IPTV over WiMAX with MIPv6 Handovers

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***Abstract*—As the IPv4 unallocated address pool nears exhaustion, an increasing number of IPv6 deployments is anticipated. In the domain of mobility management research and development, Mobile IPv6 has long been favored over Mobile IPv4. Nevertheless, although in principle WiMAX supports IPv6 in various configurations and requires MIPv6 for network-level mobility management, in practice, vendors are actively deploying these capabilities only in part. This paper provides a thorough review of the role of IPv6 and MIPv6 in WiMAX networks, surveying the work in relevant standardization bodies. The second contribution of this paper is a testbed evaluation of IPTV streaming over WiMAX. We employ two WiMAX testbeds deployed in Finland and Portugal, interconnected by GÉANT and quantify MIPv6 performance in a real-time multimedia streaming scenario over WiMAX. Beyond demonstrating the feasibility of such a deployment, our results indicate that WiMAX can provide a viable option as both access and backhauling technology.**

I. Introduction

As both fixed and mobile WiMAX network are deployed and user equipment become available in larger scales, there is an increasing interest in measuring the real-world performance of state-of-the-art IEEE 802.16 equipment in different scenarios and under various data traffic conditions. In particular, as an increasing proportion of the Internet traffic is multimedia-related, use cases that involve content dissemination are of high interest. In addition to pure WiMAX networks, converged, heterogeneous access network deployments which employ WiMAX cells as building blocks of their infrastructure are also to be expected. For example, the city of Oulu in co-operation with local research institutes, Internet service providers, and equipment manufacturers will start to provide a freely accessible public mobile WiMAX network which will extend the existing city-wide panOULU Wi-Fi network [1].

One of the most relevant multimedia applications in this respect is video streaming, in particular TV over IP (IPTV) and Video on Demand (VoD), which is expected to rapidly grow during the coming years as the emerging 4G wireless access technologies will enable high quality video reception using mobile handheld devices. Bandwidth-demanding multimedia applications will also benefit from overlay network architectures which adopt anycasting and content-replication methods and allow users to retrieve the "closest" replica of a given object. This, however, calls for multiaccess user equipment capable of performing inter-technology handovers (HO) between separate subnetworks that use different access technologies. This, in turn, requires IP mobility management operations, which impose further requirements on the involved network elements and architecture.

If a Mobile Node (MN) employs multiple network interfaces for inter-technology handovers using Mobile IP (MIP), each interface must be configured with a separate IP address. The diminishing IPv4 address space is expected to be exhausted in a few years [2] and the anticipated transition to IPv6 [3] and MIPv6 [4] appears as an urgent necessity rather than an alternative. The demand for both analytical and empirical studies of IPv6-based WiMAX deployments is evident, but only the former abound. Empirical studies are not that common.

By observing a gap in the scope of publicly available results related to the previously mentioned topics, this paper strives to provide contributions on three different fronts. Firstly, the ongoing specification work on IPv6 over WiMAX is reviewed and the solutions provided by the Internet Engineering Task Force (IETF) and WiMAX Forum are scrutinized. Secondly, inter-technology HOs between WiMAX and Wi-Fi are performed during IPTV streaming and problems arising from the usage of suboptimally configured underlay networks are observed in the process. Thirdly, and to the best of our knowledge, this study presents the first empirical evaluation for a bandwidth-intensive and time-sensitive usage scenario over an unmanaged backbone network with WiMAX as the access technology at both ends of the path. We present results from video streaming over two WiMAX testbeds located in Finland and Portugal and inter-connected with the Pan-European Gigabit Research Network (GÉANT).

The rest of the paper is organized as follows. Section II reviews the work done by IETF and WiMAX Forum on IPv6 and MIPv6 over WiMAX. Section III presents our empirical evaluation of an end-to-end video streaming use case and MIPv6 HOs. Relevant related work is presented and discussed in Section IV. Lastly, Section V concludes the paper.

II. IPv6 and MIPv6 over WiMAX

Deploying IPv6 over WiMAX networks requires that the essential PHY and MAC layer features of IEEE 802.16 standards are taken into consideration. The connection-oriented point-to-multipoint nature of the technology, along with the downlink-only native multicast support, inflicts problems into some of the core IPv6 features which rely on bi-directional multicasting. WiMAX deployments with different MAC Convergence Sublayer (CS) configurations are also complicating things as the lower protocol layers are defined with varying capabilities. The WiMAX Forum end-to-end WiMAX network model [5] extends the transport connections from the radio interface to the network layer, which calls for concrete standardization.

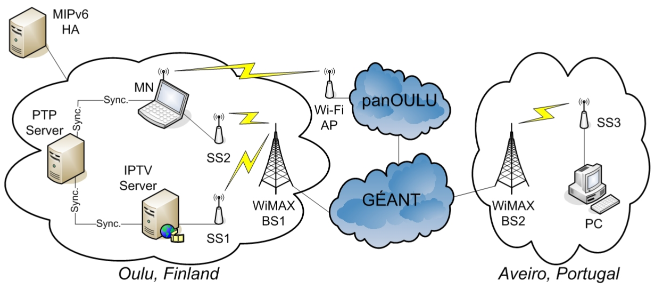

Fig. 1. Testbed topology

WiMAX networks are fully IP-based. Consequently, IETF working groups have released Request For Comments (RFC) that deal with the difficulties of IPv6 and MIPv6 operation over networks based on IEEE 802.16 standards. For example, Shin *et al.* [6] discuss the components of WiMAX access networks based on IPv6 and list the differences with IPv4 deployments. In addition, the fixed and mobile WiMAX deployment scenarios are reviewed in detail. Three different link models for operating IPv6 in IEEE 802.16 networks are presented in [7] and analyzed for their suitability in different deployment scenarios. The options presented are point-to-point, Ethernet-like, and shared IPv6 prefix link models. In addition, Jee *et al.* [8] discuss common problems encountered when operating IP over IEEE 802.16 systems with different CS configurations and provide example IP subnet models which can be used in conjunction with the IP and Ethernet CSs.

Patil *et al.* complement the aforementioned RFCs in [9] by specifying addressing schemes and operations related to the usage of IPv6 over the IPv6-specific CS. The proposed solution to some key problems in such deployments is the assignment of unique IPv6 prefix to each WiMAX Subscriber Station (SS) or Mobile Station (MS) which effectively places each terminal into a separate subnetwork. All SSs and MSs can then use multiple IPv6 addresses under their individual subnetwork prefixes. Jeon *et al.* [10] provide recommendations for IPv4 and IPv6 operation over the Ethernet CS. The Ethernet network model for IEEE 802.16-based deployments is presented and some means for performance enhancements are also provided. At the time of this writing, however, [10] is still an Internet Draft and must be considered work in progress.

Mobile IP is the network layer mobility enabler in WiMAX systems and so the performance of MIPv6 in IEEE 802.16e networks is also under study within the IETF. For instance, as Fast MIPv6 (FMIPv6) [11] enables seamless handovers at the network layer, Jang *et al.* [12] present how the necessary triggers required in FMIPv6 operation are defined using the PHY and MAC layer indicators of IEEE 802.16e.

The WiMAX Forum reference network architecture [5], [13] specifies how the IETF recommendations should be implemented in a WiMAX network. It provides an end-to-end WiMAX network solution which specifies the locations and tasks for the essential network elements. By dividing the network into three operational entities and defining dedicated interfaces between them, through which the communication of different protocols and standards is specified, the WiMAX Forum reference network architecture provides a foundation that enables service providers to deploy WiMAX networks configured according to different needs. Clearly, there is significant effort towards specifications for optimizing the operation of several IETF protocols over pure WiMAX networks, but there is less attention to MIPv6 performance over heterogeneous Wi-Fi/WiMAX networks. The following section considers the performance of MIPv6 in a converged network which employs WiMAX as well as other access technologies.

TABLE I
TESTBED CONFIGURATION

	WiMAX	Wi-Fi
Standard	IEEE 802.16-2004	IEEE 802.11-2007
PHY layer	256 OFDM FDD	DSSS CSMA/CA
Frequency band	3.5 GHz	2.4 GHz
Channel bandwidth	3.5 MHz	22 MHz
Modulation / coding	64 QAM / 3/4 FEC	DQPSK / CCK
MAC scheduling	Best effort	

III. Empirical Evaluation

We evaluate IPTV streaming over WiMAX using two separate testbeds equipped with hardware compliant with the IEEE 802.16-2004 standard [14]. The first testbed is located at VTT in Oulu, Finland and uses AirSpan WiMAX equipment. The MN receiving the IPTV content is a GNU/Linux (Ubuntu 7.04, kernel ver. 2.6.23.1) laptop with UMIP-0.4 [15] protocol stack extensions and has two network interfaces (Wi-Fi and WiMAX). The test network at VTT acts as a Home Network (HN) for the MN and contains the its MIPv6 Home Agent (HA). The public panOULU Wi-Fi network acts as a Foreign Network (FN) for the MN. The second testbed is located at Portugal Telecom Inovação (PTIn) in Aveiro, Portugal and uses Redline fixed WiMAX equipment.

The WiMAX equipment used in the measurements employ the Ethernet CS in their MAC configuration. IPv6 and MIPv6 packets are hence encapsulated into Ethernet frames before traversing a WiMAX link. The testbeds are interconnected by GÉANT and the regional University and research networks in Finland and Portugal, respectively, and have native end-to-end IPv6 support. The testbed architecture is shown in Fig. 1 while equipment configuration details are given in Table I. The maximum IPv4 goodput of the WiMAX system in the Oulu testbed is 9.4 Mb/s and 5.5 Mb/s in downlink and uplink respectively. The Aveiro testbed recorded a goodput of 5.8 Mb/s in the downlink. More information about the testbeds can be found in [16]–[18].

Two IPTV streams with H.264/AVC-encoded video [19] and MPEG-1 Audio Layer II encoded audio [20] are simultaneously transmitted over the SS1-BS1 WiMAX uplink using the open source Darwin Streaming Server (DSS) [21]. The IPTV stream is received by two VideoLAN Client (VLC) [22] media players. One receiving VLC application runs in the MN residing in the same WiMAX cell as the DSS (see Fig. 1). The second client is located in the WiMAX cell of the Aveiro testbed. The Precision Time Protocol (PTP) implementation PTPd [23] is used to synchronize the hosts in the Oulu testbed, enabling the accurate measurement of the disconnection periods during the MIPv6 handovers.

We experiment with two IPTV data rates that roughly correspond to target rates for different types of receiving hosts. The video data rate of 512 kb/s could be used with handheld mobile devices, such as Internet tablets, which have small integrated screens; the data rate of 1024 kb/s could be used with compact laptops. The audio data rate is kept constant at 192 kb/s for both video data rates. As the actual IPTV content transmitted from the server is a combination of the video and the audio, the average IPTV data rate with 512 kb/s variable bitrate video was measured to be approximately 780 kb/s in the HO tests and 796 kb/s in the end-to-end streaming tests. For the 1024 kb/s video, the average transmitted IPTV data rates were nearly 1215 kb/s in the HO tests and 1300 kb/s in the end-to-end streaming tests. As separate IPTV streams are delivered to the two clients over the SS1-BS1 WiMAX uplink, the maximum aggregated data rate transmitted from the server remains around 2.6 Mb/s which is less than the measured uplink capacity of the system as reported in [17].

As the DSS is connected to the Oulu testbed through WiMAX SS1, the path to both receiving clients includes two WiMAX links. The average link latency of the WiMAX equipment in Oulu was measured to be 23.5 ms in the uplink and 8.7 ms in the downlink. This translates into one-way end-to-end delays in the order of 40-50 ms when the MN is connected to its HN. The inter-technology HO from the HN to the FN replaces the BS1-SS2 WiMAX downlink in the last leg of the path with a Wi-Fi link. The average Wi-Fi link latency is lower than in the WiMAX downlink and decreases the one-way end-to-end delay to 20-30 ms. The one-way end-to-end delay of the network path from the DSS to the IPTV client in Aveiro was estimated to be in the order of 70-90 ms.

A. WiMAX - Wi-Fi MIPv6 Handovers

The MN in the Oulu testbed was forced to perform two HOs from the HN to the FN and back while receiving a continuous IPTV packet stream. The MN connects to its HN through the SS2-BS1 WiMAX link and to the FN through a Wi-Fi Access Point (AP). The first HO from the HN to the FN is performed without prior knowledge of the target network. After a HO back to the HN, another HO to the same FN is triggered. This time, however, the MN has a valid address binding between its Home Address (HoA) and the FN Care-of-address (CoA) in its Binding Update (BU) list. The MN can thus use the address configuration done during the first HO from the HN to the FN, which speeds up the third HO process considerably.

HOs between the networks are triggered by plugging and unplugging SS2 from the MN. This emulates a situation where the WiMAX link suddenly comes up or goes down. The Wi-Fi link between the MS and the FN is constantly up, as would be the case in mobile devices following the Always Best Connected (ABC) paradigm. However, as the MN is configured to prefer the HN over the FN, the MN connects to its HN every time the home link is up and uses the FN as a fall-back. This reduces HO latency from the FN to the HN as the MN is always connected to either of the two networks during HO execution.

TABLE II
MIPv6 HANDOVER LATENCIES

	Mean IPTV Rate	1^{st} HO	2^{nd} HO
Transition from WiMAX to Wi-Fi (HN ⇒ FN)	780 kb/s	31.98 s	9.13 s
	1215 kb/s	53.37 s	1.27 s
Transition from Wi-Fi to WiMAX (FN ⇒ HN)	780 kb/s	0.112 s	0.144 s
	1215 kb/s	0.134 s	0.114 s

The measured HO latencies, i.e. disconnetion times, are presented in Table II. In the beginning of the each test run, the MN is connected to its HN and we find that the first HO to the FN takes tens of seconds in each case. When SS2 is unplugged from the MN without any indication before the first HO from the HN to the FN, and activity is no longer detected at the home link, the MN waits for a router advertisement from the FN. After receiving the required FN information, the MN can start the MIPv6 address configuration processes, after which traffic can be received through the FN. As the public panOULU Wi-Fi network is not configured to support MNs, the router advertisement sending interval at the routers is large and the consequent HO latencies are excessive.

Because the BU lifetime at the MN is greater than the period between the successive HOs, the MN has maintained a valid binding in its BU list for the FN CoA when the second HO from the HN to the same FN is performed. The MN can now start to use the previously configured address binding as soon as it detects that its home link is down. This considerably reduces the disconnection time during the HO. As buffering is not used at the IPTV clients, all packets destined to the MN during the disconnection time are lost, resulting in a discontinuation of the IPTV stream.

In contrast, all HOs from the FN back to the HN are executed in less than 150 ms. When the MN detects a router advertisement coming from its HN through the WiMAX interface after SS2 is plugged in, the MN sends a BU to the HA indicating that it can be reached directly from its HoA again and that traffic should not be transmitted to the MN's CoA anymore. When the HA directs the IPTV stream to the MN's HoA, the last packet coming through the Wi-Fi link reaches the MN faster than the first packet coming through the WiMAX link and thus these two packets are received over 100 ms apart. As the MN retains its connection to the FN during the HO execution, it is not disconnected from the IPTV server at any time and no packets are lost.

The HO tests validate the beneficial effects of pre-HO BUs so that the number of required configuration steps is decreased. This is also the idea behind the Fast MIPv6 (FMIPv6) concept where the MN tries to set up the IP address bingings for a HO before it loses connection to the currently serving network [11]. The usage of link layer information in order to predict the imminent HOs and to prepare the address configurations beforehand in IEEE 802.16 networks is specified in [12].

It should be noted that the Oulu testbed is not solely

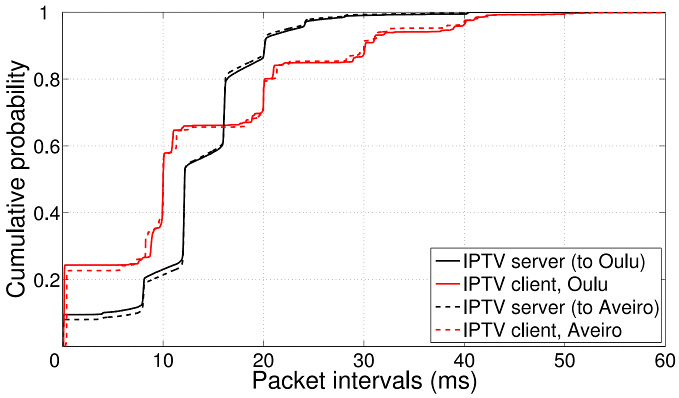

Fig. 2. CDF of packet intervals with the IPTV video data rate of 512 kb/s.

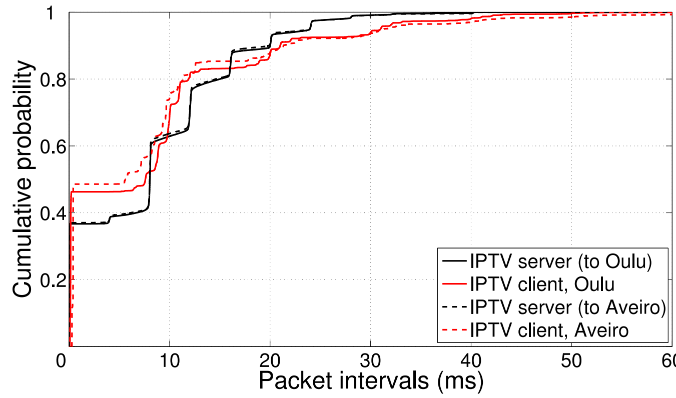

Fig. 3. CDF of packet intervals with the IPTV video data rate of 1024 kb/s.

a WiMAX network but a part of the VTT Converging Networks Laboratory, which has several access technologies implemented into its architecture. In such a heterogeneous environment, network configuration becomes more difficult and requires compromises. In our testbed, as the IP mobility agents are shared by all entities connected to the laboratory network, the MIPv6 HA is not configured according to all recommendations presented in [9]. Instead, the configuration followed the guidelines of [4]. The router advertisement sending interval, which has a direct influence to the MN's movement detection latency in MIPv6, was set to 1-3 seconds at the HA. According to [9], the upper limit of the interval should be 4 seconds or more for WiMAX networks so that dormant mobile stations operating in power saving mode are not excessively disturbed by the advertisement messages. Nonetheless, considering the way the HOs are triggered in this study, the interval setting has no effect on the HO latencies when the MN moves from the FN to the HN.

B. IPTV Streaming over Two WiMAX Testbeds

For the end-to-end tests, DSS transmits IPTV content over the SS1-BS1 WiMAX uplink to two separate receiving clients through network paths which include a WiMAX downlink, i.e. BS1-SS2 in Oulu and BS2-SS3 in Aveiro, as their last hop (see Fig. 1). As the processing delays caused by the PHY and MAC layer procedures of IEEE 802.16 links are an order of magnitude higher than those experienced in wired Ethernet and the best effort MAC scheduling is a possible source of excess delay jitter, the aim is to study the feasibility for such a use case with local and remote receiving clients using IPv6. By using a local receiving client in the same subnetwork as the server and a remote client in a separate subnetwork behind a series of unmanaged backbone networks, the effect of changing "background" backbone traffic load is also observed.

Fig. 2 presents the Cumulative Distribution Functions (CDF) of the packet sending intervals at the IPTV server and packet inter-arrival times at the receiving clients when the video data rate of 512 kb/s is used. Over 87% of the sending intervals between consecutively transmitted packets at the IPTV server remain under 20 ms. At the receiving clients, the distribution of the packet inter-arrival times is slightly wider but still 97% of the packets arrive at their destination less than 40 ms apart.

Fig. 3 presents the CDF of the packet intervals with the 1024 kb/s video data rate. Now over 90% of the packets at the IPTV server are transmitted less than 20 ms apart. The distribution of the packet intervals below 20 ms however is different than with the lower video data rate. From Fig. 2 it can be seen that approximately 10% of the IPTV packets are sent back-to-back with the 512 kb/s video data rate, whereas Fig. 3 shows that the amount of packets sent back-to-back is almost four times larger when the data rate is increased to 1024 kb/s. At the receiving hosts more than 93% of the packet inter-arrival times are less than 30 ms when the 1024 kb/s video data rate is used.

As the observed difference in the jitter of the received packet streams between the local and remote clients is small, it is evident that the primary source of excess delay jitter with both tested data rates is the two WiMAX links. However, as the WiMAX capacity is not exceeded by the IPTV packet streams, the experienced jitter stays so small in all occasions that it has no effect to the playback of the IPTV content even without the usage of pre-play buffering at the receiving clients. Our measurements indicate that despite the expressed skepticism towards the use of WiMAX as both access and backhaul technology for real-time applications, few problems arise even with multiple best effort WiMAX links and long-delay wired backbone networks present in the end-to-end path.

IV. Discussion

Issues rising when IP is deployed over WiMAX networks are thoroughly reviewed in [24]. Ksentini presents the essential mismatches between the IPv6 operation and IEEE 802.16 PHY and MAC layers, goes through the RFCs and draft specifications of IETF, and also discusses other problems and solutions presented in peer-reviewed literature outside IETF. However, some of the referenced draft documents have evolved since the writing of [24]. We both update and complement Ksentini's work by introducing and succinctly summarizing the latest versions of the specifications in Section II.

IETF specifications concentrating on IPv6 over IEEE

802.16, however, do not provide recommendations or guidelines for heterogeneous overlay networks which are accessible through multiple wireless and wired technologies. In such an environment, the operation of the network may not be optimized for WiMAX, possibly inflicting severe performance impairments to mobile users of the kind we discussed in Section III. Adopting the IEEE 802.21 Media Independent Handover (MIH) framework [25] is one possible solution to these performance problems as it enables a MN to use link-level triggers to predict imminent HOs and share HO-related information with other network elements without any ties or restrictions to any specific link layer technology. Currently we are looking into enhancing a UMIP-based MIP with the prototype mobility trigger management framework implementation introduced in [26], in order to improve HO performance and router solicitation usage in heterogeneous networks. Studying the performance of different WiMAX mobility aspects with a network dedicated to and optimized for this purpose is in our research agenda as well.

It is anticipated that in the future, a perhaps even larger fraction of the Internet's multimedia content will be created and distributed by end users in a decentralized peer-to-peer manner. As users start to use their own PCs as small multimedia servers from which they can stream their own video and audio content to other users, the uplinks of different wireless access technologies will be required to handle unprecedented traffic amounts. This paper validated the capabilities of state-of-the-art WiMAX technology in such a usage scenario, even though we employed solely rudimentary best effort MAC scheduling. As the capabilities and performance of WiMAX equipment will continue to evolve, a more realistic scenario with different levels of dynamic background traffic in the WiMAX links should be tested. Future studies will also need to exercise the WiMAX QoS support mechanisms. Some of the potential performance gains of the QoS differentiated traffic classes in WiMAX are already shown with empirical multimedia measurements in [18], but more work in assessing QoS capabilities is necessary.

V. Conclusion

This paper studied two issues related with future deployments of IPv6-based WiMAX networks as part of a converged networks architecture: heterogeneous access handovers and video streaming. As mobile devices become increasingly multiaccess-capable, users will come to expect seamless, always best connected operation, especially in the presence of overlapping network coverage. We reviewed recent developments at the IETF and the WiMAX Forum for addressing the problems caused by the mismatches in the operation of IEEE 802.16 PHY and MAC layers and IETF protocols, and summarized the salient points of their recommendations. We then empirically evaluated IPv6 and MIPv6 operation over a network path containing two separate WiMAX links. The experiments, on the one hand, validated the potential of WiMAX as a viable technology for the needs of future Internet multimedia traffic and, on the other, pointed out some probable reasons for poor performance in MIPv6 HO procedures when executed between converging heterogeneous access networks.

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References

[1] panOULU. *2008-10-31 - Oulu Opens up a free Mobile WiMAX network*. Online: http://www.panoulu.net/news/en/1225438080.

[2] G. Huston. The Changing Foundation of the Internet: Confronting IPv4 Address Exhaustion. *The Internet Protocol Journal*, 11(3):19–36, 2008.

[3] S. Deering and R. Hinden. Internet Protocol, Version 6 (IPv6). IETF RFC 2460, December 1998.

[4] D. Johnson, C. Perkins, and J. Arkko. Mobility Support in IPv6. IETF RFC 3775, June 2004.

[5] WiMAX Forum Network Working Group (NWG). *Stage2: Architecture Tenets, Reference Model and Reference Points*. Release 1, Version 1.2, January 2008.

[6] M-K. Shin, Y-H. Han, S-E. Kim, and D. Premec. IPv6 Deployment Scenarios in 802.16 Networks. IETF RFC 5181, May 2008.

[7] S. Madanapalli. Analysis of IPv6 Link Models for IEEE 802.16 Based Networks. IETF RFC 4968, August 2007.

[8] J. Jee, S. Madanapalli, and J. Mandin. IP over 802.16 Problem Statement and Goals. IETF RFC 5154, April 2008.

[9] B. Patil, F. Xia, B. Sarikaya, J. H. Choi, and S. Madanapalli. Transmission of IPv6 via the IPv6 Convergence Sublayer over IEEE 802.16 Networks. IETF RFC 5121, February 2008.

[10] H. S. Jeon, M. Riegel, and S. J. Jeong. Transmission of IP over Ethernet over IEEE 802.16 Networks. IETF Internet-Draft draft-ietf-16ng-ip-over-ethernet-over-802-dot-16, Work in Progress, November 2008.

[11] R. Koodli. Mobile IPv6 Fast Handovers. IETF RFC 5268, June 2008.

[12] H. Jang, J. Jee, Y. Han, S. Park, and J. Cha. Mobile IPv6 Fast Handovers over IEEE 802.16e Networks. IETF RFC 5270, June 2008.

[13] J. Pinola and K. Pentikousis. Mobile WiMAX. *The Internet Protocol Journal*, 11(2):19–35, 2008.

[14] Institute of Electrical and Electronics Engineers (IEEE) 802.16 Working Group. *IEEE Standard for Local and Metropolitan Area Networks. Part 16: Air Interface for Fixed Broadband Wireless Access Systems*. IEEE Std. 802.16-2004, October 2004.

[15] Universal Playground for IPv6 (USAGI) Project. *USAGI-Patched Mobile IPv6 for Linux (UMIP) 0.4*. Available: http://www.linux-ipv6.org/.

[16] K. Pentikousis, E. Piri, J. Pinola, F. Fitzek, T. Nissilä, and I. Harjula. Empirical evaluation of VoIP aggregation over a fixed WiMAX testbed. In *Proc. TRIDENTCOM*, Innsbruck, Austria, March 2008.

[17] K. Pentikousis, J. Pinola, E. Piri, and F. Fitzek. An Experimental Investigation of VoIP and Video Streaming over Fixed WiMAX. In *Proc. WiOPT*, pages 8–15, Berlin, Germany, March 2008.

[18] P. Neves, S. Sargento, R. Matos, G. Landi, K. Pentikousis, M. Curado, and F. Fontes. *WiMAX Evolution: Emerging Technologies and Applications*, chapter A WiMAX Cross-Layer Framework for Next Generation Networks. John Wiley & Sons Ltd., 2009.

[19] International Telecommunication Union (ITU). *Advanced Video Coding for Generic Audiovisual Services*. ITU-T Recommendation H.264, 2005.

[20] International Organization for Standardization / International Electrotechnical Comission. *Information Technology - Coding of Moving Pictures and Associated Audio for Digital Storage Media at Up to About 1.5 Mbit/s - Part 3: Audio*. ISO/IEC 11172-3, 1993.

[21] Apple Incorporated. *Darwin Streaming Server*. Available: http://developer.apple.com/opensource/server/streaming/index.html.

[22] VideoLAN. *VLC Media Player*. Available: http://www.videolan.org/.

[23] K. Correll. *PTP daemon (PTPd)*. Available: http://ptpd.sourceforge.net.

[24] A. Ksentini. IPv6 over IEEE 802.16 (WiMAX) Networks: Facts and Challenges. *Journal of Communications*, 3(3):1–9, 2008.

[25] Institute of Electrical and Electronics Engineers (IEEE) 802.21 Working Group. *IEEE Draft Standard for Local and Metropolitan Area Networks: Media Independent Handover Services, Work in Progress*. IEEE P802.21/D14, September 2008.

[26] J. Mäkelä and K. Pentikousis. Trigger management mechanisms. In *Proc. ISWPC*, pages 378–383, San Juan, Puerto Rico, February 2007.