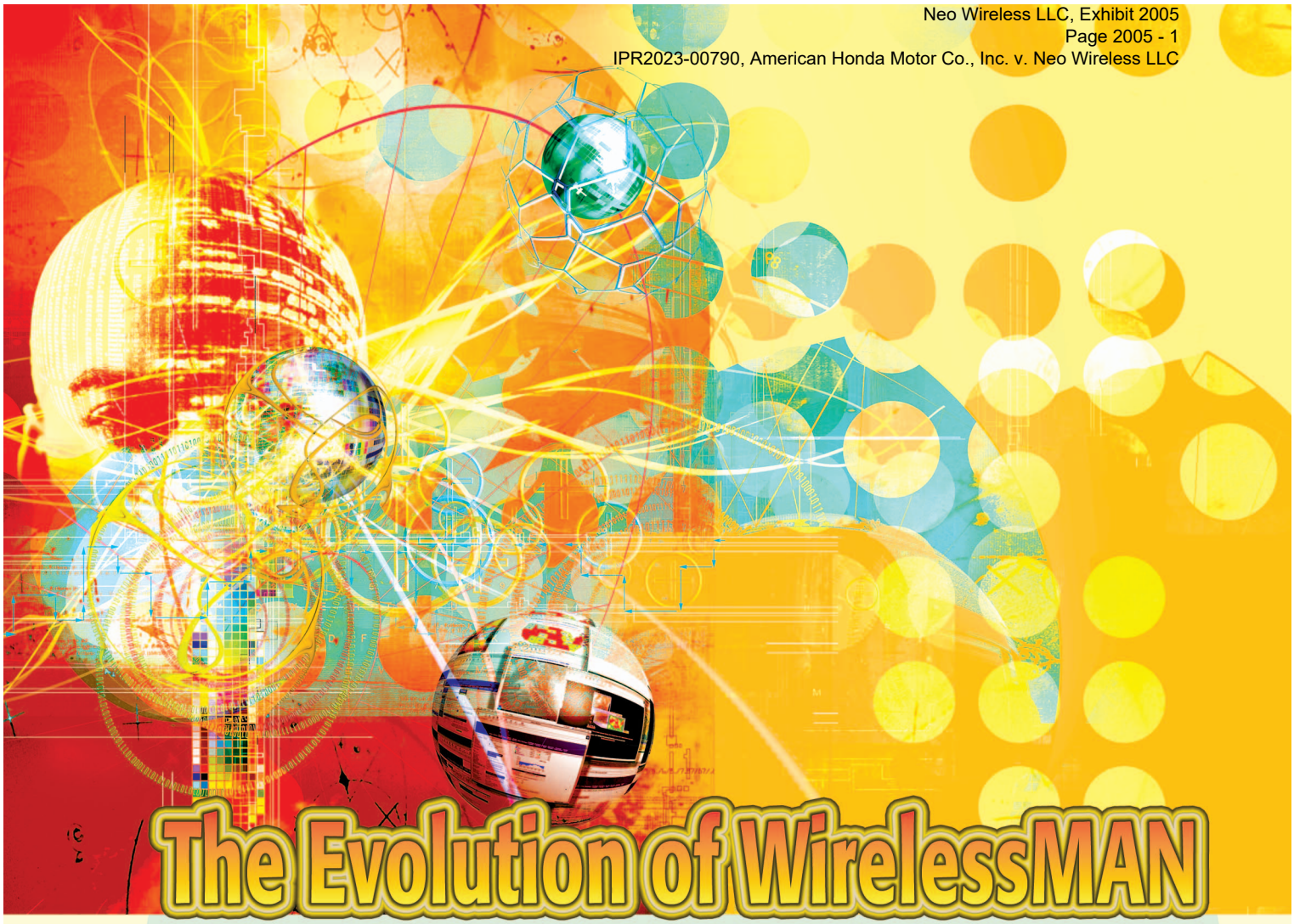
Neo Wireless LLC, Exhibit 2005
Page 2005 - 1
IPR2023-00790, American Honda Motor Co., Inc. v. Neo Wireless LLC



The Evolution of WirelessMAN

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Roger B. Marks, José M. Costa, and Brian G. Kiernan

The WirelessMAN (metropolitan area network) air interface in IEEE Standard 802.16 continues to evolve to address new opportunities in broadband wireless access. The air interface, the original design of which addressed stationary users, completed its evolution to full mobility support nearly three years ago with the completion of the IEEE 802.16e amendment in 2005. A specific version of that vintage of the standard was adopted as mobile worldwide interoperability for microwave access (WiMAX) compliance testing by the WiMAX Forum and was incorporated into the international mobile telecommunications (IMT) 2000 recommendation by the International Telecommunication Union (ITU) in 2007. While wide-scale global deployment of these systems is underway, the IEEE 802.16 Working Group (WG) is undertaking another future-looking evolution with the development of the 802.16m project, which is working towards the specification of an advanced air interface to support even more demanding applications, such as those to be included in the ITU's new IMT-Advanced recommendations, while retaining support for Mobile WiMAX mobile stations. This article summarizes the status

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of the standard and WG and outlines the directions being taken in ongoing development work. It also places the standard in the ITU context by exploring its role in IMT-2000 and reviewing the upcoming activities in IMT-Advanced development.

IEEE Standard 802.16

IEEE Standard 802.16, along with related standards and amendments, is developed and maintained by the IEEE 802.16 WG on Broadband Wireless Access (http://WirelessMAN.org). This standard specifies the WirelessMAN air interface for a wireless MAN. In this section, we begin with an overview of the 802.16 WG. We follow with a history of the WG, a review of the historical development of its projects, and a summary of the technical content of the standard. Some of this material is taken from [1], where it is described in further detail.

The development of standards within the IEEE is assigned to the IEEE Standards Association (IEEE-SA). The development of local area network (LAN) and MAN standards within the IEEE-SA is assigned to the LAN/MAN Standards Committee (LMSC), also known as IEEE 802. One of the largest, most prolific, and most influential of the IEEE-SA sponsors, IEEE 802 has operated since 1980 under the IEEE Computer Society (although, unique to IEEE 802, the IEEE 802.16 projects also have a cosponsor: the IEEE Microwave Theory and Techniques Society). It develops and maintains standards addressing the medium access control layer (MAC) and the physical layer (PHY), each of which fits under a common logical link control layer (LLC). Taken together, these make up the two lowest layers of the open system interconnection (OSI) seven-layer model for data networks. IEEE 802 oversees a panoply of network standards, using an internal structure based on WGs developing draft standards.

The IEEE 802.16 WG was initiated in 1998 and held its first authorized standards development session in July 1999. The WG meets six times a year. Attendance has varied depending on the project activity. In 2007, the attendance rose to over 450 participants at a session. WG sessions are geographically diverse and are typically held in North America, Asia, or Europe. Membership in the WG is granted to individuals on the basis of participation in sessions. As of March 2008, the WG had 433 members from Canada, China, Egypt, Finland, France, Germany, India, Israel, Italy, Japan, Korea, The Netherlands, Russia, Sweden, Taiwan, the United Kingdom, and the United States.

Since 1999, the IEEE 802.16 WG has constantly been active in developing standards projects, usually with multiple parallel activities. The IEEE-SA process allows for the development of amendments that modify an existing standard. The published amendment, which is designated by a lowercase letter after the primary standard number, is not an independent specification because it includes only the modifications, not the base material from the original standard. Upon approval of the amendment, the applicable standard is no longer the prior version but the version defined by the application of the amendment. When appropriate, a revision of the standard may be undertaken; in this case, the base standard and its published amendments are editorially merged and reballoted, with the entire document open to comment.

Standard 802.16, along with related standards and amendments, is developed and maintained by the IEEE 802.16 Working Group on Broadband Wireless Access.

The core activity of the 802.16 WG is the development and enhancement of IEEE Std 802.16 ("IEEE Standard for Local and Metropolitan Area Networks—Part 16: Air Interface for Fixed Broadband Wireless Access Systems"). The first version of this standard, approved in 2001 as IEEE Std 802.16-2001, included a single-carrier PHY for operation in the range of 10–66 GHz. Because no specific frequency bands were globally available, the PHY was designed to operate in a range of RF bandwidths in both time division duplex (TDD) and frequency division duplex (FDD) modes. Half-duplex FDD (H-FDD) terminal support was also specified. Because the standard was targeted primarily toward business applications, the connection-oriented point-to-multipoint MAC was designed to support carrier-class requirements, with full support for ATM-class quality of service (QoS), bandwidth on demand, and dynamically adaptive PHY techniques (including modulation and coding). While the PHY limitations of this mode essentially limited it to stationary terminals with line-of-sight links, many of the MAC concepts were novel for a wireless system and formed the basis of the standard's evolution with a set of increasingly capable and increasingly mobile PHY specifications. As the standard evolved, new PHY specifications were added, and the MAC evolved to support them.

Beginning in the year 2000, the WG began to develop a new PHY approach for frequencies below 10 GHz. This work led, in 2003, to IEEE Std 802.16a, which amended the base standard, introducing orthogonal frequency-division multiplex (OFDM) and orthogonal frequency-division multiple access (OFDMA) PHY specifications as well as some MAC enhancements. The WirelessMAN-OFDM air interface uses OFDM technology to provide robust connections in multipath and non-line-of-sight environments by dividing the

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Page 2005 - 3
IPR2023-00790, American Honda Motor Co., Inc. v. Neo Wireless LLC

signal into many (in this case, 256) orthogonal subcarriers. The WirelessMAN-OFDMA air interface uses OFDMA, a more sophisticated and powerful technology allowing the subcarriers (in this case, 2,048 of them) to be divided into subchannels that can be shared among multiple users at any given time. A third PHY specification, using single-carrier modulation with the assumption of frequency-domain equalization, was also included in the standard but has not been implemented by the industry. IEEE 802.16a also marked the introduction of important new features, such as adaptive antenna systems for beamforming, transmit antenna diversity using open-loop space-time coding, and hybrid automatic repeat request (HARQ).

In 2004, a revision project led to the completion of IEEE Std 802.16-2004, which superseded IEEE 802.16-2001 and its subsequent amendments. One important new feature added at this stage was multiple-input/multiple-output (MIMO) antenna systems. Another was the introduction of subchannelization into the WirelessMAN-OFDM mode, giving it an OFDMA character as well. This revision of the standard is frequently, although incorrectly, called "802.16d."

In late 2002, the WG began a new project to amend IEEE Std 802.16 again, this time to add support for mobile terminals. The work, which brought in a large number of participants and new technology ideas, led to the approval of another amendment, IEEE Std 802.16e, in 2005. This amendment expanded the IEEE 802.16 fixed-access system into a combined fixed and mobile system, allowing a single base station (BS) to support both fixed and mobile terminals. Important new features included handover, sleep and idle modes, more robust security, and closed-loop MIMO. Support continued for each the three lower-frequency PHY modes, but the OFDMA mode was made "scalable" with the addition of new subcarrier counts (128, 512, and 1,024) intended for use in narrower channels.

As the WG's attention turned to mobility, it decided that network management would be an increasingly critical issue. This led in 2005 to IEEE Std 802.16f, an amendment specifying a management information base (MIB) for fixed systems, and in 2007 to IEEE Std 802.16g, on "management plane procedures and services." Additional work to specify the MIB for the fixed/mobile case was developed in project 802.16i; however, the work was later transferred to a revision project begun in 2006. This will lead to a new revision of IEEE Std 802.16 that will supersede IEEE Std 802.16-2004 and its subsequent amendments. Completion of this revision draft, unofficially and temporarily known as 802.16Rev2, is expected in late 2008.

While the revision project is being completed, the WG continues with the development of three additional amendments:

- Project 802.16h is developing improved coexistence mechanisms for license-exempt operation.
- Project 802.16j is developing a multihop relay specification that will specify a relay station that can communicate with mobile terminals. This will offer a valuable new tool to system operators for extending range and capacity.
- Project 802.16m is developing an advanced air interface, as described in more detail below.

ETSI BRAN HIPERMAN

The IEEE 802.16 WG has long had an active liaison relationship with the Broadband Radio Access Networks (BRAN) Technical Committee of the European Telecommunications Standards Institute (ETSI). This activity was highly successful in the harmonization of the WirelessMAN-OFDM and WirelessMAN-OFDMA modes and the ETSI high performance radio metropolitan area network (HIPERMAN) standards. ETSI is also very active in the development of conformance test specifications for IEEE 802.16. ETSI conformance test documents have referenced IEEE 802.16 as their source standards, and IEEE 802.16 makes normative reference to ETSI regarding conformance test documentation. The relationship between the fully harmonized standards is illustrated in Figure 1.

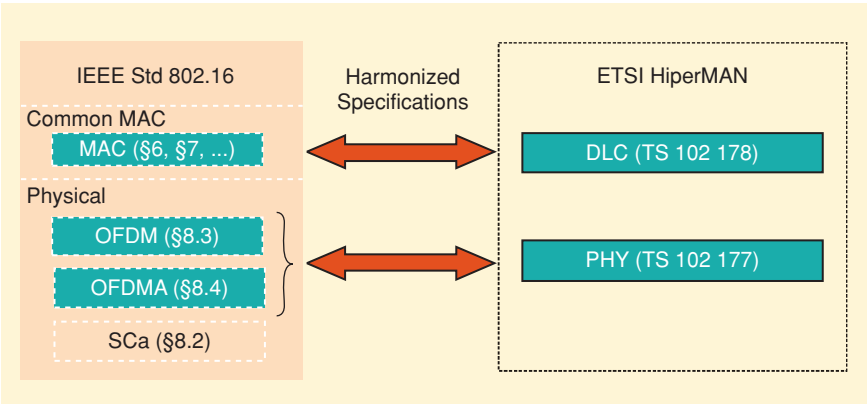

Figure 1. *Relationship between harmonized IEEE 802.16 and HIPERMAN standards. (This figure originates from Recommendation ITU-R M.1801.)*

The WiMAX Forum

By the end of 2000, even before the original IEEE 802.16-2001 was approved, several companies moved to initiate an independent body—the WiMAX Forum—to develop and conduct product tests certifying compliance to the standard. The Forum put its initial efforts on the 10–66 GHz single-carrier mode. However, once the 802.16a project was underway, the Forum turned its attention to the OFDM

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modes, developing certification tests that have led to dozens of certified TDD and FDD products. With the development of 802.16e, the Forum began to focus on a mobile solution and identified the OFDMA mode as most suitable to its interest. The Forum developed the WiMAX Forum Mobile System Profile to describe the features of the standard that would be mandatory and optional in its conformance tests. That profile, which includes TDD only, is the basis of certification tests to be implemented in 2008. The WiMAX Forum has grown into a large global organization, with over 500 corporate members.

As noted earlier, the IEEE 802.16 air interface, like the others in the IEEE 802 series, specifies only layers 1 and 2, not the higher network layers. This offers the advantage of flexibility and openness at the interface between layers 2 and 3 and it supports a variety of network infrastructures. In particular, a network architecture design to make optimum use of the WirelessMAN-OFDMA air interface is specified in the "Mobile WiMAX End-to-End System Architecture" [2] of the WiMAX Forum.

Internationalization of IEEE 802.16 in ITU, Including IMT-2000

Historically, many of the IEEE 802 standards have been entered into the more formal arena of "international" standardization through IEEE 802's relationship with the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC). However, IEEE 802.16 has, since inception, consistently looked to partner with the ITU, specifically the ITU Radiocommunication Sector (ITU-R). This is partly because 802.16 was designed to operate principally in licensed spectrum, the administration of which is significantly dependent on the ITU Radio Regulations. It is also because the ITU has always been a focal point of the telecommunications industry. IEEE 802.16 is a convergent technology, drawing heavily from the data communications community but targeting applications that have historically been supported by the telecommunications establishment. Many of the potential customers for IEEE 802.16 systems have a natural home in ITU. The relationship strengthened significantly in 2003 when the IEEE became a member of ITU-R.

As a result of the 802.16 WG's active contributions to and participation in ITU-R, IEEE Std 802.16 is specified in several ITU-R Recommendations.

Recommendation ITU-R F.1763

Recommendation ITU-R F.1763 ("Radio Interface Standards for Broadband Wireless Access Systems in the Fixed Service Operating Below 66 GHz") was published in 2006. It focuses specifically on recommending IEEE Std 802.16-2004, along with the equivalent standards from the ETSI, for use in the fixed wireless service.

Recommendation ITU-R M.1801

Recommendation ITU-R M.1801 ("Radio Interface Standards for Broadband Wireless Access Systems, Including Mobile and Nomadic Applications, in the Mobile Service Operating Below 6 GHz") was published in 2007. It recommends the use of IEEE Std 802.16 (including the 802.16e amendment), along with the equivalent ETSI HIPERMAN standards and other BWA standards, in the mobile service. A range of channel bandwidths is specified, with both TDD and FDD duplexing.

Recommendation ITU-R M.1457

In October 2007, the ITU-R updated Recommendation ITU-R M.1457 ["Detailed Specifications of the Radio Interfaces of International Mobile Telecommunications-2000 (IMT-2000)"], which specifies the radio interfaces of International Mobile Telecommunications-2000 (IMT-2000). IMT-2000 is commonly considered as the original specification of third-generation (3G) mobile standards. The update, known as Revision 7, names a specific case of IEEE Std 802.16 (including the 802.16e and 802.16f amendments) as an IMT-2000 radio interface. The specific implementation, designated as "IMT-2000 OFDMA TDD WMAN," is a version of IEEE 802.16 supported in the WiMAX Forum Mobile System Profile. A summary description of the radio interface is provided in document IEEE L802.16-06/031r2 [3], with which IEEE initially proposed the addition of a subset of 802.16 (designated "IP-OFDMA") to IMT-2000.

IMT-2000 and IMT-Advanced

At the end of 1985, long before personal communications [e.g., personal communication system (PCS) and universal mobile telecommunications system (UMTS)] was a popular topic, international consultative radio committee (now ITU-R) formed a group called Interim Working Party 8/13 (IWP 8/13) to study the requirements for future public mobile telecommunication systems (FPLMTS), which was later renamed as International Mobile Telecommunications 2000 (IMT-2000) [4]. In the early days of cellular systems, the user terminals consisted of heavy equipment that had to be transported in cars and did not conform to a global standard. The participants in those early ITU activities had the vision that user terminals would become lightweight, handheld, and easily carried from one continent to another, so that global standards would be needed. The work until 1992 identified the services that could potentially be delivered by radio and what spectrum would be needed to ensure reasonable quality and cost for those services. IWP 8/13 eventually became Task Group 8/1, which developed the first version of Recommendation ITU-R M.1457, the radio access interface specifications for IMT-2000. Through harmonization and consensus building, ten candidate proposals for terrestrial IMT-2000 radio interfaces

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Neo Wireless LLC, Exhibit 2005
Page 2005 - 5
IPR2023-00790, American Honda Motor Co., Inc. v. Neo Wireless LLC

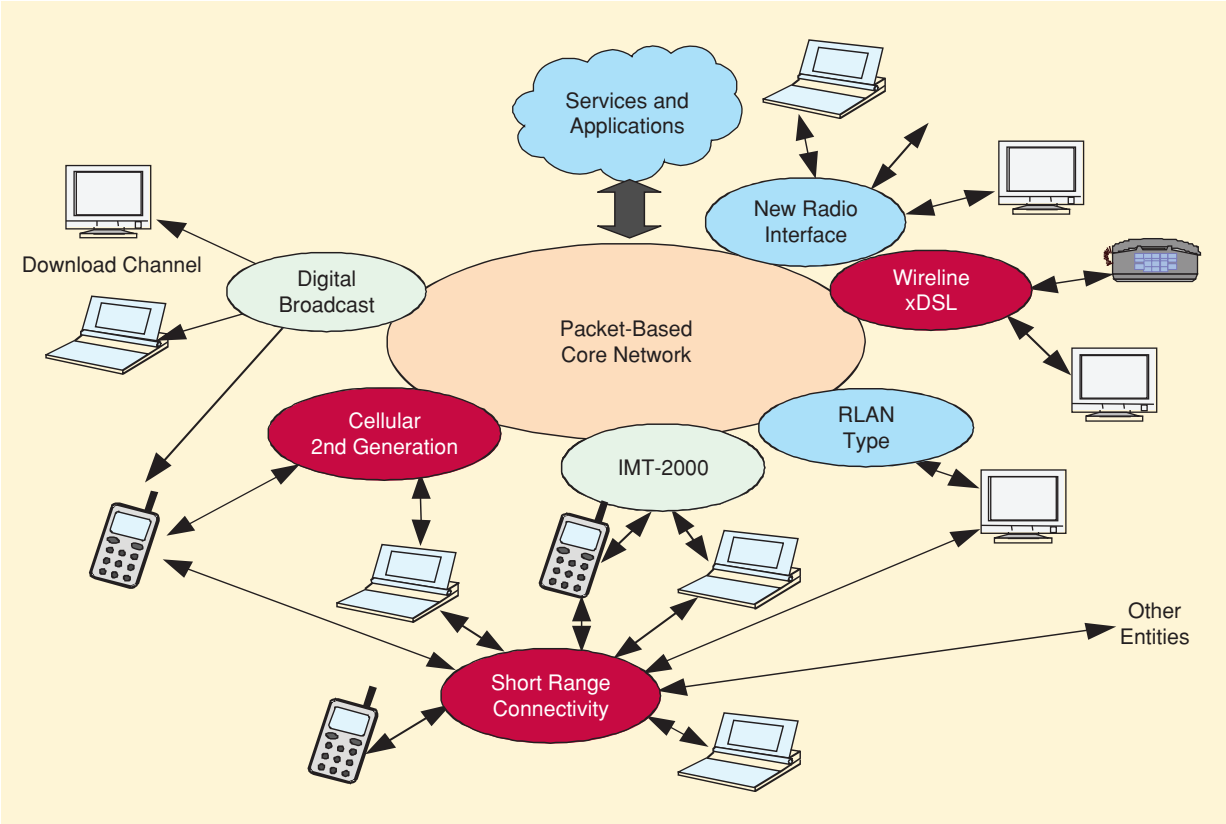

Figure 2. *Future network of systems beyond IMT-2000, including a variety of potential interworking access systems. (This figure originated in Recommendation ITU-R M.1645.)*

became five (IMT-2000 CDMA Direct Spread, IMT-2000 CDMA Multi-Carrier, IMT-2000 CDMA TDD, IMT-2000 TDMA Single-Carrier, and IMT-2000 FDMA/TDMA) in the year 2000. The Recommendation has seen yearly updates due to the fast pace of technology advancements. In 2007, the new sixth radio interface OFDMA TDD WMAN was added, as mentioned above.

As IMT-2000 system deployment began, the participants in the ITU-R work again had a vision for the future. In this case, it was a vision of systems beyond IMT-2000, which were eventually designated "IMT-Advanced." As described in Recommendation ITU-R M.1645, the targets for research for these systems include 100 Mb/s for high mobility and 1 Gb/s for low mobility, for deployment after the year 2010. IMT-Advanced systems are mobile systems that include the new capabilities beyond those of IMT-2000. Such systems provide access to a wide range of telecommunication services, including advanced mobile services supported by mobile and fixed networks which are increasingly packet-based, as illustrated in Figure 2.

The activities in ITU-R towards IMT-Advanced have been summarized graphically in Figure 3. They included the development of technology assumptions, market projections, and a methodology for spectrum calculations, that, when put together and applied, resulted in an estimate for spectrum requirements that was considered by the 2007 World Radiocommunication Conference (WRC-07). WRC identified new spectrum for IMT-2000 and IMT-Advanced, jointly designated "IMT." The new spectrum, as well as the bands previously identified for IMT-2000, are now identified collectively for IMT, rather than separately for IMT-2000 and IMT-Advanced.

Recommendation ITU-R M.1822 addresses the high-level requirements for telecommunication services and applications to be supported by IMT, including the future development of IMT-2000 and IMT-Advanced. It includes service parameters and service classifications of IMT. This Recommendation also includes examples of telecommunication services that may be supported by IMT.

The effort in ITU-R is now directed towards standardization. The principles for the process of development of IMT-Advanced, i.e., the standardization aspects, are covered in Resolution ITU-R 57. This process is similar to the one used for the development of IMT-2000, but improvements are expected based on experience. The details are published in a Circular Letter issued by ITU-R on 7 March 2008 and a Web page with additional information [5]. In summary, the Circular Letter announces that candidate radio interface technologies (RITs) and sets of RITs (SRITs) developed outside ITU-R are to be submitted to the process before October 2009. An RIT needs to fulfill the minimum requirements for at least one test environment.

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An SRIT consists of a number of RITs each individually fulfilling the minimum requirements for at least one test environment and complementing each other. These candidate RITs and SRITs will be evaluated according to specific requirements and evaluation guidelines, which remained under development when the Circular Letter was issued. The results will be discussed in ITU-R. It is expected that, through harmonization and consensus building, a set of radio interfaces will be agreed upon and recommended by early 2011. Then the deployment of IMT-Advanced systems will commence according to market requirements.

IEEE Project 802.16m

Shortly after the completion and publication of the mobile amendment (IEEE Std 802.16e-2005) to IEEE Std 802.16, the ITU-R IMT-Advanced discussions had progressed to the point at which the initial vision and framework were available, particularly through Rec. M.1645. The targets included higher data rates (around 100 Mb/s), improved spectral efficiency, and support for a wide range of multimedia services.

It soon became apparent to members of the IEEE 802.16 community that an enhanced version of IEEE Std 802.16 could satisfy the stated requirements of IMT-Advanced. In 2006, work began within the 802.16 WG to address this possibility. This effort culminated in late 2006 with the authorization of the IEEE 802.16m Project, which has the stated scope of amending the IEEE 802.16 WirelessMAN-OFDMA specification to provide an advanced air interface to meet the cellular layer requirements of IMT-Advanced next-generation mobile networks while providing "continuing support for legacy WirelessMAN-OFDMA equipment." The first official meeting of the 802.16m Task Group (http://wirelessman.org/tgm), which was created to develop the project, occurred in January 2007 in London, where an initial project work plan and approach were agreed upon.

While the ITU-R's view of the IMT-Advanced process timeline has varied over time, the Task Group's view of the 802.16m project schedule has remained mostly independent. The basic intent of the project, and the planned 2009 completion date for the 802.16m amendment, have remained constant.

The 802.16m Task Group has generated a set of system requirements (titled the Systems Requirements Document, or SRD [6]) that in many areas reflects the evolving IMT-Advanced requirements but also includes unique additions of its own. Primary among these additions is a requirement for support for legacy WirelessMAN-OFDMA systems.

The 802.16m Task Group has also developed an extensive evaluation methodology by which alternate technical approaches to meeting the system requirements can be assessed and evaluated. The evaluation methodology document, or EMD [7], as well as the 802.16m SRD have also been used to develop input contributions to ITU-R to assist it in completing its IMT-Advanced technical requirements and evaluation criteria and methodology.

The 802.16m Task Group is pioneering an approach new to the 802.16 WG with its development of a system description document (SDD) before generating the draft standard. The primary purpose of the SDD is to allow alternative technical approaches to be assessed and agreed upon before reviewing the detailed text needed in the draft standard. Development of the SDD is currently ongoing and is expected to be completed by late summer 2008. This document could also serve other purposes. For instance, it could be the centerpiece of an IEEE 802.16-based IMT-Advanced air interface proposal to the ITU-R.

As mentioned previously, one of the key requirements of the 802.16m project is legacy support of WirelessMAN-OFDMA systems. The SRD mandates additional strong and explicit requirements for legacy support, including the following:

- An IEEE 802.16m mobile station (MS) shall be able to operate with a legacy BS, at a level of performance equivalent to that of a legacy MS.

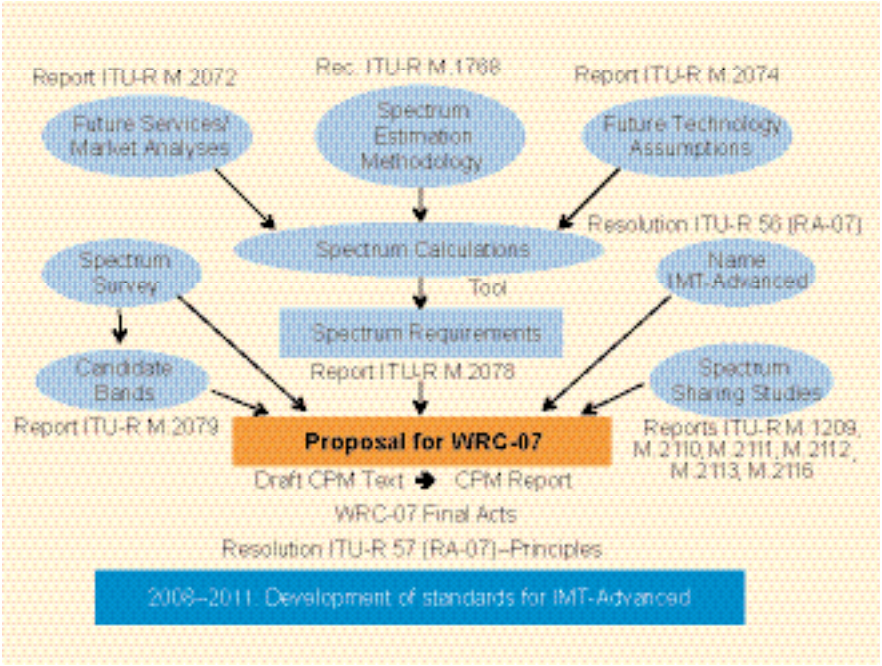

Figure 3. *ITU-R preparations for WRC-07 (Agenda Item 1.4) and RA-07.*

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Beginning in the year 2000, the WG began to develop a new PHY approach for frequencies below 10 GHz.

- Systems based on IEEE 802.16m and the WirelessMAN-OFDMA Reference System shall be able to operate on the same RF carrier, with the same channel bandwidth, and should be able to operate on the same RF carrier with different channel bandwidths.
- An IEEE 802.16m BS shall support a mix of IEEE 802.16m and legacy MSs when both are operating on the same RF carrier. The system performance with such a mix should improve with the fraction of IEEE 802.16m MSs attached to the BS.
- An IEEE 802.16m BS shall support handover of a legacy MS to and from a legacy BS and to and from IEEE 802.16m BS, at a level of performance equivalent to handover between two legacy BSs.
- An IEEE 802.16m BS shall be able to support a legacy MS while also supporting IEEE 802.16m MSs on the same RF carrier, at a level of performance equivalent to that which a legacy BS provides to a legacy MS without sacrificing the performance of the legacy or advanced-mode systems.

Fortunately, the flexibility of WirelessMAN-OFDMA allows for the possibility of satisfying all these requirements. A number of potential approaches are currently under consideration by the 802.16m Task Group as part of the SDD development. Another important current topic within the development of the overall 802.16m architecture is the role of fixed and/or mobile relay stations, particularly as specified in the 802.16j draft.

Generations of Wireless Systems

The mobile industry has usually referred to advances in wireless communications networks in terms of "generations." It is generally understood that analog mobile wireless systems were the "first generation" (1G) of mobile communications systems, initially deployed in the 1980s and only now going into disuse some 25 years later. The second-generation (2G) systems are characterized by the use of digital techniques. These digital systems were first deployed in the 1990s and continue to have a strong presence in the market

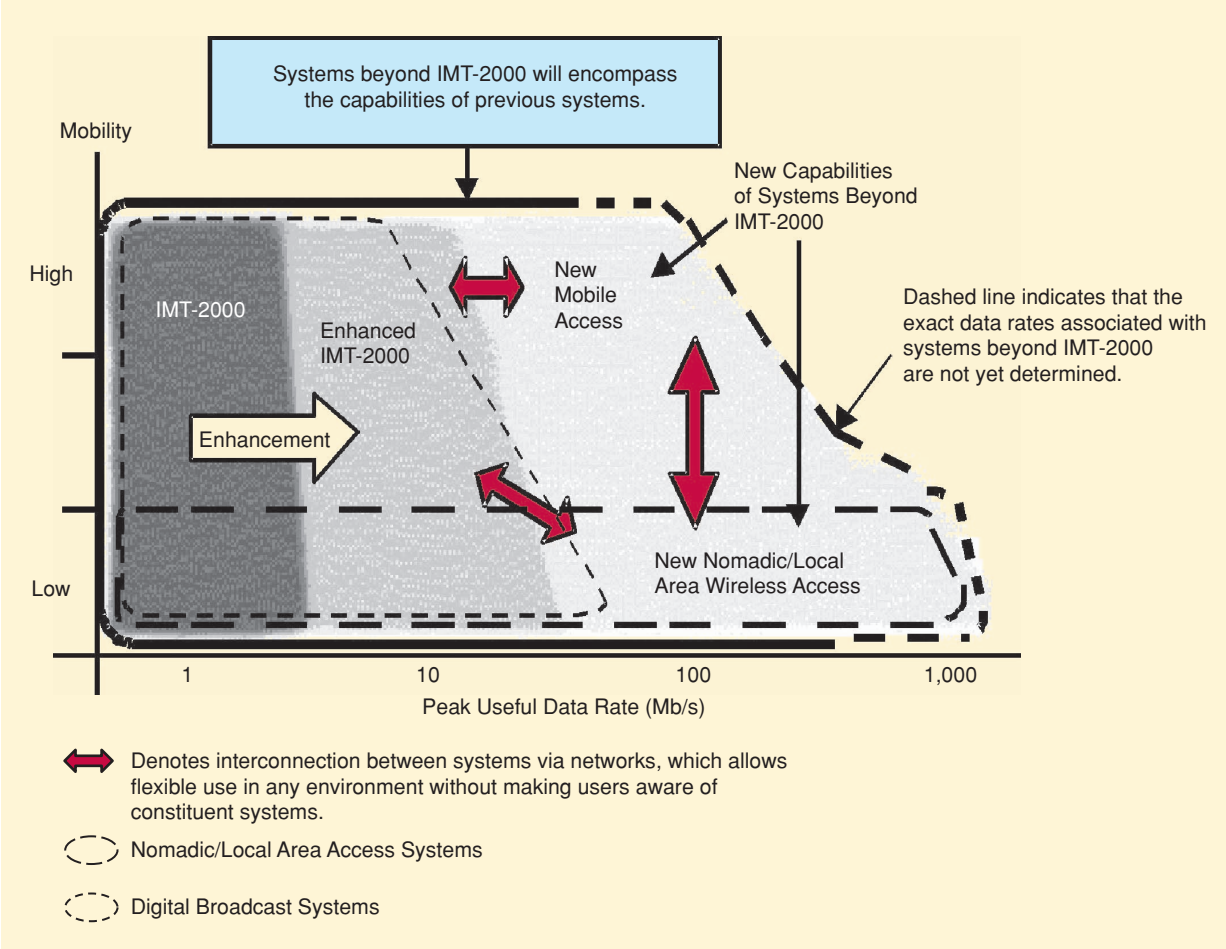

Figure 4. *Illustration of capabilities of IMT-2000 and systems beyond IMT-2000. (This image originated in Recommendation ITU-R M.1645.)*

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today. 1G and 2G systems support voice and low bandwidth data, although some of the 2G systems have continuously been enhanced to provide higher-speed data communications. In fact, some of their capabilities compare well with those of IMT-2000, which are generally considered to be at least 3G systems and are characterized primarily by their extensive broadband data communications and multimedia capabilities in addition to voice.

It has been noted that a new generation of mobile communications systems appears about once every ten years. However, the life of each generation extends much longer than ten years [8]. Moreover, with the increasing flexibility and adaptability of new networks, it is expected that the life expectancy of networks will increase even further.

Since the 3G standards were introduced around the year 2000, using the ten-year model, a new generation is now anticipated. The "van" diagram (Figure 4) in Recommendation ITU-R M.1645 provides a good picture of the evolving capabilities of wireless networks. It should be noted that the system capability boundaries are moving targets and that there cannot be a rigid distinction of capabilities between generations of systems. Therefore, a distinction by capabilities may be neither useful nor possible to distinguish between 3G and fourth-generation (4G) systems. Furthermore, while the authority to define the 3G was, in effect, granted by the community to an ITU committee, the same appears not to be the case with the 4G. It appears instead that technology is coming from the ground up to challenge 3G, and it may no longer be within the power of a single committee to anoint a 4G monarch.

For example, while some are still looking to IMT-Advanced to declare the next generation, new technologies like OFDMA and MIMO have burst forth out of standardization organizations like IEEE 802.16 to define what is a clearly new approach compared to CDMA-based 3G technologies. When Rec. M.1457 adopted 802.16 into its Revision 7, it at the same time accepted 3GPP2's ultra mobile broadband (UMB) proposal and an initial framework description of 3GPP's LTE (long-term evolution), in two different forms. As a result, M.1457 suddenly contained, in Revision 7, six radio interfaces, of which four included OFDMA. This radical change of technologies, broadly supported across a variety of independent standards organizations, seems to represent a turn to a new generation and could be said to mark the start of the fourth. However, we reserve the final judgment to history.

Outlook for IEEE 802.16 Systems

IEEE 802.16 systems are uniquely positioned at the intersection of several crossroads. From the point of view of technology evolution, they offer a quantum jump in capabilities, along with other standardized systems that have incorporated similar component technology advancements (e.g., 3GPP's LTE and 3GPP2's UMB). From the point of view of core network evolution, IEEE 802.16 systems fit perfectly in the trend towards fully packet-based core networks. They also fit uniquely in the trend towards fixed-mobile convergence. Indeed, while many initial fixed wireless access systems were based on mobile wireless access standards, IEEE 802.16 systems were originally designed for fixed applications and have been evolved and optimized for mobile applications. Therefore, they are well adapted for the network infrastructure of the future desired by operators: high spectral efficiency, packet-based, and supporting high-data-rate services and applications for both fixed and mobile users.

Industry is currently investing great effort in the creation of mobile broadband wireless systems based on IEEE 802.16. BSs of many varieties are deployed, and many more are in development. About two dozen companies are developing application-specific intergrated circuit (ASIC) hardware to implement the standard, and subscriber stations in many formats have been demonstrated—small handheld VoIP units and multimedia players, universal serial bus and PC cards, desktop modems, and rooftop-mounted radios. Large deployments are underway or in development throughout Asia, Europe, and the Americas. Thanks to the power of technology and standardization, the world is getting access to new opportunities to stay connected whenever and wherever it may roam.

Acknowledgments

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