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Techno-Economic Vision and Challenges

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To our families and to our students

Preface

इन्द्रियस्येन्द्रियस्यार्थे रागद्वेषौ व्यवस्थितौ ।
तयोर्न वशमागच्छेत्तौ ह्यस्य परिपन्थिनौ ॥

indriyasyendriyasyārthe rāga-dveṣau vyavasthitau
tayor na vaśam āgacchet tau hy asya paripanthinau

> Attraction and aversion of the senses to their corresponding sense objects is unavoidable. One should not be controlled by them; since they are obstacles in one's path.
>
> —The Bhagvad-Gita (3.34)

Worldwide Interoperability for Microwave Access (WIMAX) is a technology covering broad range of topics. To the best of our knowledge, WiMAX Networks is a first book that deals with all the relevant areas shown in Fig. 1 namely, quality of service (QoS), security, mobility, radio resource management (RRM), multiple input multiple output (MIMO) antenna, planning, and cost/revenue optimization, medium access control (MAC) layer, physical layer, network layer, and so on.

Chapter 1 introduces the WiMAX and locates its place among the existing and future wireless systems.

Aspects of OFDM and OFDMA WiMAX physical layer is well covered in Chapter 2.

Chapter 3 covers link layer issues, having its main focus on Medium Access Control (MAC) Layer. The term quality of service (QoS) is clearly explained in Chapter 4, considering the WiMAX into account.

Security is a primary subject for WiMAX and for secure communications, privacy and confidentiality are fundamental issues. Chapter 5 has taken care of this important subject.

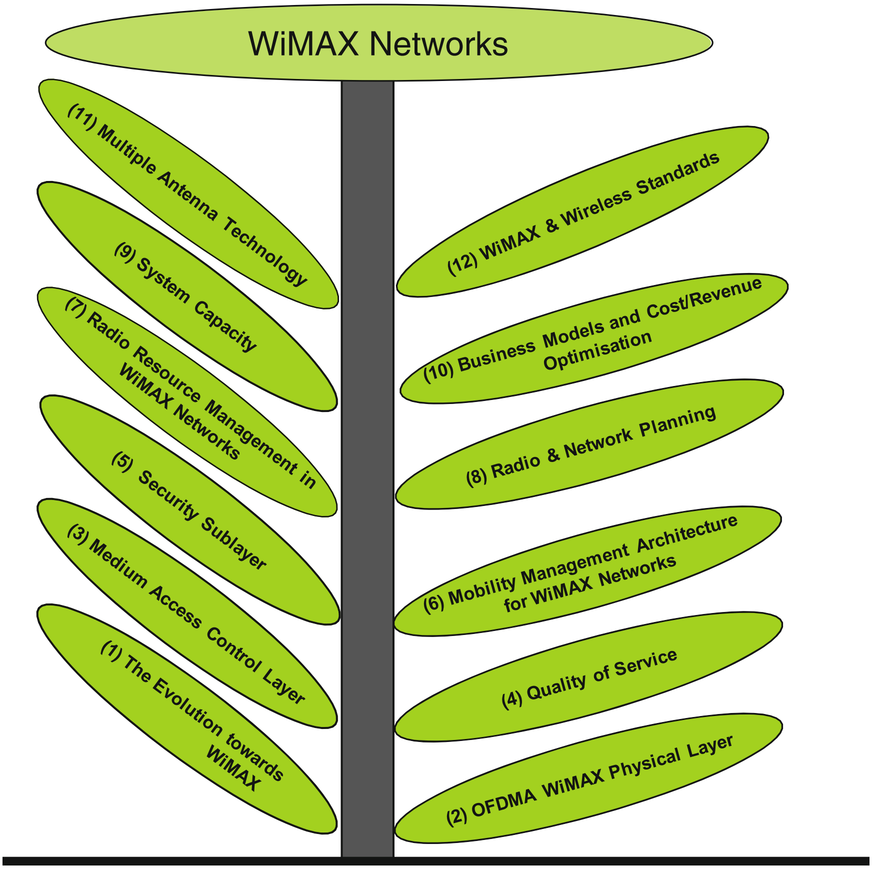

Fig. 1 Tree structure of the book

Chapter 6 presents mobility architecture with integrated QoS support and the proposed architecture can accommodate different wired and wireless technologies.

The radio resource management (RRM) in OFDMA based cellular networks such as WiMAX is addressed in Chapter 7. Four different sub-carriers allocation algorithm with low complexity are evaluated for WiMAX cellular systems.

Chapter 8 first discusses the propagation models and then introduces the cellular planning in the context of WiMAX.

A model to compute the support physical throughput is proposed for WiMAX in Chapter 9 as a function of the achievable carrier-to-noise-plus-interference ratio (CNIR).

Chapter 10 first introduces general aspects about the business models for WiMAX and then address the cost/revenue optimization for these networks, for cellular configuration with and without relays.

Multiple Input and Multiple Output (MIMO) technology options for the WiMAX has been discussed in Chapter 11.

Finally, Chapter 12 concludes the WiMAX Networks by comparing WiMAX with other wireless standards and highlights its potential.

We would greatly appreciate if readers would provide extra effort in improving of the quality of the book by pointing out any errors. We strongly believe nothing is errorless.

Ramjee Prasad
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About Authors

Ramjee Prasad is currently Professor and Director of Center for Teleinfrastruktur (CTIF), and holds the chair of wireless information and multimedia communications. He was coordinator of European Commission Sixth Framework Integrated Project MAGNET (My personal Adaptive Global NET) and MAGNET Beyond. He was involved in the European ACTS project FRAMES (Future Radio Wideband Multiple Access Systems) as a project leader in Delft University. He was also project leader of several international, industrially funded projects of Technology. He has published over 700 technical papers, contributed to several books, and has authored, co-authored, and edited over 25 books. His latest book is "Introduction to Ultra Wideband for Wireless Communications".

Prof. Prasad has served as a member of the advisory and program committees of several IEEE international conferences. He has also presented keynote speeches, and delivered papers and tutorials on WPMC at various universities, technical institutions, and IEEE conferences. He was also a member of the European cooperation in the scientific and technical research (COST-231) project dealing with the evolution of land mobile radio (including personal) communications as an expert for The Netherlands, and he was a member of the COST-259 project. He was the founder and chairman of the IEEE Vehicular Technology/Communications Society Joint Chapter, Benelux Section, and is now the honorary chairman. In addition, Prof. Prasad is the founder of the IEEE Symposium on Communications and Vehicular Technology (SCVT) in the Benelux, and he was the symposium chairman of SCVT'93. Presently, he is the Chairman of IEEE Vehicular Technology/Communications/Information Theory/Aerospace and Electronics Systems/Society Joint Chapter, Denmark Section.

In addition, Prof. Prasad is the coordinating editor and editor-in-chief of the Springer International Journal on Wireless Personal Communications. He was the technical program chairman of the PIMRC'94 International Symposium held in The Hague, The Netherlands, from September 19 to 23, 1994 and also of the Third Communication Theory Mini-Conference in Conjunction with GLOBECOM'94, held in San Francisco, California, from November 27 to 30, 1994. He was the conference chairman of the fiftieth IEEE Vehicular Technology Conference and the steering committee chairman of the second International Symposium WPMC, both held in Amsterdam, The Netherlands, from September 19 to 23, 1999. He was the general chairman of WPMC'01 which was held in Aalborg, Denmark, from September 9 to 12, 2001, and of the first International Wireless Summit (IWS 2005) held also in Aalborg, Denmark on September 17–22, 2005. He was the General Chair of the First International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology (Wireless VITAE) held on May 17–20, 2009 in Aalborg.

Prof. Prasad was also the founding chairman of the European Center of Excellence in Telecommunications, known as HERMES and now he is the honorary chairman. He is a fellow of IEEE, a fellow of IETE, a fellow of IET, a member of The Netherlands Electronics and Radio Society (NERG), and a member of IDA (Engineering Society in Denmark). Prof. Prasad is advisor to several multinational companies. He has received several international awards; one of this is the "Telenor Nordic 2005 Research Prize" (website: http://www.telenor.no/om/).

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Contents

Chapter 1
The Evolution Towards WiMAX

Ramjee Prasad and Fernando J. Velez

Abstract Convergence is a step towards the unpredictable future of wireless communications. Important increases are foreseen in supported bit rates and remarkable improvements in services, applications and wireless communication components. After presenting a brief history of wireless communications, a vision on nowadays wireless ecosystem is presented and the path towards broadband wireless access is explored. Details on IEEE 802.16 evolution are given and the reasons for the existence of the WiMAX Forum are explained. WiMAX service classes are described and salient features of WiMAX are highlighted.

1.1 Introduction

The rapid growth of wireless communication and its pervasive use in all walks of life are changing the way we communicate in all fundamental ways. It is one of the most vibrant areas in the communication field today. Wireless communication dates back to the end of the nineteenth century when Maxwell showed through his equations that the transmission of information can be achieved without the need for a wire [1]. Later, experimentations by Marconi and other scientists proved that long distances wireless transmission may be a reality.

True Wireless communications have gained a momentum in the last decade of twentieth century with the success of second Generation (2G) of digital cellular mobile services. Worldwide successes of Global System for Mobile Communications (GSM), Interim Standard 95 (IS-95), Personal digital Cellular (PDC) and digital Advanced Mobile Phone System (IS-54/136) have enabled pervasive ways of life for the new information and communication technology era. Second

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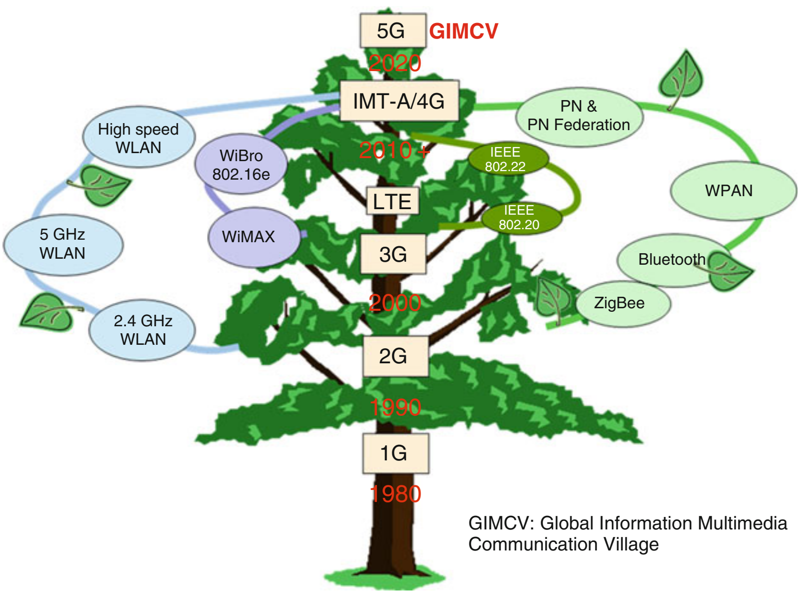

Fig. 1.1 The progress tree for communication technology [5, 6]

Generation (2G), 2.5G, and Third Generation (3G) standards of mobile systems are being deployed everywhere worldwide, with different versions of Universal Mobile Telecommunications System (UMTS), while efforts are going on towards the development and standardization of Beyond 3G (B3G) systems, for example, High Speed Packet Access (HSPA), Wireless Local and Personal Area Networks (WLANs/WPANs) and ultimately towards Fourth Generation (4G) [2–4]. Figure 1.1 illustrates how the progress towards the next generation in communication technology, 4G, can be perceived as a tree, with many branches. But this is not the end of the tunnel; ever increasing user demands have drawn the industry to search for always best connected solutions to support data rates of the range of tens of Mbps in a context of interoperability and cognitive radio. It will lead to 5G as shown in Fig. 1.1.

This chapter is organized as follows. Section 1.2 addresses the history of wireless communications and presents convergence as a step towards the unpredictable future. Section 1.3 presents the path towards wireless broadband access, the types of broadband technologies and gives details on Digital Subscriber Line (DSL) broadband technology. Section 1.4 describes the evolution of wireless broadband, from narrowband wireless local loop to different generations of broadband wireless systems, towards the emergence of a global standard based wireless broadband. Section 1.5 addresses fixed wireless access. Section 1.6 present broadband wireless accesses and distinguishes between licensed and licensed-exempt frequency bands. Section 1.7 gives the background on IEEE 802.16 and Worldwide Interoperability for Microwave Access (WiMAX), namely IEEE 802.16 evolution, from IEEE 802.16 to 802.16a, 802.16b, 802.16-2004, 802.16e and 802.16m as well as their characteristics. Section 1.8 compares fixed and mobile WiMAX. Section 1.9 presents the convergence of personal broadband while Section 1.10 describes the WiMAX Forum perspective. Section 1.11 presents the frequency band allocation for WiMAX while Section 1.12 gives details about ITU classification for WiMAX. Section 1.13 addresses WiMAX services and applications. Section 1.14 presents the salient features of WiMAX. Section 1.15 presents fixed, portable and mobile WiMAX terminals. Finally, Section 1.16 presents the conclusions.

1.2 History of Wireless Transmission

The notion of transmitting information without the use of wires seemed to be a magic in the nineteenth century. But in the year 1896 Marchese Guglielmo Marconi made it possible for the first time by demonstrating the ability of radio waves instant communication [1]. Since then new wireless communication methods and technologies have been evolving in the last over 100 years. The exciting history of Wireless can be divided into four periods, as shown in Tables 1.1–1.4:

Table 1.1 Pioneer Era

1600	Dr. William Gilbert detects electromagnetic activity in the human body and describes it as "electricity".
1837	Samuel F.B. Morse invents the Morse telegraph and sends messages over wires by using Morse code.
1865	Scientists, inventors, and hobbyists begin performing experiments with wireless.
1860s	James Clark Maxwell's EM waves postulates.
1880s	Proof of the existence of EM waves by Heinrich Rudolf Hertz.
1905	First transmission of wireless and first patent of wireless communications by Gugliemo Marconi.
1909	Gugliemo Marconi received the Nobel prize.
1912	Sinking of the Titanic highlights the importance of wireless communications on the seaways. In the next years marine radio is established.

Table 1.2 Pre-cellular Era

1921	Detroit police department conducts field tests with mobile radio.
1933	In the United States, four channels in the 30–40 MHz range.
1938	In the United States, ruled for regular services.
1940	Wireless communications is stimulated by World War II.
1948	First commercial fully automated mobile telephone system is deployed in Richmond, United States.
1950s	Microwave telephone and communication links are developed.
1958	A-Netz was introduced in Germany.
1960s	Introduction of trunked radio systems with automatic channel allocation capabilities in the United States.
1970s	Commercial mobile telephone system operated in many countries (e.g. 100 million vehicles on US highways, B-Netz in (West-)Germany).

Table 1.3 Cellular Era/Broadband Era [1–3]

1980s	Deployment of analogue cellular systems: 1G.
1990s	Digital cellular deployment and dual mode operation of digital systems: 2G.
2000s	International Mobile Telecommunications 2000 (IMT-2000)/deployment with multimedia services: 3G
	WPAN: Bluetooth, UWB
	WLAN: Wi-Fi
	WMAN: WiMAX, WiBro

Table 1.4 Convergence/Personalisation Era

2010+	Fourth generation (4G)
2015+	Mega-communications
2020'	Fifth generation (5G)

- Pioneer Era
- Pre-cellular Era
- Cellular/Broadband Era
- Convergence/Personalisation Era

The pioneer era was marked by fundamental research and development, with contributions from Oersted, Faraday, Maxwell, Helmoltz, Rudolf Hertz, Righi, Lavernock, among many others.

The history of modern wireless communications started in 1896 when Marconi submitted his first patent, the first one ever in the field of wireless telegraphy, and 1901, also with Marconi, who demonstrated wireless telegraphy by sending and receiving Morse code, based on long-wave (>>1 km wavelength) radiation, using high-power transmitters [4]. It had happened at the 11 December 1901. With a transmission range larger than 3,000 km, radio waves connected wirelessly Europe and America. How was it possible if the two terminals were not in Line-of-Sight (LoS)? The answer is the reflection onto the ionosphere, whose existence was postulated by Heaviside and Kennely.

In 1907, the first commercial trans-Atlantic wireless service was initiated, using huge ground stations and 30×100 m antenna masts. World War I saw the rapid development of communications intelligence, intercept technology, cryptography, and other technologies that later became critical to the advent of modern wireless systems.

Later, Marconi discovered shortwave (<100 m wavelength) transmission. Such waves undergo reflections, refractions, absorption, and bounce off the ionosphere, making much more efficient transmission possible. The higher frequencies needed were made possible by vacuum tubes, which were discovered by J.A. Fleming in 1904 and became available around 1906. In addition, cheaper, smaller, and better-quality transmitters became available. In 1915, wireless voice transmission between New York and San Francisco, USA, was achieved while, in 1920, the first commercial radio broadcast took place in Pittsburgh, Pennsylvania, USA. In 1921, police cars in Detroit, Michigan, USA, were already equipped with wireless dispatch radios. In 1935, the first telephone call around the world was made. In Europe, there have also been some advances as the inclusion of telephones in trains in the railway Hamburg-Berlin, Germany, in 1926, with cables parallel to the railway, as well as several experiences with television (TV) broadcast in 1928, across the Atlantic, colour TV and TV news.

During the World War II years, although commercial exploitation was delayed, radio technology developed rapidly to assist with the war effort. After the end of the War, in 1946, the first public telephone service started in 25 major US cities. It used 120 kHz RF bandwidth in half-duplex mode.

Then, in 1950, the FCC doubled the number of mobile channels, and improved the technology, which enabled to cut the RF bandwidth to 60 kHz. In 1960, in the context of the Improved Mobile Telecommunications System (IMTS), the FM bandwidth was again cut, to 30 kHz. Besides, trunking was also introduced, and telephone companies could start to offer full-duplex, auto-dial systems. In Germany, A-Netz was introduced in 1958. It was an analogue system operating at 160 MHz ant it achieved coverage of 80%. Calls could only be established from the mobile terminal. In 1971, it had reached a total of 11,000 users.

In 1968, based on research initiated in 1947, AT&T proposed the cellular concept to the FCC. Bell Mobile offered 12 channels for the entire metropolitan area of New York serving 543 customers in the year 1976. Meanwhile, B-Netz was introduced in Germany in 1972. It was analogue too and operated at 160 MHz. The novelty was the possibility of establishing the calls from the fixed network if the location of the mobile terminal was known in advance. It reached 13,000 users in Germany but it was also deployed in Austria, Luxembourg and Holland. Although the concept of cellular telephony was developed by Bell Labs before, the first cellular mobile systems began its operation in August 1981 in Sweden. This was called Nordic Mobile Telephone system (NMT). NMT was followed by Total Access Communication System (TACS) in Austria (in 1984), Italy and the UK (in 1985), by C-450 in Germany and by Radiocom2000 in France. These different European systems belong to the first generation (1G) and were totally incompatible with each other.

In 1983, cellular service began in USA when FCC allocated 666 duplex channels for the Advanced Mobile Phone System (AMPS) .The market situation in Europe was not favourable as there was no single standard to provide economies of scale. This pushed Europe to develop a unified and single Digital Pan-European standard called GSM, which was developed in early 1980s and deployed in 1992.

In 1989, the FCC granted an additional 166 channels (10 MHz worth) to AMPS. In 1991, US digital cellular (USDC), or IS-54, which supports three users in each 30 kHz channel, was released. This was later improved to accommodate six users per channel. All the standards were developed in the 1980s for voice communications and used frequency modulation (FM) for speech, frequency shift keying (FSK) for signalling and Frequency Division Multiple Access (FDMA). AMPS and IS-54 were 1G systems, too. Only later, in the 1990s, GSM and IS-95 standards evolved to include wireless data transmission as an integral part of their set of services. The standards deployed later in 1090s were based in Time Division Multiplexing

(TDMA), FDMA, or Code Division Multiple Access (CDMA). Frequency Division Multiplexing (FDD) was employed. In 1993, the 1.8 GHz band was released for the digital Personal Communications System (PCS), followed in 1994 by the introduction of IS-95 CDMA. With the advent of new digital standards, wireless data communication became more prevalent. These standards enabled data capabilities from 9.6 to 14.4 kb/s and were termed second Generation (2G) mobile systems.

Fundamentally, 2G networks use telephone-like circuit switching that proved to be optimal for voice communications, which require low latency. But this system is relatively inefficient for data communications, and research efforts to move towards packet switching communications were needed. Meanwhile, intermediate systems were introduced beginning in the late 1990s to achieve higher data rates. These systems are designed “Towards 3G” (sometimes called 2.5G) since they perform better than 2G. The first GSM upgrade was the High Speed Circuit Switched Data (HSCSD) system. HSCSD is the first multi-slot data deployed based in software only upgrade. In 2001, General Packet Switched Service (GPRS) emerged and enabled data streams to flow more easily via packet switching. It proved to be better than HSCSD for higher data rates. As GPRS is a packet switched solution, it enables billing to be based on data volume rather than on time .There also were protocol enhancements to the cdmaOne protocol (originally called IS/95) named IS-95B, and Single Carrier (1x) Radio Transmission Technology (IXRTT) with an extension of GPRS called EDGE (Enhanced Data Rates for GSM Evolution). EDGE is an evolution of GPRS towards 3G standards, compatible with other TDMA systems such as D-AMPS and Japan’s Pacific Digital Cellular, PDC, originally embodied in the UMTS WCDMA and CDMA2000 standards and have now been included in IMT2000, discussed below [4, 5].

In the context of fixed access, traditionally, most users connected to the Internet through the same telephone line that can be used for traditional voice communication. A personal computer equipped with a modem is used to hook into an Internet dial-up connection. These lines provided a relatively low data transmission rate (called “narrowband”) of 56 kbps.

As Internet market continued to explode and the content on the World Wide Web became more sophisticated, the need for greater bandwidth and faster connection speeds was felt. This led to the development of several technological approaches to provide broadband. Broadband service provides higher data transmission speed and facilitates more content to be carried through the transmission “pipeline”. Users can view video, make telephone calls, or download software and other data rich files in a matter of seconds. In addition to offering speed, broadband is “always on” connection (no need to “dial-up”), does not block phone lines and no need to reconnect to network after logging off. Broadband also has “two-way” capability that means, the ability to both receive (download) and transmit (upload) data at very high speeds.

In the context of wireless access, the growing demand for Internet also fuelled with the triple play multimedia required packet based higher bit data rate communication. The term 3G was coined in the 1990s by the global industry to indicate the next generation of mobile devices. The development of third-generation (3G) mobile systems began when the World Administrative Radio Conference (WARC) in 1992.The international 3G standards have been accepted by the ITU (International Telecommunications Union) under the name of International Mobile Telecommunications 2000 (IMT-2000). The WARC'92 identified 1885–2025 and 2110–2200 MHz as the frequency bands for the IMT-2000 [7]. The goal of the 3G standards is to provide users with worldwide coverage via handsets that the capability to seamlessly roam among multiple cellular networks. ITU has recommended several different air interfaces for third-generation systems, based on either CDMA or TDMA technology. The specifications for IMT-200 standards are developed by the Third Generation Partnership Project (3GPP) and 3GPP2 [5].

Amongst the most important 3G concerns for operators are backward compatibility and protection of existing investments. Compatibility with 2G systems is also one of the main goals of 3G system. Thus, an evolution rather than a revolution to 3G from 2G would succeed in this scenario.

Finally, third-generation (3G) wireless systems, based on CDMA technologies, are being developed and deployed, with data and voice communications in tight integration. It is now projected that wireless data traffic will actually surpass that of voice traffic. Moreover, the cost of wireless data devices is now low enough to allow wide penetration in the home and office markets.

Today in every sphere of life (vertically and horizontally), from 'ways of transition the way it has always been done' to more flexible, seamless and effective way of communicating and managing data must be explored. This will facilitate new and competitive services, delivered to new broader markets, beyond the boundaries of the existing communities. This will lead to new revenue streams and higher profit margins. Existing business processes and workflows will be automated and optimized, which will lead to cost control and increased use of assets and resources, and consequently increased revenues.

Wireless Innovative System for Dynamic Operating Mega-communications (WISDOM) adopts the thesis that the digital evolution and successful businesses can be made financially viable, only if the complexity of rapidly increasing costs against rapidly declining real payments is balanced against the backdrop of a complex technological uptake that will leave certain players obsolete, Fig. 1.2.

Wireless data rates have recently been increasing starting from Mbps to Gbps and possibly moving onto Tbps [8]. A concept which has gained high popularity for the future of the telecommunications sector in the recent years is that of convergence. Convergence can be defined as the coming together of voice, facsimile, data, video, and image applications, systems, and networks, both wire line and wireless and several others. It is a fundamental change in the relationship between content producers and content consumers with economic, social and political implications. Converging Technologies are changing the way we live, work and play. Information and knowledge is readily accessible in rich media formats from a very early age. The boundaries between what is real and virtual are blurring. Convergence is really what future generation is all about and is illustrated in Fig. 1.3. WISDOM proposes to combine two innovative concepts to achieve global dynamic

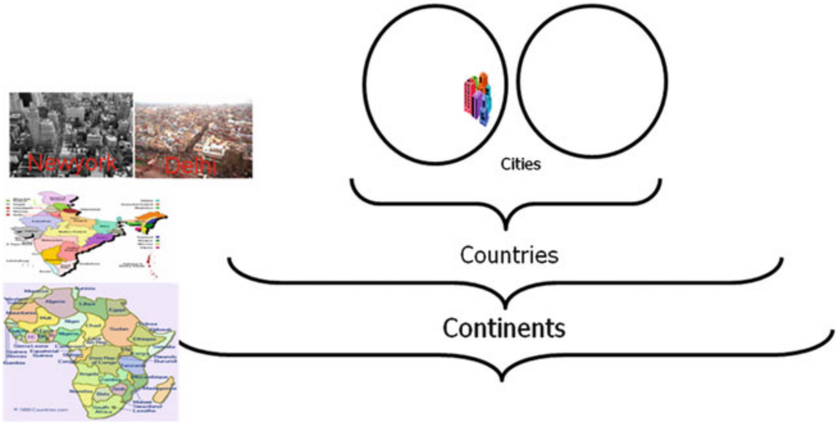

Fig. 1.2 Dynamic mega-communications to assist the digital world evolution (the C^3W approach of WISDOM)

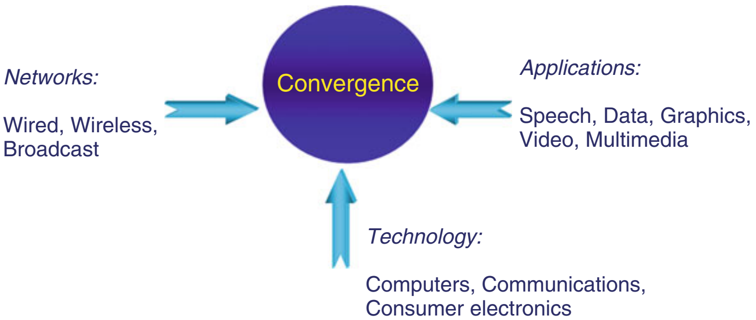

Fig. 1.3 Convergence of networks, applications and technology

mega-communications in the convergence/personalization Era, namely, cognitive technology and personal networks.

The combination of these two concepts by WISDOM offers a dynamic communication system that breaks down the barriers between communications modes, in a comprehensive and cost-effective manner. The offered benefits include the following aspects:

- Consolidation and cost reduction with a secure and easily managed converged network infrastructure
- Knowledge sharing and improved user safety through intelligent rich presence and collaboration
- Accessibility of users and knowledge by integrating WISDOM-based services into workflow and applications, regardless of the device
- Protection of existing investments with a migration path from traditional to WISDOM-based services

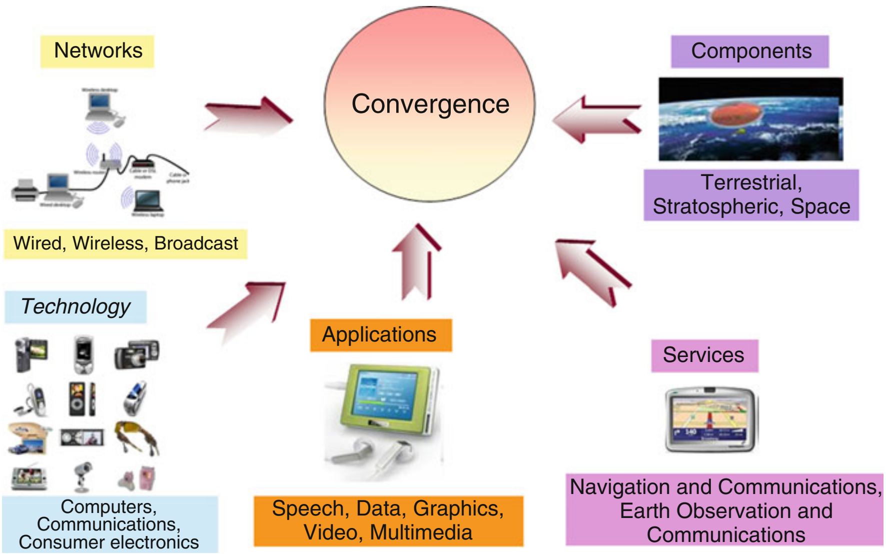

Fig. 1.4 Important elements of convergence

- The freedom for users to work from home, office or other location using high-speed internet connections

Gilder's Law predicts a sixfold increase of the available Bit Rate every 1.5 years. It will take approximately 6 years to achieve the 1 Tbps (Megacommunications). Other two important elements of convergence in the future will be services and components as shown in Fig. 1.4. Various examples for 1 Tb/s wireless aggregation are given as follows:

- **Indoor/Outdoor/In Car (M2M):** Assuming an average of 1,000 sensors per person, and a sampling rate of 1 kbps/sensor for environmental monitoring purposes, in the case of country of population 1 M, we have an aggregate network capacity of 1 Tbps (1,000 sensors per person × 1 kbps × population 1 M = 1 Tbps).
- **Human Centric:** "your own pocket Internet" on a burst, with very fast downloads from hotspots, for example, a movie about 10 GB, transmitted in less than 1 s when you pass with your "multimedia cell" over a portal. The whole network becomes a fast burst environment, thanks to the high speed short range portals widely available (a movie of about 10 GB in 1 s × 100 users = 1 Tbps).
- **Outdoor micro/macro cellular:** At the WMAN scale, the vision of Tbps wireless corresponds to aggregate capacity of all users served in a metropolitan area. For instance 400 radio cells in a metropolitan city, each cell serving 10 users, using 250 Mbps each for virtual reality applications (400 radio cells × 10 user/cell × 250 Mbps = 1 Tbps).

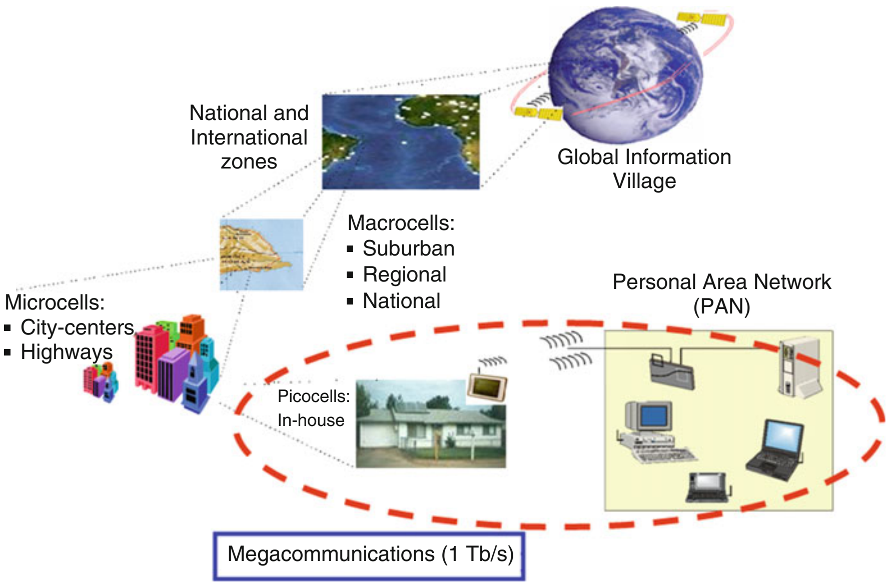

Fig. 1.5 Global Information Multimedia Communication Village (GIMCV)

- **Regional Continental Scales:** The regional/continental scenario covers the need for global and reliable connectivity anywhere and anytime, such as on trains, airplanes, ships, remote areas and dense urban areas, as well as during emergency and disaster scenarios. For instance, delivering via satellite, high-quality video at a rate of 250 Mbps, to an average of 40 people on-board a plane, to a fleet of 100 planes calls for an aggregate traffic of 1 Tbps at the system level (40 people × 100 planes × 250 Mbps = 1 Tbps).

So finally, in the future one can expect to see a global information multimedia communication village (GIMCV) as shown in Fig. 1.5. The various applications of such GIMCV networks are summarized in Fig. 1.6. The evolution of GIMCV can be understood from the family tree of wireless communications shown in Fig. 1.1. In Fig. 1.1, IMT-A is defined as the integration of existing systems to interwork with each other and with a new interface.

It envisions new radio interfaces which are as follows: mobile class targets 100 Mbps with high mobility and nomadic/local area class targets 1 Gbps with low mobility (Licensed or maybe licensed-exempt).

$$4G = IMT\text{-}A + Pers \tag{1.1}$$

Pers stands for Personalisation and this topic has been investigated in My Personal Adaptive Global NET (MAGNET) & MAGNET-Beyond project.

The emerging 4G technologies and the proposed Wireless Innovative System for Dynamic Operating Megacommunications (WISDOM) concept (explained in next

Fig. 1.6 Applications for GIMCV networks

section) will lead the wireless communication towards the realization of true 5G systems.

$$5G = 4G + WISDOM \tag{1.2}$$

1.3 Broadband Access

1.3.1 The Path Towards Wireless Broadband Access

Since the beginning of 1990s, the development of innovative Wireless communication systems has marked the start of the new Era. The transition from fixed to Wireless really started during the Internet revolution. The Internet world evolved as an exchange mechanism for electronic data, but soon sparked worldwide demand for anytime/anywhere computing and communications. Today the role of broadband is changed from a limiting user wired experience to an anytime, anywhere, anyway personal experience for use at home, office, or away. In an Era when both Wireless and broadband have achieved mass market adoption, Wireless broadband technologies provide ubiquitous broadband access to users, enabling services that were previously only available to wireline users.

This wireless revolution is occurring mainly at the last mile, the final point at which connectivity is delivered from a service provider to a customer. This includes end user access, for example, via Wireless Local Loop (WLL), but also Broadband Wireless Access (BWA). BWA features several techno-economic advantages over wireline solution. It provides a cost effective solution along with straightforward

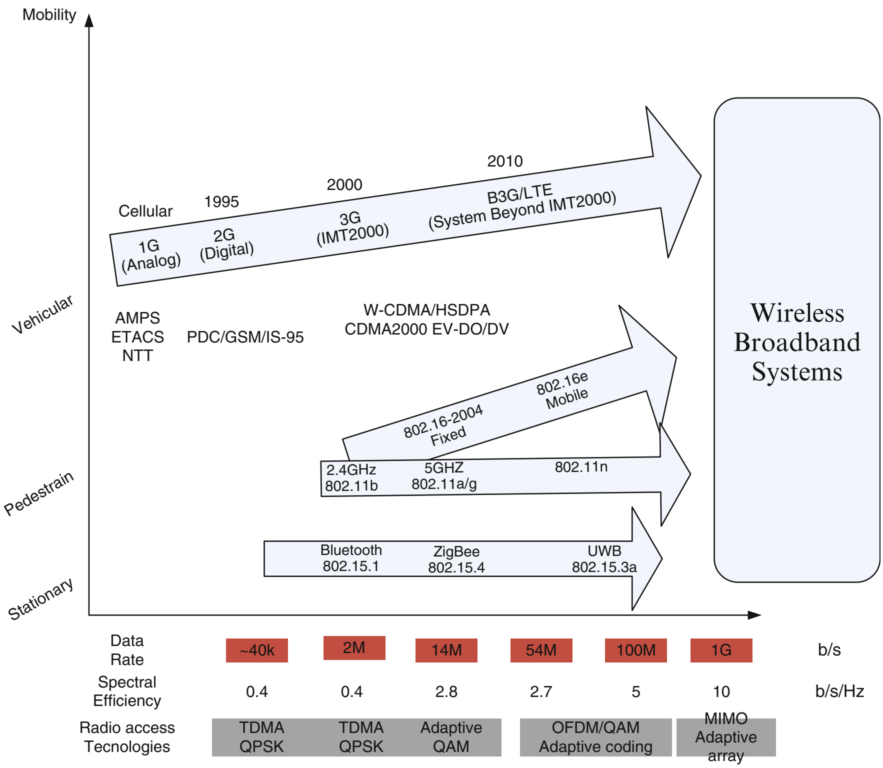

Fig. 1.7 Evolution of wireless towards wireless broadband systems [1, 4, 6, 7]

scalability and extensibility to support growth and expansion of the user base. These systems will not only provide wireless high speed data but also an alternative wireless backhaul solution for existing cellular systems. WLL provides a non-wired loop for customer access. It has already established itself as the primary alternative to the twisted pair copper wire (local loop) in providing central office connectivity to homes and small offices. The successful deployment of WLL in rural and congested metropolitan area is enticing BWA to address both point-to-point (PtP) and point-to-multipoint (PtM) metropolitan coverage.

As depicted in Fig. 1.7, Wi-Fi, WiMAX, 3G and Ultra-Wideband (UWB) technologies are essential to form the global wireless infrastructure needed to deliver high-speed communications and Internet access. While Wi-Fi is ideal for isolated connectivity "islands", WiMAX and 3G are needed for long distance wireless connectivity.

Meanwhile, WiMAX and 3G are both required because their optimum platforms differ: WiMAX is conceived for computing platforms, such as laptops, while 3G envisages mobile devices, like PDAs and cell phones. In turn, UWB offers very short range connectivity, perfect for the home entertainment environment or wireless USB.

In short, each technology envisages a different niche of the Wireless market and supports different types of mobility, being important for different reasons.

Mobile WiMAX is a step towards the evolution of WiMAX. Mobile WiMAX was the first mobile broadband wireless-access solution based on the IEEE 802.16e-2005 standard [1] that enabled convergence of mobile and fixed broadband networks through a common wide-area radio-access technology and flexible network architecture. The mobile WiMAX air interface utilizes OFDMA as the preferred multiple-access method in the downlink (DL) and uplink (UL) for improved multipath performance and bandwidth scalability. Since January 2007, the IEEE 802.16 Working Group has embarked on the development of a new amendment of the IEEE 802.16 standard (i.e., IEEE 802.16m) as an advanced air interface to meet the requirements of the International Telecommunication Union — Radiocommunication/International Mobile Telecommunications (ITU-R/IMT)-advanced for fourth-generation (4G)systems, as well as the next-generation mobile network operators [9].

Depending on the available bandwidth and multi-antenna mode, the next-generation mobile WiMAX will be capable of over-the-air data-transfer rates in excess of 1 Gb/s and support a wide range of high-quality and high-capacity IP-based services and applications while maintaining full backward compatibility with the existing mobile WiMAX systems to preserve investments and continuing to support first-generation products. There are distinctive features and advantages such as flexibility and the extensibility of its physical and medium access layer protocols that make mobile WiMAX and its evolution more attractive and more suitable for the realization of ubiquitous mobile Internet access.

The next-generation mobile WiMAX will build on the success of the existing WiMAX technology and its time-to-market advantage over other mobile broadband wireless access technologies. In fact, all OFDM-based, mobile broadband access technologies that have been developed lately exploit, enhance, and expand fundamental concepts that were originally used in mobile WiMAX.

The IEEE 802.16m will be suitable for both green-field and mixed deployments with legacy mobile stations (MSs) and base stations (BSs). The backward compatibility feature will allow smooth upgrades and an evolution path for the existing deployments. It will enable roaming and seamless connectivity across IMT-advanced and IMT-2000 systems through the use of appropriate interworking functions. In addition, the IEEE 802.16m system utilizes multi-hop relay architectures for improved coverage and performance.

1.3.2 Types of Broadband Services

There are various transmission media or technologies that can be used to provide fixed broadband access. These include cable modem, digital subscriber line (DSL, an enhanced telephone service), satellite technology and terrestrial wireless technologies for providing wireless access. Among all these cable and DSL are the currently the most widely used Broadband services are provided by using a variety of different technologies, network architectures, and transmission paths.

Broadband includes therefore several high-speed transmission technologies as the following ones:

- Digital Subscriber Line (DSL)
- Cable Modem
- Fiber
- Wireless
- Satellite
- Broadband over Powerlines (BPL)

The Organisation for Economic Co-operation and Development (OECD) recently opened a new broadband data portal containing a wealth of information on broadband statistics among OECD member countries, Fig. 1.8, including graphs that track broadband prices, speeds, and technologies as well as overall penetration.

The number of broadband subscribers in the OECD reached 267 million in December 2008, or the equivalent of 22.6 subscribers per 100 inhabitants that is 13% during 2008, Fig. 1.9. The broadband growth during the last 6 months of the year was slightly stronger at 6.23% than in the first 6 months at 6.16% showing no slow down due to economic crisis.

It is worthwhile to highlight the following facts:

- Denmark, the Netherlands, Switzerland, Korea and Norway and Iceland lead the OECD in broadband penetration, each with over 30 subscribers per 100 inhabitants.
- The strongest per-capita subscriber growth over the year was in Slovak Republic, Greece, New Zealand and Norway, Germany, France and the United States. Each country added more than three subscribers per 100 inhabitants during the past year.

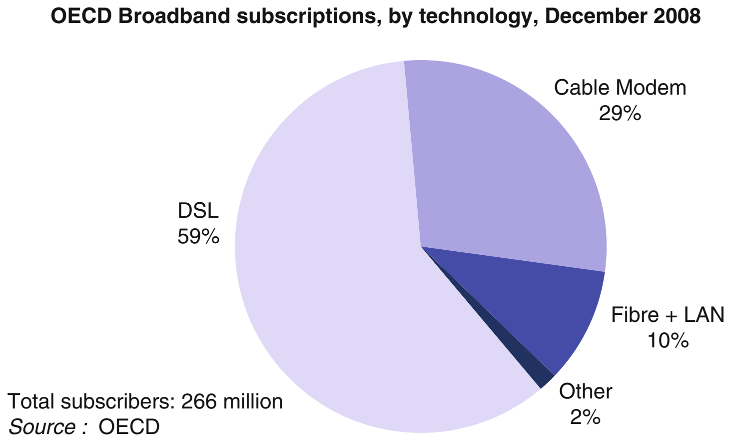

Fig. 1.8 OECD broadband subscriptions

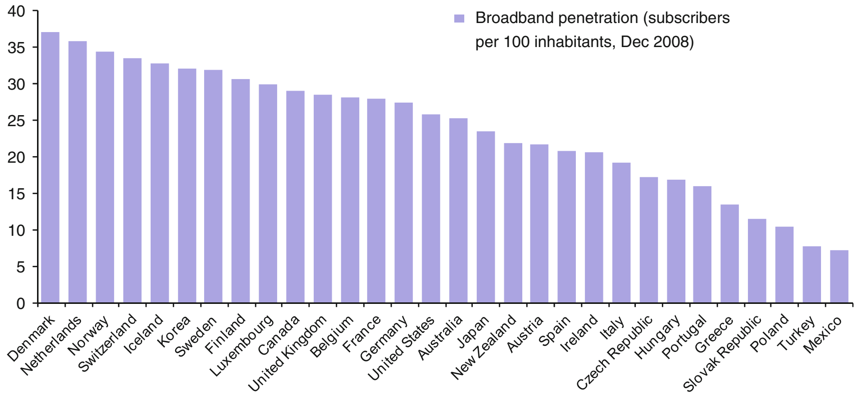

Fig. 1.9 Broadband penetration

- Operators in several countries continue upgrading subscriber lines to fibre. Fibre-to-the-home (FTTH) and Fibre-to-the-building (FTTB) subscriptions now comprise 10% of all broadband connections in the OECD (up from 9% in June 2008). Fibre is the dominant connection technology in Korea and Japan and now accounts for 48% of all Japanese broadband subscriptions and 43% in Korea. Korea has the highest fibre penetration rate at 13.8 fibre subscribers per 100 inhabitants.
- The United States (US) is the largest broadband market in the OECD with 80 million subscribers. US broadband subscribers represent 30% of all broadband connections in the OECD.

1.3.3 DSL Technology

DSL is an entire family of technologies, all of which provide digital transmission over the copper wires used in the local loop, or last mile. The xDSL technologies offer many home users their first taste of broadband, and most users find that once they have tried broadband, they will never go back. It is exciting how much broadband can improve performance; despite the fact that today's broadband is not as fast as the data rates we will see in the coming years. As discussed in detail in the following sections, the xDSL family of standards includes a large variety of speeds and distance specifications:

- High-Bit-Rate Digital Subscriber Line (HDSL)
- Symmetrical (or Single-Line) Digital Subscriber Line (SDSL)

Speeds for DSL can depend on the condition of the telephone wire and the distance between the home and the telephone company's central office. Because ADSL uses frequencies much higher than those used for voice communication, both voice and data can be sent over the same telephone line. Thus, customers can talk on their telephone while they are online, and voice service will continue even if the ADSL service goes down. ADSL line is an "always on" connection with no dial-up required. Unlike cable, however, ADSL has the advantage of being unshared between the customer and the central office. Thus, data transmission speeds will not necessarily decrease during periods of heavy local Internet use. The disadvantage relative to cable is that ADSL deployment is constrained by the distance between the subscriber and the central switching centre.

1.3.3.1 Cable Modem Service

The same cable network that currently provides television service to consumers is being modified to provide broadband access. The cable modems use the existing cable TV networks and coaxial cable to give subscribers higher Internet speeds. However as a means of providing broadband Internet cable have several shortcomings. As cable networks are shared by users, access speeds can decrease during peak usage hours, when bandwidth is being shared by many simultaneous customers. Network sharing has also led to security concerns and fears that hackers might be able to eavesdrop on a neighbour's Internet connection. The cable industry is developing "next generation" technology which will significantly extend downloading and uploading speeds.

1.3.3.2 Fiber

Another broadband technology is optical fiber to the home (FTTH). Fiber optic technology converts electrical signals carrying data to light and sends the light through transparent glass fibers about the diameter of a human hair. Optical fiber cable is used by businesses as high speed links for long distance voice and data traffic. It has tremendous data capacity, with transmission speeds dramatically higher than what is offered by cable modem or DSL broadband technology. While the high cost of installing optical fiber in or near users' homes has been a major barrier to the deployment of FTTH, both Verizon and AT&T (formerly SBC) are rolling out fiber-based architectures that will offer consumers voice, video, and high-speed data (sometimes referred to as a "triple play"). Some public utilities are also exploring or beginning to offer broadband access via fiber inside their existing conduits. Networks that depend on a fiber-optic cable backbone are capital-intensive and usually more profitable in high-density urban areas. A number of rural communities have used their resources to install fiber-optic broadband services in part because they were too small a market to interest for-profit companies. Increasingly, communities are looking at wireless technologies to support their networks.

1.4 Evolution of Wireless Broadband

1.4.1 Narrowband Wireless Local Loop

The primary need for the development and deployment of Wireless Broadband was voice telephony. In developed countries like India, China, Indonesia, Brazil, and Russia, where there was lack of basic infrastructure WLL served basic need for telephone services [5]. Nevertheless, in the developed markets, where voice telephony infrastructure already existed, WLL led to the advent of new consumer telecommunications services such as video conferencing and increased usage of existing services such as email and web access. After the commercialization of the Internet in 1993, the demand for Internet-access service began to surge, as many provided high speed Internet access as a way for wireless systems to differentiate themselves. In 1997, AT&T announced that it had developed a wireless access system for 1,900 MHz personal communications service (PCS) band that could deliver a wireless phone service similar to cellular telephone service but emphasizing personal service and extended mobility. It is sometimes referred to as digital cellular (although cellular systems can also be digital). Like cellular, PCS is for mobile users and requires a number of antennas to blanket an area of coverage. In the mean time many start-up companies also started focusing on Internet access services using wireless These wireless Internet service providers (WISP) companies deployed systems in the license exempt bands, typically 900 MHz and 2.4 GHz [10].

1.4.2 First Generation Broadband Wireless Systems

Wireless systems started to be evolved to support much higher speeds as Digital Subscriber Line (DSL) and cable modems began to be deployed. Proprietary technologies like Local Multipoint Distribution System (LMDS) began to be developed for higher frequencies such as 2.5 and 3.5 GHz. LMDS is a broadband wireless PtM communication system that can be used to provide digital two-way voice, data, Internet, and video services. It is a microwave system that provides two-way transmission in the 28 GHz range. It became known as "wireless cable" for its potential to enable competition with the cable television companies for broadband video to the home. Due to the very high frequency range in which it operates, it has very severe line of sight requirements and needs a transmitter every couple of miles. LMDS has a range of up to only 5 km and is only really suitable for urban settings [11, 12].

In late 1990s, some telephony companies started deployments of wireless broadband in the Multichannel Multipoint Distribution Services (MMDS) band at 2.5 GHz. These services, called MMDS, target data rates of several Mbps. In 1998, FCC allocated frequency bands for these services. This band was historically used to provide cable broadcast video services, especially in rural areas where cable TV services were not available. But after the introduction of satellite TV the wireless cable business was ruined and the band was set free. MMDS is a microwave system that provides 33 analogue channels and from five to ten times as many digital channels. Operating in the 2.5 GHz range, it requires line of sight between the transmitter and receiving antenna. Digital signals let MMDS support more channels and also deal better with the topography. Signals can be beamed to a high building, which can serve as one or more cell sites transmitting in various directions. MMDS systems were only available in a specific frequency band and available through licenses from the regulatory agency. This method limited the number of operators in a given geography to only one. The success of BWA in that market became dependent on the success of that one operator. Today, there is a large swath of unused spectrum as a result of those operators not succeeding with their MMDS deployments. In the last 3 years, the use of license-exempt spectrum has been an attractive way for a competitive BWA market to emerge. Operators can enter a market quickly and with minimal expense to provide either the first broadband connection or a competitive service to wired offerings.

First generation networks were designed by applying cable modem technology to create a wireless solution. These networks have substantial performance limitations due to the following to issues:

- First generation systems do not respond well to rain fades, obstructions, or non-line-of-sight (NLoS) conditions. They require very tall base station antennas and line-of-sight (LoS) access to all of the customer-premise equipment (CPE). They suffered poor response to link impairments.
- Also these systems had poor response to co-channel interference.

These distinctive issues put restrictions on their deployment on the First Generation Broadband Wireless Systems.

1.4.3 Second Generation Broadband Wireless Systems

The LoS issue was resolved in second generation broadband systems and were able to provide more capacity. The companies tried to develop advanced proprietary solutions to overcome the short comings of the first generation broadband wireless systems. This was done by the use of a cellular architecture and implementation of advanced –signal processing techniques to improve the link and performance systems. The use of Orthogonal frequency division multiplexing (OFDM), code division multiple access (CDMA), and multi antenna processing solved the problem of NLoS. The second generation fixed wireless systems offered a few megabits per second throughput over cell ranges of few miles. Proprietary systems developed by Navini Networks and Soma Networks offered adequate link performance over a few miles without the need of antenna mounted outside. Thus, Second Generation

Broadband Wireless Systems were able to overcome the LoS issue and to provide more capacity.

1.4.4 Emergence of Global Standard Based Wireless Broadband

LMDS and MMDS failed to be considered as viable means of providing wireless broadband access because of combination of factors like lack of economies in silicon, expensive equipment, poor deployments, weather conditions, and ultimately, over-hyping and under-delivering on performance. There was a growing need of a global standard based broadband access technology that can provide high speed packet data services for IP applications, support portability as well as mobility, give nationwide coverage (including rural areas), voice support at high speeds, and provide moderate data rates.

To address these needs for next generation broadband wireless Access Systems, IEEE formed The Work Group 16 in 1998 [13, 14].This group called 802.16 developed a wireless metropolitan area network or Wireless MAN .The standard was completed and approved in December 2001, Table 1.5.

Table 1.5 Important dates in the development of broadband wireless [5]

Date	Event
Feb 1997	AT&T announces development of fixed wireless technology code named “Project Angel”.
Feb 1997	FCC auctions 30 MHz spectrum in 2.3 GHz band for wireless communications services (WCS).
Sept 1997	American Telecasting (acquired later by Sprint) announces wireless Internet access services in the MMDS band offering 750 kbps downstream with telephone dial-up modem upstream.
Sept 1998	FCC relaxes rules for MMDS band to allow two-way communications.
Apr 1999	MCI and Sprint acquire several wireless cable operators to get access to MMDS spectrum.
July 1999	First working group meeting of IEEE 802.16 group.
Mar 2000	AT&T launches first commercial high-speed fixed wireless service after years of trial.
May 2000	Sprint launches first MMDS deployment in Phoenix, Arizona, using first-generation LOS technology.
June 2001	WiMAX Forum established.
Oct 2001	Sprint halts MMDS deployments.
Dec 2001	AT&T discontinues fixed wireless services.
Dec 2001	IEEE 802.16 standards completed for > 11 GHz.
Feb 2002	Korea allocates spectrum at 2.3 GHz for wireless broadband (WiBro).
Jan 2003	IEEE 802.16a standard completed.
June 2004	IEEE 802.16-2004 standard completed and approved.
Sept 2004	Intel begins shipping the first WiMAX chipset, called Rosedale.
Dec 2005	IEEE 802.16e standard completed and approved.
Jan 2006	First WiMAX Forum–certified product announced for fixed applications.
June 2006	WiBro commercial services launched in Korea.

1.5 Fixed Wireless Access

Three options are popular today for design of wireless networks – Point-to-Point (PtP), Point-to-Multipoint (PtM), and Mesh topologies.

The types of fixed wireless network topologies can be categorized into four types:

- PtP networks
- PtM networks
- NLoS PtM networks
- Mesh networks

1.5.1 Point-to-Point Networks

As the name implies, a point-to-point wireless network is a direct link between two distinct locations. In the diagram, PtP connections are represented by the red lines. These connections are commonly used in cellular backhaul (from the Base Station, BTS, site towards the network operations centre) and for building-to-building extensions of IP and circuit-switched services (i.e. analogue PBX). Fiber optics and leased copper connections are examples of "wired" PtP networks.

PtP networks consist of one or more fixed PtP links, usually employing highly directional transmitting and receiving antennas, as illustrated in Fig. 1.10. Networks of such links connected end to end can span great distances. Links connected end to end are often referred to as tandem systems, and the analysis for the end-to-end reliability or availability of the whole network must be calculated separately from the availability of individual links [15].

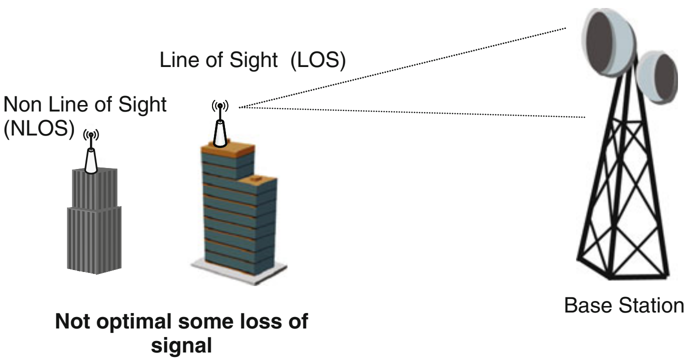

Fig. 1.10 PtP network connecting two cities through mountaintop repeaters

1.5.2 Point-to-Multipoint Networks

PtM networks used a 'hub and spoke' approach to deliver data services as illustrated in Fig. 1.11. The hub is analogous to the base station in a cellular system. It consists of one or more broad-beam antennas that are designed to radiate toward multiple end-user terminals. Depending on the frequency band employed, and the data rates to be provided to end users, normally several hubs are needed to achieve ubiquitous service to a city. The remote end-user terminals are engineered installations in which directional antennas have been installed in locations that are in the LoS to the hub and oriented by a technician to point at the hub location. In some cases this may require extensive work at each terminal location. PtM network architecture is by far the most popular approach to fixed broadband wireless construction. It mimics the network topology successfully used for decades in wired telephone networks, cable television networks, and even electrical, gas, and water utilities of all sorts. For wireless, the major drawback is the cost of the infrastructure to construct the hubs needed to achieve comprehensive LoS visibility to a large percentage of the service.

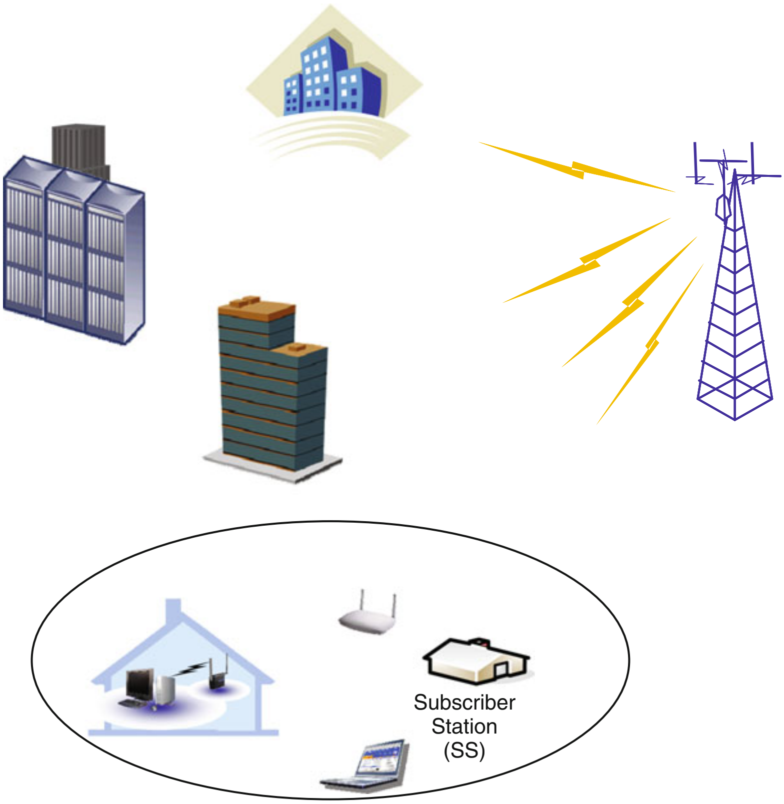

Fig. 1.11 PtM network

1.5.3 NLoS Point-to-Multipoint Networks

NLoS PtM networks are identical in topology to the PtM networks described above. The difference lies in the nature of the remote terminals. Instead of the remote terminals being engineered and professionally installed to achieve successful performance using an outside antenna, the terminals are arbitrarily positioned at the convenience of the end user inside a house or office. In most cases, the location of these terminals will be places that do not have a clear, obstruction-free view of a network hub and are thus called NLoS. The signal attenuation and amplitude variability that occurs along the wireless signal path from the network hub to NLoS location present new challenges to system designers in their efforts to provide a reliable high-speed data service to every terminal.

1.5.4 Mesh Networks

Mesh networks are a relatively new, evolving type of wireless broadband technology that may enable more flexible and more efficient expansion of wireless broadband services, Fig. 1.12. In the mesh topology each node has redundant connections to other nodes in the network, as shown in the figure. Unlike traditional Wireless Metropolitan area Networks (WMANs) or Wireless Local Area networks (WLANs), in which each "node" (or consumer device) in the network communicates only with a central antenna or base station, in a mesh network, each node

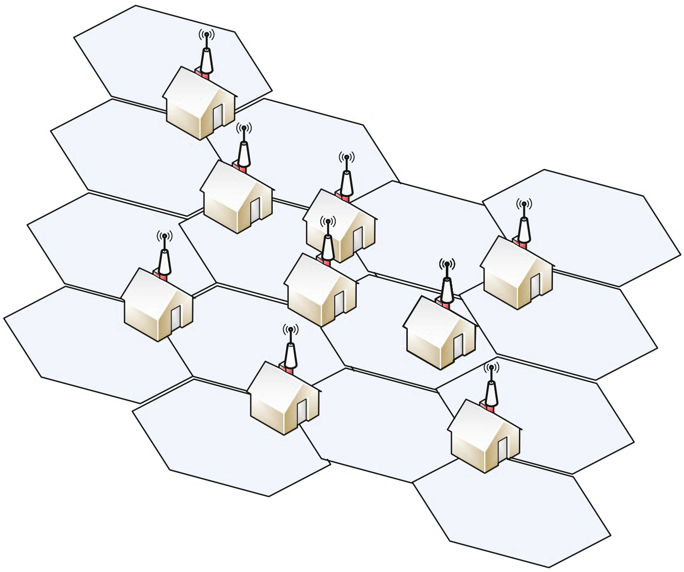

Fig. 1.12 Mesh networks

can function as an access point and transmit information to other nodes in close proximity. If one node goes out of service, the other nodes will route the traffic around it, making mesh networks a relatively robust communications technology.

One of the key aspects of a mesh network is the routing functionality of its nodes which allows them to take the best route in communication with other nodes or networks. When a backhaul-based network is deployed in mesh mode, it does not only increase the wireless coverage, but it also provides features such as lower backhaul deployment cost, rapid deployment, and reconfigurability. Various deployment scenarios include citywide wireless coverage, backhaul for connecting 3G RNC with base stations, and others.

1.6 Broadband Wireless Access

1.6.1 Licensed Frequency Bands

International Telecommunications Union (ITU) regulates the use of radio spectrum worldwide, which operates with the participation of all member nations [16]. The spectrum available for the construction of broadband wireless systems can be divided into licensed and license-exempt frequency bands. In general, licensed spectrum provides for some degree of interference protection because each new licensee must demonstrate compliance with certain standards for limiting interference to other existing nearby licensed systems. There are also radiated transmitter power level and other parameter limitations that each licensee must observe. License-exempt bands do not require individual transmitters to be licensed in order to operate, but there are still radiated power restrictions that usually keep power at low levels as a de facto way of limiting interference. There may also be a rudimentary channelization scheme and modulation standard; again, to make possible as many successful operations as possible without destructive interference. Some cooperation and coordination may sometimes be necessary to make the most of these measures. Cordless telephones, remote control toys, and IEEE802.11b/802.11a wireless LAN devices are examples of license-exempt systems.

There are a number of frequency bands that have been allocated throughout the world for use by licensed fixed broadband services. Within the general ITU band designations, individual countries may elect to implement or not implement policies that allow those frequencies to be licensed and used within their country boundaries. This is especially true for fixed broadband wireless services.

However, Table 1.6 provides a convenient summary for most of the European countries. The frequency bands listed are intended as examples of the variety of services that have access to the microwave spectrum for fixed services. The table include the major bands used for newer PtP and PtM broadband services such as Local Multipoint Distribution Service (LMDS).