of this substantial increase in capacity:

Since 1957, we’ve seen:

- A 25X information theoretic improvement (modulation and coding advances, equalizers, advanced receivers, interference cancellation, etc.)
- A 25X statistical improvement (wider contiguous spectrum, advanced scheduling techniques, etc.)
- A 1600X improvement due to reducing transmission distances, i.e. cell sizes

While reduction of the size of cell has provided most of the gains over these years, there are several factors that present practical limits to what can be achieved by this practice. For example, more base stations are needed, as is more real estate on which to deploy them. These factors become economic and logistic barriers at some point. Furthermore, there are practical limits to the granularity of mobility control, because a substantial amount of signalling capacity and mobile terminal battery life may be consumed by
the mobile constantly informing the network where to reach it. A Work Item (WI) in 3GPP is related to the standardization of LTE Relays. These relays may provide vital low-profile links between primary cells and users who would receive a substantial increase in data rates in the presence of greater link margin, but only in places where they’re needed.

What is 4G Anyway?

The authors of this book are helping to answer that question. Let’s consider a cross-section of the research community’s efforts to push wireless technology into the next generation as seen by the authors of the following chapters.

As of 2009, there was no precise formal definition of 4G, as was pointed out by authors Aravantinos and Fallah, who present an economic rank-based survey of market readiness for 4G later on in this book. The survey combines the dimensions of technology, business, consumer, legal/regulatory and R&D investment into a single rank-based index for what the market would require to support a next generation. Although not yet formally defined by the ITU, there existed many informal definitions for 4G in 2009, primarily based on the extension of the ITU definition for IMT-Advanced which defines the basic working assumptions for systems extending beyond IMT-2000.

New Business Designs and Opportunities

What 4G will eventually become depends on more than just technological forces. There are social, environmental, economic and political forces at work too, and these forces are vital in shaping the next generation of wireless networks and services. In the chapters to follow, our contributors explore technical innovations in the wireless domain, but they also go beyond in their exploration of the other strategic forces. For example, the next generation may also provide substantial economic opportunities for the industry to migrate from a Subscriber Business Model (SBM) to a Consumer Business Model (CBM). As applications become more creative and wireless becomes ubiquitous, an economic differentiation between the subscriber and the actual consumer of services has begun to appear. Today, the consumer and subscriber are largely treated as the same entity. This is to say that the person using the service is also the subscriber in the case of the SBM. But what if the subscriber is an individual, but that individual hosts multiple consumers for different services? This would be the case for a subscriber whose intelligent consumer devices or even other users may comprise the consumers of service, each consumer having differing service requirements and even commercial relationships that transcend the current generation of network capabilities. Authors Ganchev, O’Droma, Jakab, Ji and Tairov propose possibilities for business design based on the definition of a CBM for 4G networks.

Short-Range Wireless

In addition to ultra-high data rates and other features planned for 4G, a parallel evolution is occurring that is already enabling the ubiquity of short-range personal communication. Some personal area networks are already in use, e.g. Bluetooth, but as authors Rasheed and Javaid point out, these short-range technologies have not yet been used to their full potential. The implications of Personal Network Federation (PN-F) architectures and cooperative techniques are explored, which may have far-reaching effects in social, technological, economic and political domains. Why the impact in the political domain? Short-range technologies may operate on RF spectrum that is licence-free in some countries, or possibly spectrum that is licensed to a network operator. The proliferation of such miniature networks is already raising concerns
regarding the coordination of spectrum regulation across the globe. Even today, users may carry devices that are legal to operate in one country and illegal in another, creating confusion for consumers, regulators and equipment manufacturers.

Cross-Layer Design

Before the year 2001 or so, the concept of state or control information crossing layers in a protocol stack was largely thought of as protocol violation. Today, there is a name for this: Cross-layer design, and it’s expected to play an increasingly important role in next generation wireless networks. The cross-layer concept addresses a fundamental challenge that the industry has learned over time: that the needs of the wireless domain are vastly different from those of the wire-line. Transport and application layers behave differently than e.g. Radio Link Control (RLC) and Physical wireless layers. Authors Chao, C. Chang, Chen and K. Chang analyze the impacts of the design of new interfaces, merging multiple layers, design coupling without new layers and vertical collaboration across layers. These concepts may move 4G another step closer to having wireless-aware applications and application-aware wireless interfaces, providing the ability to better smooth out the effects of wireless channel variability and resulting race conditions over the span of protocol stacks.

Authors Alshaer and Elmirghani, who note that each network element may present large characteristic variability in itself which occurs across multiple dimensions, present further work on QoS control using cross-layer design. Highly variable characteristics include data rates, end-to-end latency, jitter and packet re-ordering. When variability cascades across multiple network elements, performance often degrades rapidly due to the adaptive nature of one element working against that of another. Authors Alshaer and Elmirghani examine the concept of cross-layer intelligent control in an end-to-end QoS architecture. They identify the possible extreme differences in behaviour among the wireless air-interfaces themselves, plus the impacts of cognitive radio, Medium Access Control (MAC) design and Link Layer active probing. They further propose some intelligent routing techniques to mitigate the effects of end-to-end variability, and present simulation results for their Network Mobility (NEMO) techniques. Routing is also the topic of work done by authors Sadok, J.A. de França, Oliveira and R.R. de Abreu, but within the context of knowledge sharing among the multiple, differing wireless interfaces. Data must be routed over interfaces having extremely different characteristics, and it’s no longer the case that one method can be forced to fit a wide range of routing problems in the practical world. The authors explore the introduction of concepts learned from biological, epidemic and social behaviour into the development of a non-traditional routing technique.

Authors Lamy-Bergot and Panza note that the complexity of wireless user data traffic is increasing steadily over recent years, as users and application builders invent novel ways to utilize the available bandwidth of today’s networks. As a result, better and better performance of wireless applications and services is expected by the time that next generation wireless networks are fully deployed. To address the trend of steadily increasing traffic, the authors explore the possibility of cooperative, cross-layer optimization with their proposal of a novel Joint-Source Channel Coding and Decoding (JSCC/D) technique that is specifically designed to address the impairments that are likely to be encountered by IP multimedia applications. Again, cross-layer design is central to their concept of end-to-end optimization based on a variety of traffic types and the variability of system loading. An entirely new architecture is proposed utilizing the concept of intelligent cross-layer controllers to address the problem of the lack of end-to-end supervisory control which is characteristic of current network architectures in which each layer operates autonomously, in a vacuum of system information of sorts. Their method and architecture show encouraging results, taking into account the limitations and variability of all system layers, from the wireless radio interface to the application.
Hybrid Wireless Environments

Cost of deployment and network maintenance is the issue addressed by Authors Dantu and Guturu. The propose a general network architecture using WiMAX as the air-interface, comparing cost of deployment to existing 2G/3G networks. They find that it may be economically advantageous to replace the traditionally expensive components of legacy networks with scalable IP-Radio Access Networks (RANs) configured to distribute mobility and QoS control across many network elements. The high degree of interest in integrating heterogeneous radio networks is further examined by authors Shen, Pesch, Atkinson and Du. These researchers examine some possibilities for developing a next generation Hybrid Wireless Network (HWN*) with a primary focus on mobility management and routing. A HWN* is an integrated architecture that combines multiple heterogeneous wireless air interfaces with seamless service delivery across the multiple networks. Building such a network is much easier said than done, due to the completely different characteristics of each wireless interface and their resource management demands. This challenge is especially relevant because a HWN* may be implemented from any off-the-shelf air-interface such as GSM, WiFi, CDMA-2000 and others, all under common control to some degree.

End-to-End Packet Architecture

The heterogeneous nature of networks goes far beyond the wireless air interface. Authors Wu and Choi present a comprehensive overview of the end-to-end Quality of Service (QoS) control in LTE’s Enhanced Packet System (EPS) concept. The EPS is the first all-IP based mobile cellular system, which presents many challenges to managing QoS to both IP-based data services and the addition of packet-based voice services. Previously, voice over cellular networks was handled over a dedicated, circuit-switched environment. As we move toward all-IP systems, EPS must manage packet-based voice in a much more hostile network environment, where the quality of one voice call can depend on the characteristics and loading of non-voice data. Wu and Choi present a rigorous end-to-end QoS performance analysis of the basic services such as VoIP, e-mail and web browsing through simulation study of the EPS QoS model.

Consumers have exhibited a greater interest in mobile streaming services in recent years. Since around 2005, existing networks report an exponential increase in traffic created by users downloading YouTube videos, podcasts and short news clips. Other streaming services like VoIP and gaming have yet to be fully explored due to the tenuous ability of today’s wireless networks to handle these services. The industry’s vision of higher data rates and lower latencies is intended to address the need for better service quality, efficiency and availability of wireless streaming services. Primary impairments to streaming are the instantaneous variations in inter-packet arrival time, or jitter, and the periodic loss and/or re-ordering of data. Authors Macías and Suarez acknowledge and quantify a number of these challenges. Rather than proposing newer protocols to address the existence of a wireless component in a given service path, they propose the concept of a cross-layer optimization-theoretic framework. This framework may incorporate an objective function containing a set of parameters distributed across many unrelated network layers, many of which may not even physically reside in the same geographical area with one another. In this manner, end-to-end system characteristics may be optimised for a particular traffic type, provided that relevant aspects of system performance may be estimated in a manner timely enough to enable optimization. Macías and Suarez also foresee the introduction of traffic type adaption, so that networks not only optimize for the requirements of a particular traffic type such as streaming, but would also be able to sense subtle changes in traffic characteristics themselves.
Wireless Environments are Drastically Different from Wired Ones

Further related to the tremendous differences between the operational environment of the wired and wireless domains is the ability to quantify what the user may experience under certain conditions that may in fact be predictable. For example, the current state of the art for characterizing the voice quality experience makes use of Mean Opinion Scores (MOS), which are subjective evaluations on the part of the listener and therefore require a substantial number of observations in order to achieve reasonable confidence intervals. Common causes of user perceived degradation of application experience include changes in underlying network conditions. These include increases in Bit Error Rates (BER), handover artefacts, radio link CODEC rate adaptation to changing channel conditions and changes in system latency. Authors Vidales, Wältermann, Lewcio and Möller have developed techniques to extend the concept of MOS from the wireless voice domain to that of the user data domain. They introduce the Quality of Experience (QoE) abstraction for next generation services parametrically. This is done by constructing mappings between subjective a) MOS measurements and b) quantitative properties that can be acquired or objectively measured within the system. Using QoE is expected to streamline service evaluations, and therefore time to market of network equipment, devices, applications and services.

Scheduling and Routing

Next generation wireless networks will require highly effective scheduling. Author Ukil presents a comprehensive overview of 19 different scheduling techniques within a game-theoretic framework. Game theory has been used to predict behaviour of individuals and groups based on a set of preference functions, each party to the game having their own individual preference function and time horizon. As long as preference functions and time horizons are accurately identified, resulting behaviour of the parties may be predicted. Researchers have recently applied game theory to the analysis of network routing, radio link adaptation and scheduling. Author Ukil specifically concentrates on techniques to maintain overall system throughput while minimizing outage probability and maximizing the number of users obtaining service in heterogeneous QoS-bound traffic scenarios. Next generation scheduling is also the topic of authors Mohammed, Hashem, Gupta within the context of end-to-end coordination of system elements. They propose multi-level scheduling techniques, which would control both the radio access portion and core network portion of the systems. They present simulation results based on the existing HSPA system, and further propose a system architecture to incorporate two layer queuing and scheduling which is expected to provide lossless handover and QoS differentiation in future generation systems.

System Capacity and Data Rates

Radio system efficiency and information theory is at the heart of next generation wireless. Authors Raad and Huang discuss the characteristics of OFDM and present a comparison between OFDMA, Code Division Multiple Access (CDMA) and Time Division Multiple Access (TDMA) methods as a basis for introducing a new concept for information coding. The authors propose a Block Spread OFDM called Parallel Concatenated Spreading matrices OFDM (PCSM-OFDM). Their results show that this technique improves Bit Error Rate (BER) performance in frequency-selective channels by over 3dB by utilizing coding gain, and is similar to Turbo Coding. Coding efficiency is also the topic of research by author H. Chen, but within the context of CDMA systems. Chen introduces a new complementary code design called Real Environment Adapted Linearization (REAL), having inherent immunity against multipath interference and multiple access co-channel interference for both the uplink and downlink. Analysis demonstrates that REAL shows
promise when contrasting its performance against the performance of traditional CDMA codes, such as Gold, Kasami, Walsh-Hadamard and Orthogonal Variable Spreading Factor (OVSF) codes. Authors Yang, Sun, Cavallaro, Zhu and Goel add scalability to the well-known Turbo Coding techniques. Their method uses scalable parallelism in order to enable coding/decoding at the high rates made possible by the requirements for the new generation air interfaces. They achieve scalable parallelism by using contention-free interleavers. They introduce a new address generation technique that supports multiple Turbo interleaving patterns and avoids requiring interleaver address memory typical of the traditional designs. The capacity of MIMO systems cannot be achieved unless by using an outer channel code concatenated with the space-time mapper acting like an inner code. Hence, authors Nikopour, Mobasher, Khandani, and Saleh proposed a list MIMO detector based on combining sphere decoder and m-algorithm approaches in conjunction with iterative turbo decoding.

Over the years, cellular systems have gone from being sensitivity bound to almost completely interference bound. Estimation of radio link and system capacity of a sensitivity bound system is fairly straightforward because it makes the assumption of a Gaussian-distributed noise floor. The case of an interference bound system is much more mathematically complex, as the underlying interference takes the form of a long-tailed distribution approximating a log-logistic curve at times. Authors A.C.G. de Carvalho Reis and P.R. de Lira Gondim present an analytical approach to capacity estimation of OFDMA networks using WiMAX as the example air-interface. The approach utilizes a new analytical method for computing Signal to Interference and Noise Ratio (SINR) based on the probability of the collision of subcarriers. The authors validate their results against published experimental data. As discussed previously, the greatest gains in wireless system capacity have been the result of aggressive frequency re-use by reducing the coverage of individual cells, (please see box, “About Wireless Capacity”). There exists a fabric of cellular tower installations throughout the developed world that is largely based on the delivery of voice services. While the number of cells and their coverage radii are far from completely static, it’s questionable whether we’ll see a large increase in cell density in the near future. Addressing data rates and system capacity by doubling or tripling cell density is just not economically feasible in most cases because of real estate availability, equipment and maintenance costs. Relays, in effect, may increase system capacity by adding small cells to a wireless network that not only extend coverage, but also increase SINR by their deliberate close proximity to the user. Authors Tooher and Soleymani explore ways to enhance radio system capacity by utilizing the concept of cooperative communications implemented as relays. They examine the differences between the amplify-and-forward approach and the decode-and-forward approach to relay design. The authors further extend the concept of the decode-and-forward method by introducing a cooperative approach to signal detection, fundamentally a distributed Multiple Input Multiple Output (MIMO) implementation where the reception and detection of information is split between multiple relay nodes. Traditional MIMO deployments utilize antenna spacing that is largely contained within some practical limits. Because these relays have substantial spatial separation when contrasted to traditional MIMO deployments, the channel transfer function may be dramatically different for the collaborative MIMO case implemented as relays, and therefore open many new possibilities for technical advancement such as collaborative coding. Because relays are a potential solution to the serious issue of system capacity, we’re likely to see much more work in this area as we move toward the next generation.

Radio Over Fibre

In addition to the relay concept, Radio over Fibre (RoF) is another approach that may help solve the cell density issue for next generation networks. RoF is essentially the modulation and demodulation of a laser light source by a native RF signal, e.g. GSM, WCDMA, CDMA-2000. Rather than deploying base sta-
tions, the network would deploy remote antenna units that a) modulate a laser source with uplink signals within a specific RF passband and b) demodulate and amplify RF signals received from the fibre on the downlink. At a Central Office (CO), a bank of base stations would be connected to the other end of the fibre using a similar RF modulation/demodulation scheme. Authors Llorente, Morant and Martí explore this concept within the framework of next generation networks, and specifically some of the challenges and opportunities of RoF systems. For example, group delay can be problematic, but if managed properly it’s possible to multiplex various frequency bands up to 150 GHz together on one fibre.

Challenges for Terminal Manufacturers

As of 2009, Long-Term Evolution (LTE) had greatest level of industry support as a next generation wireless technology. At mid-2009, some LTE standards were complete and a number of prototyping efforts and trials were underway among network equipment manufacturers, handset developers and network operators. LTE utilizes Orthogonal Frequency Division Multiple Access (OFDMA) technology for its air-interface, which provides both a number of advantages as well as challenges for the handset manufacturer. Authors Xu, Berkmann, Carbonelli, Drewes and Huebner provide a comprehensive overview to LTE air-interface technology and its continuing evolution LTE-Advanced (LTE-A) from the perspective of the handset. Mobile terminals must be small and portable, and a primary challenge for the terminal manufacturer is therefore battery life, which itself is challenged by the mathematical complexity of signal processing algorithms required by the LTE/LTE-A specifications. The authors provide an in-depth examination of system synchronization, timing estimation, equalization detection and other algorithmic requirements in terms of mathematical complexity and memory usage all within the context of mobile terminal implementation.

Management of User Mobility

Mobility management is fundamental to cellular technologies. The ability to select cells and handover calls and data sessions from one cell to another is the feature that made cellular frequency re-use a reality. Authors D. Kim, H. Lee, H. Yoon and N. Kim have identified some of the challenges to mobility control in the next generation, and they propose a bi-casting technique as an alternative or add-on to the hard handover method. Bi-casting is a technique that prepares multiple base stations for handover and requires each base station to keep bi-casted data until handover time, which reduces handover-related latency. Bi-casting techniques are well-known, but they’re often cited as a challenge to signalling capacity and backhaul usage. The authors’ proposed solution is one that conserves backhaul and signalling capacity. They supply evidence to support their proposal with simulation results.

Wireless Mesh Networks

Wireless Mesh Networks (WMN) have been a popular and promising research topic in recent years. These networks are based on the concept that multiple wireless devices such as user equipment and sensor nodes can act as dynamic routers. Authors Rizvi, Elleithy, and Riasat examine the possibility of applying Orthogonal Frequency Code Division (OFCD) to WMN systems. OFCD combine the multiple carrier aspect of OFDM with the multiple access mechanism of CDMA. Receiver design criteria and simulation results are presented that suggest a capacity gain in WMN systems by using OFCD, provided that the receiver is optimized correctly. The Wireless Mesh Network is also the topic of the work of authors Zhou and Kong, but from the perspective of MAC layer design for WiMAX. Their overview covers system architecture, frame structure, synchronization admission control, scheduling and scheduler performance and an analysis of Distributed Adaptive Timeslot Allocation (DATSA). Field trial results of a maritime mesh network system are also presented.
Additional Mobile IP Addresses

The main characteristic of 4th Generation (4G) Networks is being based on all IP architecture, operating mainly on IPv6. This includes services such as voice, video, and messaging. LTE is considered to be a 3rd Generation (3G) network and one of 4th Generation (4G) roadmap mobile access technologies. LTE-Advanced (LTE-A), on the other hand, is a 4G technology concept with evolving features. Therefore LTE is the key feature in the understanding of LTE-A evolution. The main focus of LTE is the enhancement of the packet-switched (PS) mechanisms on top of the UMTS enhancements, based on All IP Network (AIPN). IPv6 networking provides maximum service delivery flexibility, user decoupling, and scalability improvements, while leveraging the existing IETF standards. This requires major focus on network simplification, end-to-end delay reductions, optimal traffic routing, seamless mobility, and IP-based transport provisioning. Authors Mendahawi and Adibi provided an IPv6 perspective for LTE. The proliferation of Internet nodes has created a shortage of Internet addresses. Subscribers often have more than one Internet address, and we’re moving into an era in which inanimate entities such as webcams and household appliances have Internet addresses as well. This issue is well-known, but within the context of mobile data systems, it’s even more pronounced. Mobile Internet Protocol version 6 (MIPv6) is a fairly well-developed protocol with mobility control specifically designed in. Because it provides many more Internet addresses and is specifically suited to the mobility requirements of next generation networks, MIPv6 is part of the roadmap for work on LTE/EPS in 3GPP. Authors Bålan and Sandu present a comprehensive survey of MIPv6 as it relates to the implementation in LTE.

High Altitude Platforms

High Altitude Platforms (HAPs) are planes or lighter-than-air craft operating in the stratosphere at altitudes of approximately 20 km (about 75,000 feet). At these heights, the coverage areas provided by HAPs essentially split the difference between terrestrial systems and Low Earth Orbit (LEO) satellites, which operate at altitudes of around 600 km. The difference in altitudes provides a significant trade-off between LEOs and HAPs. The coverage of HAPs is smaller than LEOs, but the link margins for HAP systems are much higher for a given amount of uplink/downlink power. End-to-end delay for HAP systems is also substantially smaller for HAPs as well. Authors Mohammed, and Yang explore the potential use of HAPs for next generation systems, particularly for applications where large coverage areas are needed. This is important, because cellular systems are not well-suited to broadcast or multicast services, and it’s often desirable to interface with a broadcast or multicast service from time to time, e.g. an emergency notification system.

Promises and Challenges

It’s easy to look at the promises for the next generation. It’s also easy to ignore many of the challenges that need to be addressed in order to commercially realize that next generation. Authors Govil and Govil present a comparison of the widely-deployed legacy wireless technologies to one another and to the 4G contenders, WiMAX and LTE. They make it clear that the next generation is not without some extremely serious challenges. They cite some major issues including mobility management – the ability to seamlessly control connectivity among heterogeneous radio interfaces is far from straightforward. 4G will require multi-technology vertical handover and system selection in addition to the fundamental mobility management functions. Even in 2009, we’ve experienced 2G/3G mobility issues just starting to manifest - as the adoption of 3G terminals continues, more users are able to notice 2G/3G handover and country boundary issues that didn’t exist before. Other challenges include the practicalities of latency reduction, migration
from conventional networks to the all-IP approach, system complexity, power consumption of the mobile
terminal, spectrum issues, interference, intelligent billing and cost.

The next generation is all about possibilities and challenges – amazing possibilities, and some difficult
challenges for sure. As researchers, we find the challenges to be an all important fuel for enthusiasm and
innovation. Let’s learn what we can from the experts who have contributed to this book and have helped
to ease the industry forward into the next generation.

Mark Pecen
Research In Motion, Limited
June 24, 2009

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