Evaluation of 3GPP LTE and IEEE 802.16 as Candidate IMT-Advanced Systems

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***Abstract*—In 2003 the ITU-R published Recommendation M.1645 outlining the ITU's vision for the development of 4G systems. In 2007 the ITU initiated the standardisation of 4G, which they named IMT-Advanced systems. Currently the ITU is inviting interested parties to submit proposals for their mobile communication systems to be considered for inclusion in the IMT-Advanced standard. Two such candidate systems are the 3GPP's LTE standard and the IEEE's 802.16 WiMAX standard. This paper outlines both systems' requirements and architectures and evaluates their potential to meet the requirements specified for IMT-Advanced. Based on the analysis conducted, it was determined that both systems meet the preliminary requirements specified. Future work must be conducted to refine the IMT-Advanced specifications and additional candidate systems need to be investigated to determine their potential to be included in the final version of the standard.**

***Index Terms*—IMT-Advanced, 4G, LTE, 802.16, WiMAX**

I. Introduction

In 2003 the International Telecommunication Union's Radiocommunication Sector (ITU-R) published Recommendation M.1645 [1] outlining the ITU's vision for the development of post IMT-2000 mobile communication systems. At the time this publication was seen as significant as it was the first time any major standards organisation had addressed the growing interest in the development of Fourth Generation (4G) mobile systems.

In 2007, perhaps partly in response to the widespread development of regional and proprietary "4G" mobile systems, the ITU-R initiated the development of a global 4G mobile systems standard and named the standard IMT-Advanced [2]. This first step was followed by the publication of a procedure for the development of the IMT-Advanced standard [3] and discussions at the World Radiocommunication Conference '07 regarding which part of the spectrum would be made available for IMT-Advanced systems [4]. Most recently the ITU-R issued a circular letter inviting interested parties to submit proposals for their candidate mobile communication systems to be included in the IMT-Advanced standard [5]. Based on the work plan issued by the ITU-R, the IMT-Advanced standard should be completed between 2010 and 2011, with initial deployment of IMT-Advanced systems occurring between 2012 and 2015 [1].

This paper examines two candidate IMT-Advanced mobile communication systems, namely the 3GPP's Long Term Evolution (LTE) standard and the IEEE's 802.16 WiMAX standard. The rest of this paper proceeds as follows: Section II provides an outline of the ITU's vision and requirements for IMT-Advanced, Section III and IV examine two candidate IMT-Advanced mobile communication systems, namely the 3GPP's Long Term Evolution (LTE) standard and the IEEE's 802.16 WiMAX standard. Lastly, Section V will compare these two candidate mobile systems against the requirements to be included in the IMT-Advanced standard to determine their suitability as IMT-Advanced systems.

II. IMT-Advanced Vision and Requirements

The ITU's vision for the development of IMT-Advanced systems is outlined in the ITU-R's Recommendation M.1645 [1]. In stark contrast to previous generations of mobile systems, the ITU believes that IMT-Advanced systems should be the result of the convergence and evolution of all existing and evolved wireless and mobile communication systems. It also makes provision for the development of new advanced air-interface systems, which will be capable of providing advanced mobile services that current mobile systems are incapable of supporting. This dual approach has the advantage of allowing network operators to deploy IMT-Advanced air-interface systems when needed, while maintaining their legacy mobile systems to provide traditional services such as Voice, Web browsing and so forth. Figure 1 illustrates the concept of an IMT-Advanced network with a central packet-switched core and numerous access network systems attached, including new IMT-Advanced air-interface technologies.

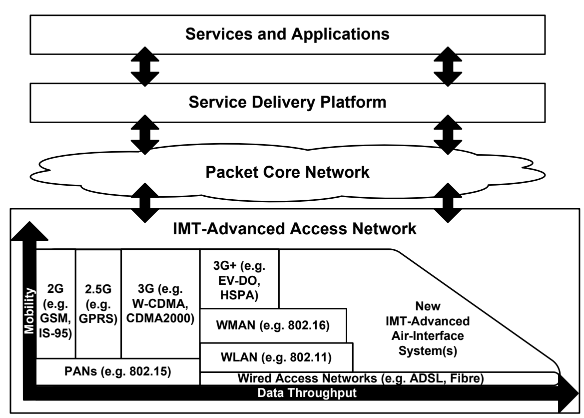

Fig. 1: IMT-Advanced Reference Model (Developed using [1])

In previous generations of mobile network systems each access network technology would traditionally be deployed in a separate network with gateways being used to interconnect the networks. In IMT-Advanced systems a packet-switched core will provide connectivity to a variety of access network systems, a concept inherited from the current trend towards network convergence. Through the use of multiple access network systems (each with different physical characteristics) users will be able to connect to the core network using the type of access network most appropriate to their individual service requirements, geographical location and terminal capabilities. Potential access systems that could be incorporated into an IMT-Advanced network include the traditional cellular mobile systems, wireless networking systems, broadcasting systems, satellite communication systems and even fixed access network systems. This concept is illustrated in Figure 1 where different access network systems are related based on their mobility and throughput characteristics.

While the evolution and integration of existing access networks will provide users with adequate resources for the short term, new and advanced services will continue to be developed which current access systems, or evolved versions of such systems, will be unable to support. Based on this the ITU has developed a basic set of specifications for new types of access network technologies which could be classified as IMT-Advanced air-interface technologies. The requirements for new air-interface technologies include (but are not limited to) increased peak and average throughput rates, efficient use of the frequency spectrum and lower costs for operators and end-users. It is hoped that a more concrete set of specifications for IMT-Advanced air-interface technologies will be published in the near future.

Presently there are a number of regional standards bodies making efforts to develop new radio access technologies based on the IMT-Advanced specifications. Two such systems, the 3GPP's LTE standard and the IEEE's 802.16 WiMAX standard, will be discussed in the following two sections.

III. 3GPP Long Term Evolution (LTE)

The 3rd Generation Partnership Project (3GPP) is a collaborative standards organisation which includes a variety of regional standards bodies. The 3GPP is responsible for the evolution of cellular mobile communication standards from the Second Generation (2G) Global System for Mobile Communications (GSM) standard up to and including the current 3G Universal Mobile Telecommunications Service (UMTS) standard [6]. In 2004 the 3GPP began work on the evolution of the 3GPP UMTS standard to ensure the competitiveness such technologies beyond UMTS enhancements such as High Speed Packet Access (HSPA). This project has been dubbed the Long Term Evolution (LTE) of 3GPP and includes the evolution of the air-interface and the core network architecture [7]. The 3GPP LTE standard is expected to be finalised in early 2009, with network deployment commencing late in 2009 or early in 2010. The requirements for the development of LTE are intended to mirror those of IMT-Advanced and will be discussed in Section III-A and the LTE core architecture and air-interface characteristics will be examined in Section III-B.

A. The 3GPP LTE Requirements

The requirements for the 3GPP LTE project are contained in the 3GPP Technical Specification 25.913 [7] and are summarised as follows [6], [7]:

- *Packetised Traffic:* All data transmitted is viewed as packetised data.
- *Multi-Traffic QoS Support:* Support must be provided for a variety of different forms of traffic each with their own Quality of Service (QoS) requirements.
- *Increased Throughput:* A peak downlink rate of 100 Mb/s within 20 MHz of spectrum and a peak uplink rate of 50 Mb/s within 20 MHz of spectrum must be supported. An increase on the data rate available at the edge of cells is also required.
- *Increased Spectral Efficiency:* An increased spectral efficiency of 3-4 times that of HSDPA for the downlink and 2-3 times that of HSUPA for the uplink is required.
- *Lower Latency:* A maximum of 10 ms latency is permissible for user data and 100 ms for access-core signalling traffic.
- *Faster Terminal State Transition:* Terminal transition from an Idle to an Active state should take a maximum of 100 ms and transition from Standby to an Active state should take a maximum of 50 ms.
- *High Mobility:* The 3GPP LTE system will be provide maximum throughput and spectral efficiency when the terminal travels at a speed not exceeding 15 km/h. Speeds in excess of 15 km/h will result in increasingly lower levels of performance.
- *Flexible Bandwidth Allocation:* To allow network operators to determine the amount of spectrum they require within a single cell, the evolved air-interface will support a variety of flexible bandwidth allocation schemes in paired and unpaired spectrum. The schemes are: 1.25, 2.5, 5, 10, 15 or 20 MHz.
- *Wide Coverage:* The evolved air-interface will provide maximum throughput and spectral efficiency when the cell radius does not exceed 5 km. Cells with radii in excess of 5 km will result in increasingly lower levels of performance.
- *Low Cost:* The deployment and operational costs of core system, air-interface and terminals must be minimised.
- *Efficient Radio Resource Management:* Allocation of radio resources must be made based on a user's specific requirement so that more efficient management of such resources is achieved.
- *Backwards Compatibility:* The 3GPP LTE system must be capable of handover to legacy 3GPP systems with a maximum handover time of 300 ms for real time services and 500 ms for non-real time services.
- *Interworking with Other Access Systems:* Provision must be made to connect the evolved core network to other access systems such as the IEEE's 802.11 WiFi and 802.16 WiMAX systems and legacy systems such as the PSTN.

B. Overview of the 3GPP LTE Architecture

The 3GPP LTE architecture consists of two parts, the evolved access network, referred to as the Evolved UTRAN (eUTRAN), and the evolved core network, referred to as the Evolved Packet Core (EPC) [6], [8], [9]. The 3GPP LTE architecture and these two parts are illustrated in Figure 2. Within the eUTRAN and EPC there exist a number of logical network elements connected by means of interfaces. Operational and management functions performed within the network are grouped within these network elements. The interfaces represent the flow of signalling and user data between the network elements. The following sections will outline the functions performed within the eUMTS and EPC network elements:

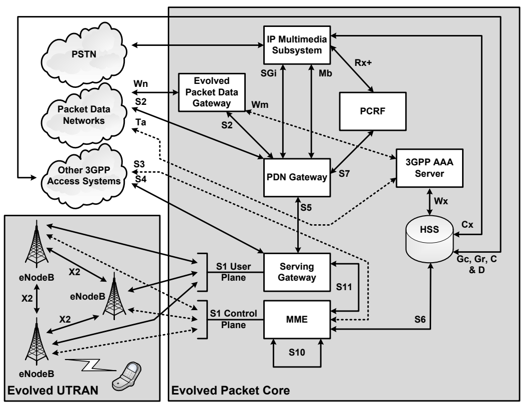

Fig. 2: The 3GPP LTE Architecture [6], [8], [9]

1) Evolved UTRAN: The eUTRAN is the evolved access network in the 3GPP LTE system [6], [8]. In 3GPP LTE there is now only one network element in the eUTRAN namely the eNodeB. The eNodeB supports all Physical and Data Link Layer functions used to connect terminals to the network, including: modulation, channel coding, radio bearer management, radio resource control including QoS control, mobility management including handover decisions, detection of errors using Hybrid Automatic Retransmission Request (HARQ), IP header compression and encryption [6], [8], [10]. The X2 meshed interface allows multiple eNodeBs to convey user data between one another during handover thereby minimising packet loss [6], [8]. Table I lists the physical layer parameters for the 3GPP LTE air-interface housed within the eNodeB.

The eNodeB communicates with the EPC using the S1 interface. The interface is broken into two components, the S1 User Plane and the S1 Control Plane. The S1 User Plane connects the eNodeB to the Serving Gateway and conveys user data and application layer signalling information to the evolved core network [6], [8]. The S1 Control Plane connects the eNodeB to the Mobility Management Entity (MME) and conveys access-core signalling information relating to subscriber and session management. The eNodeB is also responsible for selecting which MME will be used to establish the terminal-network session.

TABLE I: Physical parameters of the 3GPP LTE air-interface [6], [10]

Properties	Parameters	
Throughput	Downlink:	100 Mb/s in 20 MHz band
	Uplink:	50 Mb/s in 20 MHz band
Multiple Access Scheme	Downlink:	OFDMA
	Uplink:	SC-FDMA
Cyclic Prefix	Short for Small Cells:	5.21 µs
	Long for Large Cells:	16.67 µs
Duplexing	FDD or TDD in paired and unpaired spectrum	
Transmission Bandwidth	1.25, 2.25, 5, 10, 15 or 20 MHz	
Subcarrier Spacing	15 kHz or 24 kHz	
Modulation	QPSK, 16-QAM or 64-QAM	
Channel Coding	Turbo Coding R = 1/3, two 8 state constituent encoders and a contention-free quadratic permutation polynomial (QPP) turbo code internal interleaver	
No. Antennae	eNodeB:	2 normally, however a maximum of 4 are possible
	Terminal:	2 normally, however a maximum of 4 are possible
MIMO Scheme	Spatial Diversity or Spatial Multiplexing in Closed or Open Loop	
Radio Frame Duration	10 ms	
Subframe Duration	1 ms	

2) Evolved Packet Core: The EPC consists of a number of network elements responsible for the management of various network functions. Each of these network elements and their responsibilities are briefly discussed below [6], [8], [9]:

- *Mobility Management Entity (MME):* The Mobility Management Entity (MME) contains all functionality relating to subscriber and session management. The MME initiates Non Access Stratum (NAS) signalling between itself and the terminal to allow network attachment and session setup. The MME connects to the Home Subscriber Server (HSS) allowing it to access subscriber information and decides which Serving Gateway and Packet Data Network (PDN) Gateway to use for session establishment. The MME's responsibilities also extend to end-user authentication, encryption, idle terminal location management and handover from the EPC to other networks or other MMEs.
- *Serving Gateway:* The Serving Gateway is the termination point for all user sessions between the terminal and LTE network. It is responsible for routing user data and application level signalling information between the eUTRAN and EPC and will buffer packets destined for a terminal until a session has been established. Lastly, the Serving Gateway minimises errors that could occur in the handover of user sessions from the LTE network to other access systems through buffering and forwarding of user data.
- *Packet Data Network (PDN) Gateway:* The Packet Data Network (PDN) Gateway is the network element responsible for interconnection between the LTE network and other packet-switched networks such as the IEEE's 802.11 WiFi and 802.16 WiMAX systems. The PDN Gateway is the termination point for all user sessions between the LTE network and terminals in the packet-switched network. Functions performed by the PDN Gateway include routing of packets between the EPC

and PDN, assigning IP addresses for PDN terminals, LTE network operator policy enforcement, packet filtering and charging support based on information supplied by the Policy and Charging Rules Function (PCRF).

- *Policy and Charging Rules Function (PCRF):* The Policy and Charging Rules Function (PCRF) is responsible, based on rules established by the network operator, for making and enforcing policy and charging decisions. This information is then conveyed to the network elements using the most appropriate interface. The PCRF is a combination of the traditional Policy Decision Function (PDF) and Charging Rules Function (CRF) seen in previous 3GPP networks.
- *3GPP AAA Server:* The 3GPP Authentication, Authorization and Accounting (AAA) Server supports end-to-end authentication when a terminal in a Packet Data Network (PDN) is establishing a session with a terminal in the LTE network. The 3GPP AAA Server accesses the Home Subscriber Server (HSS) to retrieve user related subscription information and 3GPP authentication vectors.
- *Evolved Packet Data Gateway (ePDG):* In the event that a terminal in a non-trusted packet data network attempts to access the LTE network, the Evolved Packet Data Gateway (ePDG) establishes a secure tunnel with that terminal using IP Security Protocols (IPSec) and filters unauthorised traffic. The connection is then forwarded to the PDN Gateway.
- *Home Subscriber Server (HSS):* The Home Subscriber Server (HSS) is a concatenation of the Home Location Register (HLR) and the Authentication Centre (AuC) in older 3GPP systems. The HSS is a database that contains all user subscription information and generates security information from user identity keys.
- *IP Multimedia Subsystem (IMS):* The IP Multimedia Subsystem (IMS) is a signalling system used to indirectly establish application level sessions between network application servers and terminals. It is standardised by the 3GPP and contains several network elements outside the scope of this paper. Most importantly, it contains the Media Gateway used to connect the LTE EPC to the legacy PSTN.

IV. Mobile and Evolved WiMAX

The Institute for Electrical and Electronic Engineers (IEEE) is responsible for the standardisation of a large number of networking systems and protocols, including Ethernet, Bluetooth and WiFi. In 2001 the IEEE's 802.16 working group produced a standard for a Wireless Metropolitan Area Network (WMAN) system which it named the Worldwide Interoperability for Microwave Access or WiMAX. The WiMAX standard has evolved significantly from its initial form by means of amendments to the original standard. The present version of the WiMAX standard (802.16e) supports full mobility including handover between base stations, radio resource management and various security protocols [11].

The WiMAX Forum is a non-profit organisation formed by interested companies to promote the WiMAX standard and certify equipment as interoperable. As the IEEE's 802.16 working group specified only the Physical and MAC Layers in the standard, the WiMAX Forum has produced an end-to-end network architecture for WiMAX [12]. This architecture is generic and is viewed as an extension of the IEEE's 802.16 WiMAX standard.

In 2007 the ITU announced that WiMAX would be included in the IMT-2000 standard as an official 3G system [13]. Prior to this event many network operators were trying to determine whether WiMAX systems competed with traditional cellular systems or if they complemented them. As a result of the inclusion of WiMAX within the IMT-2000 standard, it has become clear that evolved versions of WiMAX will compete for inclusion in the IMT-Advanced standard.

Presently, the WiMAX standard is not capable of meeting the requirements outlined in Recommendation M.1645 and therefore is not IMT-Advanced compliant. The IEEE has taken steps to evolve the WiMAX standard to meet IMT-Advanced requirements through the creation of the 802.16m amendment [14]. As the standardisation of 802.16m is still in the early draft stages, the final architecture cannot be evaluated for IMT-Advanced compliance at this time. However, as the 802.16m will evolve from the 802.16e version of the WiMAX standard it is possible to use the current architecture as a reference model. Section IV-A will provide an overview of the current WiMAX architecture and Section IV-B will look at the IEEE's requirements for the development of 802.16m.

A. Mobile WiMAX (802.16e)

The WiMAX network architecture [12] contains three main components representing the different business models which a company may use when deploying WiMAX systems. Each component has a role to play in the architecture and contains a network responsible for performing specific functions. Components are connected by means of interfaces representing the flow of user data and signalling information. These three components, and the functions performed by each, are described in the sections that follow. Figure 3 illustrates the WiMAX network architecture.

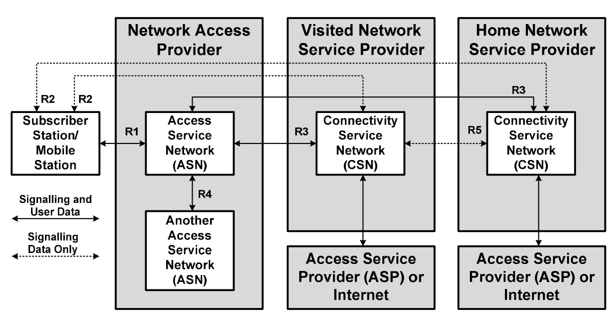

Fig. 3: The WiMAX Forum's WiMAX Network Architecture [12]

1) Network Access Provider (NAP): The Network Access Provider (NAP) is a business entity which provides WiMAX access network systems to one or more Network Service Providers. A NAP provides WiMAX access network systems through the creation of one or more Access Service Networks (ASN). An ASN contains one or more WiMAX base stations and one or more ASN Gateways. The ASN provides all Physical and MAC Layer functionality including: modulation, coding, radio bearer management, radio resource management, mobility management and transmission of messages to the NSP for Authentication, Authorisation and Accounting purposes.

Table II lists the physical layer parameters for the 802.16e air-interface housed within a WiMAX base station. It is interesting to note that while the 802.16e standard does not meet the IMT-Advanced air-interface requirements, its current performance parameters far exceed those of current and evolved 3G systems. This means that deployed WiMAX systems are far closer to meeting the requirements IMT-Advanced than both deployed and evolved 3G systems.

TABLE II: Physical parameters of the 802.16e air-interface [11]

Properties	Parameters	
Throughput	Downlink:	46 Mb/s in 10 MHz band
	Uplink:	32 Mb/s in 10 MHz band
Multiple Access Scheme	Downlink:	OFDMA
	Uplink:	OFDMA
Cyclic Prefix	10.4 μs	
Duplexing	TDD	
Transmission Bandwidth	5, 7, 8.75 or 10 MHz	
Subcarrier Spacing	10.94 kHz	
Modulation	QPSK, 16QAM or 64QAM	
Channel Coding	Convolutional Coding or Turbo Coding	
No. Antennae	Base Station:	Maximum of 2
	Terminal:	Maximum of 2
MIMO Scheme	Spatial Diversity or Spatial Multiplexing	
Radio Frame Duration	5 ms	

2) Network Service Provider (NSP): The Network Service Provider (NSP) is a business entity that provides IP connectivity and WiMAX services to subscribers by making use of a NAP. The NSP will sign a contractual agreement with one or more NAP and will interconnect with other NSPs. A subscriber will sign a contractual agreement with a NSP which will be regarded as that subscriber's Home NSP. If a subscriber is roaming on another NSP's network, the Visited NSP will access the subscriber's information from the Home NSP. A NSP is also capable of interconnecting to other network systems, such as the 3GPP's LTE standard.

A NSP provides IP connectivity and WiMAX services through the creation of one or more Connectivity Service Networks (CSN). A CSN is responsible for all core network-related functions, including: issuing IP addresses to terminals, providing access to the Internet or other networks via interworking gateways, storing all subscriber information in database systems, policy enforcement, billing functions, and handling Authorisation, Authentication and Accounting systems.

3) Access Service Provider (ASP): An Access Service Provider (ASP) is the simplest business entity within the WiMAX network architecture and is responsible for providing applications or services to subscribers by means of the Home or Visitor NSP.

B. Requirements for 802.16m

The requirements for the development of the 802.16m amendment for WiMAX were published by the IEEE's 802.16 working group in 2007 [14]. The requirements for 802.16m are specifically tailored to meet the requirements for IMT-Advanced, but the 802.16 working group has stated that they only plan to enhance those components of the WiMAX standard that currently do not meet the IMT-Advanced requirements. Based on the current working plan, the 802.16 working group should publish the final standard in the latter half of 2009, with early equipment deployment starting in 2010. The following list summarises the requirements for 802.16m [14]:

- *Multi-Traffic QoS Support:* Support must be provided for a variety of different forms of traffic each with their own Quality of Service (QoS) requirements.
- *Increased Spectral Efficiency:* The peak spectral efficiency target for a cell's downlink is 15 bits/sec/Hz when making use of a 4x4 MIMO antennae configuration and 5.6 bits/sec/Hz for a cell's uplink when making use of a 2x4 MIMO antennae configuration.
- *Lower Latency:* A maximum of 10 ms latency is permissible for user data steams.
- *Faster Terminal State Transition:* Transition from any terminal state to another may take a maximum of 100 ms.
- *High Mobility:* The 802.16m system will provide maximum throughput and spectral efficiency when the terminal travels at a speed not exceeding 10 km/h. Speeds in excess of 10 km/h will result in increasingly lower levels of performance.
- *Flexible Bandwidth Allocation:* To allow network operators to determine the amount of spectrum they require within a single cell, the 802.16m standard will support a variable bandwidth allocation between 5 and 20 MHz in paired and unpaired spectrum.
- *Wide Coverage:* The 802.16 base station will provide maximum throughput and spectral efficiency when the cell radius does not exceed 5 km. Cells that exceed a coverage radius of 5 km will decrease the performance of the system.
- *Backwards Compatibility:* The 802.16m system must be capable of supporting legacy 802.16 systems, however this functionality can be overridden at the network operator's discretion.
- *Interworking with Other Access Systems:* All 802.16m systems must coexist and interwork with other IMT-Advanced systems and IMT-2000 systems.

V. Evaluation of 3GPP LTE and IEEE 802.16 as Candidate IMT-Advanced Systems

Both the 3GPP's LTE standard and the IEEE's 802.16m standard are being developed for the purposes of meeting

IMT-Advanced requirements and being included in the IMT-Advanced standard. At this stage in the development of IMT-Advanced it is useful to examine these two candidate systems to determine their suitability to be classified as IMT-Advanced and hence 4G systems.

The requirements for IMT-Advanced outlined in Section II described two main criteria for development of 4G systems, namely the convergence and evolution of existing systems and the creation of new advanced air-interfaces. The following two sections will examine if the two candidate systems are capable of meeting these criteria.

A. Convergence of Existing and Evolved Access Network Systems

A single converged network with multiple access network systems is viewed as a requirement for IMT-Advanced based on Recommendation M.1645. The 3GPP's LTE standard and the WiMAX Forum's WiMAX Network Architecture make provision for handover and interconnection between themselves and other access network standards using functions contained within their respective core networks. While this may not entirely meet the model proposed by the ITU, it does allow subscribers to obtain access to services from multiple different access network systems. It will probably be up to the network operators to simplify subscribers' experiences by signing interworking contractual agreements with various service providers.

Currently the 3GPP's LTE core network is thoroughly defined compared to the generic WiMAX Forum network architecture. This has the disadvantage that network operators wishing to deploy LTE systems will need to replace their entire core network. In contrast network operators that have already deployed WiMAX networks should only require minimal adjustments to their core networks as the 802.16m standard involves an amendment to the Physical and MAC Layers only. This difference perhaps makes the WiMAX Forum's WiMAX network architecture standard better positioned to meet the requirements for IMT-Advanced.

B. Development of New Air-Interface Systems

The development of new air-interface systems designed to provide advanced services that current systems are unable to support is a key requirement for IMT-Advanced systems. Currently the basic requirements provided in Recommendation M.1645 are the only publicly available specifications for new IMT-Advanced air-interface systems. Currently both the 3GPP LTE's eUTRAN and the IEEE's 802.16m amendment should ensure that both systems meet these specifications based on their respective standards documentation. The only advantage the 3GPP LTE standard enjoys relative to the IEEE's 802.16 standard is that based on current working plans the 3GPP LTE standard should be finalised and therefore deployed at an earlier stage.

VI. Conclusion

The requirements for the development of IMT-Advanced systems include the two main criteria, namely the convergence and integration of existing and evolved access network systems using a single packet-switched core network, and the development of new advanced air-interface systems capable of providing access to advanced services which current systems are unable to support. The 3GPP's LTE standard and the IEEE's 802.16 standard are two systems whose requirements largely match those specified in the ITU-R's Recommendation M.1645, and which should therefore be capable of becoming IMT-Advanced systems. Both systems are capable of providing access to multiple access network systems and both systems should provide access to advanced services that current systems are unable to support. Future work needs to be conducted to further refine the specifications outlined in Recommendation M.1645 and additional access network standards need to be investigated to determine their suitability as IMT-Advanced systems.

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Biographies

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