Fixed Mobile Convergence Architectures for Broadband Access: Integration of EPON and WiMAX

Gangxiang Shen, Rodney S. Tucker, and Chang-Joon Chae, University of Melbourne

ABSTRACT

EPON and WiMAX are two promising broadband access technologies for new-generation wired and wireless access. Their complementary features motivate interest in using EPON as a backhaul to connect multiple dispersed WiMAX base stations. In this article we propose four broadband access architectures to integrate EPON and WiMAX technologies. The integrated architectures can take advantage of the bandwidth benefit of fiber communications, and the mobile and non-line-of-sight features of wireless communications. Based on these integrated architectures, we elaborate on related control and operation issues to address the benefits gained by this integration. Integration of EPON and WiMAX enables fixed mobile convergence, and is expected to significantly reduce overall design and operational costs for new-generation broadband access networks.

INTRODUCTION

With the emergence of bandwidth-intensive applications such as IPTV and VoD, broadband access is becoming increasingly important. New-generation fiber-based access techniques have been standardized and are gradually permeating from fiber to the curb (FTTC), to the building (FTTB), and to the home (FTTH). Ethernet passive optical network (EPON) is a promising fiber-based access technique [1–3] expected to offer a cheap solution to broadband access due to the ubiquitous deployment of Ethernet-based network equipment. On the other hand, wireless access techniques are also continuously expanding their transmission bandwidth, coverage, and quality of service (QoS) support. With the huge market success of wireless LAN (WLAN, IEEE 802.11) systems, the new-generation wireless technique WiMAX (IEEE 802.16) has now been standardized and deployed [4–6].

Fiber-based techniques offer super-high bandwidth. However, it is still quite costly to deploy a fiber directly to each home. In contrast, wireless has low deployment costs. Another important advantage of wireless techniques is support of mobility. Nonetheless, wireless techniques generally suffer from a limited wireless spectrum, which is shared by many users, thereby severely limiting the bandwidth allocated to each user. Moreover, a wireless system usually requires a broadband fiber feeder to interconnect many disperse access stations to a central office (CO). A combination of EPON and WiMAX may be an attractive solution to broadband network access, which enables the two techniques to complement each other in many aspects. Specifically, there are several important factors that motivate such integration.

First, EPON and WiMAX provide different levels of bandwidth, which shows a good match in capacity hierarchies. EPON supports a total 1 Gb/s bandwidth in both downstream and upstream, which is shared by a group of (say 16) remote optical network units (ONUs). On average, each ONU accesses about 60 Mb/s bandwidth, which matches the total capacity offered by a WiMAX base station (BS) that supports ~70 Mb/s over a 20 MHz channel. Second, integration enables integrated bandwidth allocation and packet scheduling that helps to better support service QoS and improve network throughput. Third, the integration can support broadband network access and mobility, and help to realize the ambition of fixed mobile convergence (FMC) [7], thereby significantly reducing network design and operational costs.

INTEGRATION OF EPON AND WIMAX

ARCHITECTURES

We consider four different architectures that can be used to support the integration of EPON and WiMAX. Because of the simplicity of downstream data communications of both EPON and WiMAX technologies, all following discussion on packet forwarding and bandwidth allocation is focused on the more complicated upstream direction.

Independent Architectures — The most intuitive way to integrate EPON and WiMAX is to use independent architectures as shown in Fig. 1, in which EPON and WiMAX systems are oper-

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ated independently by considering a WiMAX BS a generic user attached to an ONU (see the upper ONU in Fig. 1). As long as the two devices support a common standard interface (e.g., Ethernet), they can be interconnected. In addition, each ONU can have interfaces to home users for wired access. Thus, the system can offer integrated FMC service.

With a common standardized interface (e.g., Ethernet), the direct benefit of the independent architecture is that the ONU and BS can be connected without any special requirements being met. However, because the EPON and WiMAX systems operate independently, the ONU cannot see the details of how the WiMAX BS schedules packets for its associated subscribed stations (SSs), while the BS cannot see the details of how the ONU schedules and sends upstream data to an EPON optical line terminal (OLT). Thus, the architecture may not take full advantage of the integration, particularly in optimal bandwidth allocation of the whole system. Moreover, two independent devices, an ONU and a WiMAX BS, are required at the boundary of the two systems, which is likely to be more costly than using an integrated box as discussed later.

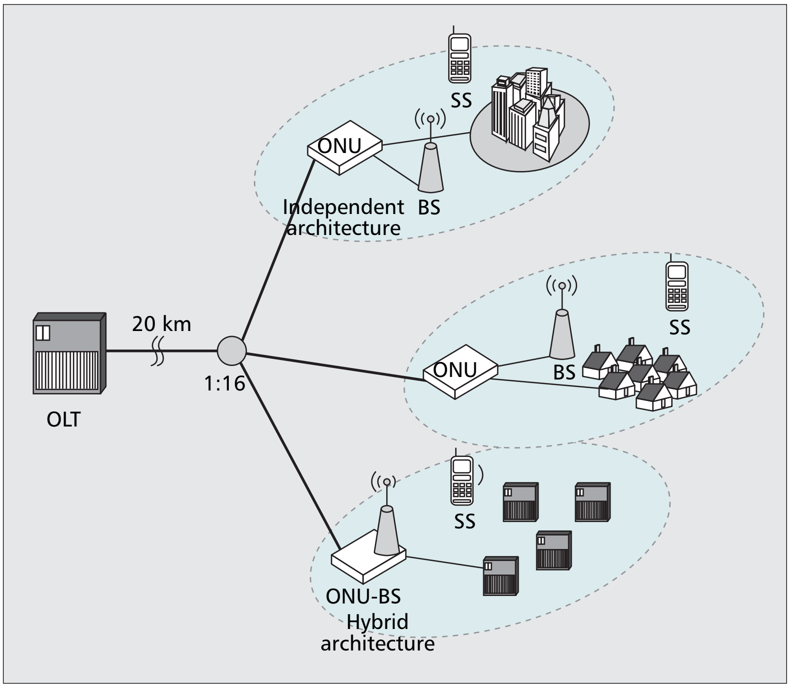

Figure 1. *Architectures for integration of EPON and WiMAX.*

Hybrid Architectures — A hybrid architecture is an enhanced integration, in which an ONU and a WiMAX BS are integrated in a single system box (ONU-BS), illustrated in the lower ONU in Fig. 1. Such an arrangement enables full integration of these two devices in both hardware and software. Figure 2 illustrates key functional modules inside the ONU-BS. In hardware, there can be three CPUs; for better integration, these three CPUs can be further integrated into a single CPU. CPU-1 is responsible for data communications within the EPON section and runs the EPON protocols. CPU-3 is responsible for data communications within the WiMAX section and runs the WiMAX protocols. Between them, a central CPU, CPU-2, coordinates the behavior of the other two CPUs. CPU-1 and CPU-3 report their section states, and bandwidth allocation and request details to CPU-2; the latter makes decisions, and then instructs the other two CPUs to request bandwidth from the upstream and allocate bandwidth to each SS in the downstream. The functional modules corresponding to the three CPUs in Fig. 2a are shown in Fig. 2b, which mainly illustrates the modules for upstream data communication. Specifically, CPU-1, related to the EPON section, contains the functional components of EPON packet scheduler, priority queues, and EPON packet classifier. CPU-3, related to the WiMAX section, contains the functional components of WiMAX packet reconstructor and WiMAX upstream scheduler. Finally, CPU-2 corresponds to the ONU-BS central controller in Fig. 2b.

One of the major benefits of this hybrid architecture is that the cost of equipment can be reduced as only a single device box is required. Moreover, because the integrated ONU-BS possesses full information on bandwidth request, allocation, and packet scheduling of both the ONU and the WiMAX BS, optimal mechanisms can be adopted for bandwidth requests in the upstream direction of the EPON network, and bandwidth allocation and packet scheduling in the downstream direction of the WiMAX network. Thus, compared to the previous independent architecture, this hybrid architecture is expected to improve the overall system performance in terms of throughput and service QoS.

Unified Connection-Oriented Architectures — WiMAX is a connection-oriented transmission technique under which each service flow is allocated with a unique connection ID (CID) [5, 6], and bandwidth requests and QoS support are connection-oriented. Based on connection-oriented bandwidth requests, an aggregate bandwidth is allocated to each SS, and this bandwidth is then allocated to each service connection associated with the SS. In contrast, EPON technology does not support this type of connection. Rather, bandwidth requests are queue-oriented; an aggregate bandwidth is allocated to each ONU, and then the latter makes a local allocation for the granted bandwidth to up to eight different priority queues in the ONU [1]. Although the overall operational principles of the two types of networks are quite similar, particularly in the aspect of bandwidth request and allocation, WiMAX systems generally allocate bandwidth more finely than EPON systems. In addition, the connection-oriented bandwidth allocation generally shows a more predictable QoS than the queue-based bandwidth allocation, which implies that WiMAX technology is expected to support QoS better than EPON technology. In contrast, EPON technology shows better operational scalability than WiMAX technology as each ONU is required to manage only up to eight priority queues.

Because EPON and WiMAX use different operational protocols in spite of similarity in their bandwidth request/grant mechanisms, it

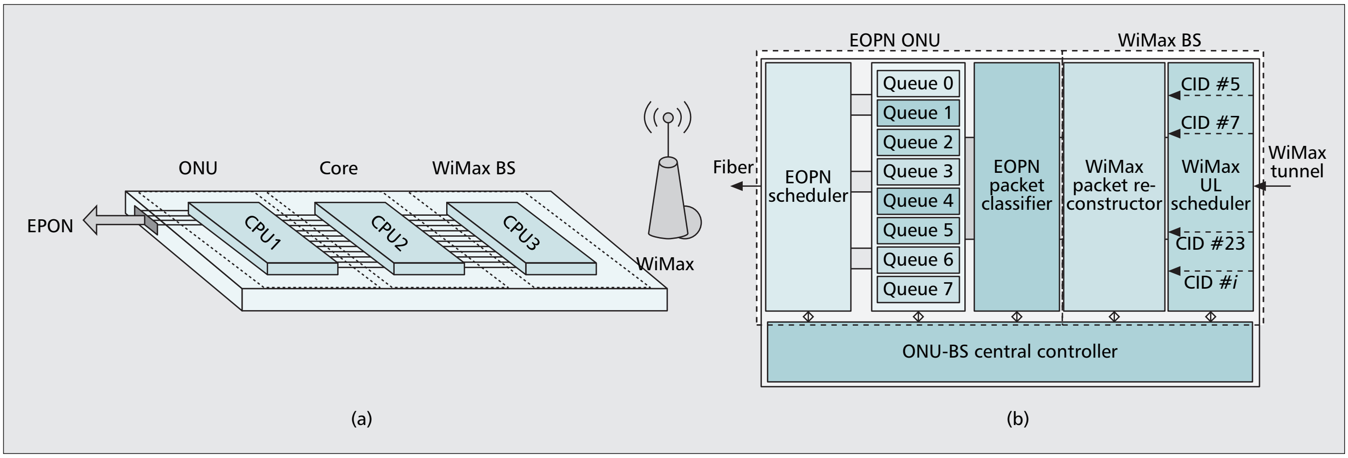

Figure 2. *Function modules and architecture of ONU-BS: a) hardware layout; b) functional modules.*

may make sense to modify the medium access control (MAC) layer protocols of EPON to also enable it to support connection-oriented services as in WiMAX systems. We expect such a modification can bring many advantages to the integration due to unified operation of the protocols in both systems. The new integrated architecture has almost the same layout as that of the hybrid architecture. The only difference is that rather than directly carrying Ethernet frames in upstream and downstream frames/bursts of EPON, WiMAX MAC PDUs replace the Ethernet frames, and the Ethernet frames are then encapsulated as client data in the WiMAX MAC PDUs.

Figure 3 shows how EPON data is transmitted after Ethernet frames are replaced by WiMAX MAC PDUs and the former are encapsulated in the latter. Specifically, the field of logic link ID (LLID) is kept for the preamble and addressing purposes (for MAC links). However, after LLID the frames become WiMAX MAC PDUs, and each PDU encapsulates Ethernet frames. Thus, the protocol stack of the new architecture can be seen to contain a new convergence sublayer (CS) below the Ethernet frame layer. The new sublayer functions to control and allocate bandwidth in the passive optical network. The overall operation will be the same as in WiMAX networks. As a result, the whole integrated system can be controlled by a unified set of connection-oriented control protocols extended from WiMAX technology. No control frames are required in the Ethernet frame layer for the bandwidth allocation and network control as in conventional EPON systems. From a network operational point of view, this is a type of FMC for network control and management: a single network control system and a set of protocols control and manage both wired and wireless access networks.

Figure 4 depicts an example of bandwidth request and allocation across an integrated WiMAX and PON network. SSs send requests (e.g., Request CID #x1 and Request CID #x2) to an ONU-BS, and the ONU-BS intercepts and digests these requests and sends abstract information as a request (e.g., Request CID #y1) to an OLT. The classification and aggregation of different requests from SSs depend on their individual QoS. In general, requests with similar QoS requirements are aggregated together at the ONU-BS. As a response, the OLT grants an aggregate bandwidth to the ONU-BS (e.g., Grant for ONU-BS1), and then the latter makes a finer reallocation for the granted bandwidth to each SS (e.g., Grant for SS1). The operation consists of two hierarchies. The OLT cannot see any detailed request information from each SS; the information is summarized by the ONU-BS before it is forwarded to the OLT. The CIDs in the two hierarchies are independent and the same CIDs can appear in the different hierarchies without affecting the operation of the whole system.

It is also viable to adapt a WiMAX network to run the EPON MAC protocols. In that way, all the WiMAX devices will be operated under the Ethernet technique with unified Ethernet interfaces. The shortcoming of this modification is that there is less control of QoS for each service connection. Also, special extensions are required to handle coding and modulation of wireless signals, as wireless channels are usually less stable than fiber media. Finally, for both of the above integration architectures, a common disadvantage is that they are not standardized.

Microwave-over-Fiber Architectures — To further reduce the cost on the boundary of the EPON and WiMAX systems as well as better utilize the transmission capacity of fiber, another alternative architecture can be proposed as shown in Fig. 5. Each remote node is made up of an ONU unit, responsible for data communications of the EPON, and a dumb antenna, responsible for relaying a WiMAX radio signal from and to its associated microcell. The EPON signal is located at baseband and occupies frequencies up to 1.25 GHz. The WiMAX signal is modulated on a wireless carrier frequency. These two signals are then multiplexed and modulated onto a common optical frequency (wavelength) and transmitted to an upstream central node. The modulation of a WiMAX carrier frequency (e.g., 2.5 GHz) over an optical frequency is termed *microwave-over-fiber* (MOF) [8]. In this architecture, there are two types of subcarriers.

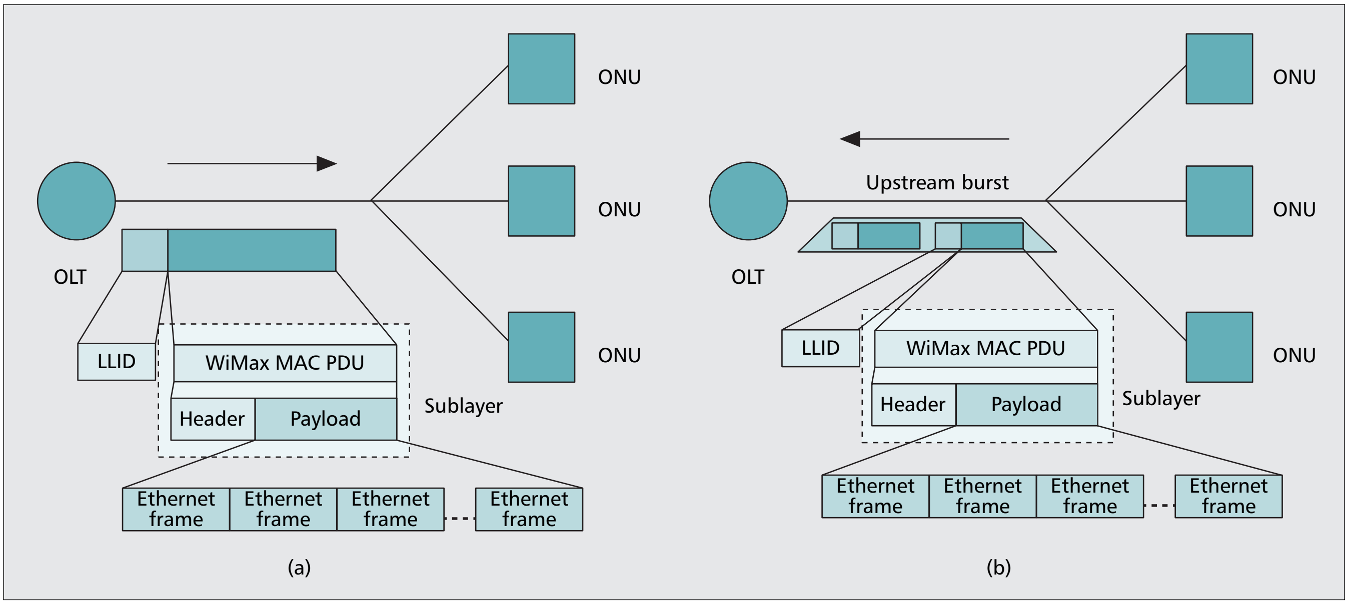

Figure 3. *Applying the WiMAX MAC layer to EPON: a) downstream; b) upstream.*

One is a wireless subcarrier in the WiMAX system, in which a several-megahertz (e.g., 10 MHz) spectrum is divided into multiple subcarriers (say 1024 subcarriers) with typical 10.94 kHz subcarrier frequency spacing [6]. The second type of subcarrier is the optical subcarrier in the PON that carries WiMAX signals from a dumb antenna to the central node. We term the first type of subcarrier *WiMAX subcarrier*, and the second *optical subcarrier*. A WiMAX subcarrier is thus a subcarrier on an optical subcarrier. To distinguish wireless signals from different dumb antennas at the central node, the optical subcarrier frequencies from different dumb antennas must be different. A radio frequency (RF) shifter (converter) (as shown in Fig. 5) is therefore required after each antenna to convert, for example, a 2.5 GHz WiMAX modulation frequency to a higher frequency of 7 GHz before modulating an optical frequency. If an EPON system has a 1:16 splitter ratio, which allows for deploying up to 16 WiMAX dumb antennas, a total of 16 optical subcarriers are required in the optical spectrum. Figure 5 shows an example of optical spectrum allocation in which the baseband is used to carry the EPON (1.25 Gb/s) signal, and 16 higher-frequency subcarriers are used to multiplex WiMAX signals at a 750 MHz frequency spacing.

Corresponding to the remote stations, the central node as shown in Fig. 5 consists of two major modules, an OLT and a central WiMAX BS. We call the central WiMAX BS a *macro-BS*, which consists of multiple WiMAX BS units and a macro-BS central controller/coordinator. The macro-BS processes all the frames or data packets from the microcells. It also coordinates bandwidth allocation and packet scheduling for each of the WiMAX BS units. After an optical signal enters the central node and is converted into an electronic format, the signal is first demultiplexed into two portions: a baseband EPON signal and a group of optical subcarrier signals. The baseband signal is forwarded to the OLT for further data processing, and the optical subcarrier signals are forwarded to the WiMAX macro-BS, where the optical subcarrier signals are first demultiplexed into multiple independent signals, and then each is passed to a frequency converter to shift its frequency up or down. Finally, the shifted frequency is forwarded to a WiMAX BS unit, and the latter processes the packets carried on the frequency.

One of the major advantages of the macro-BS architecture is simplified handover operation for mobile users. We discuss this point in detail later. However, the macro-BS may itself become a potential bottleneck of the whole WiMAX network as it needs to handle all the packets from a

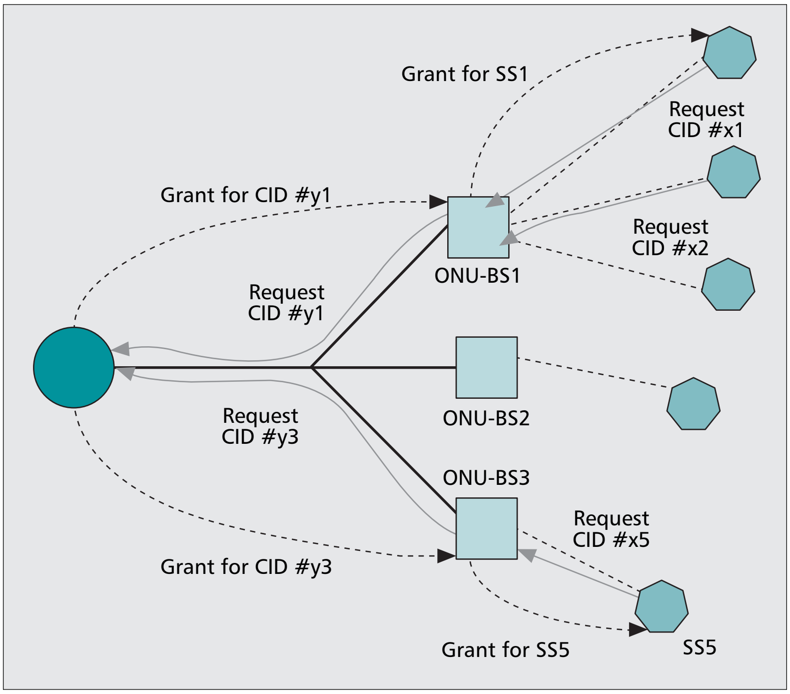

Figure 4. *Bandwidth request and allocation.*

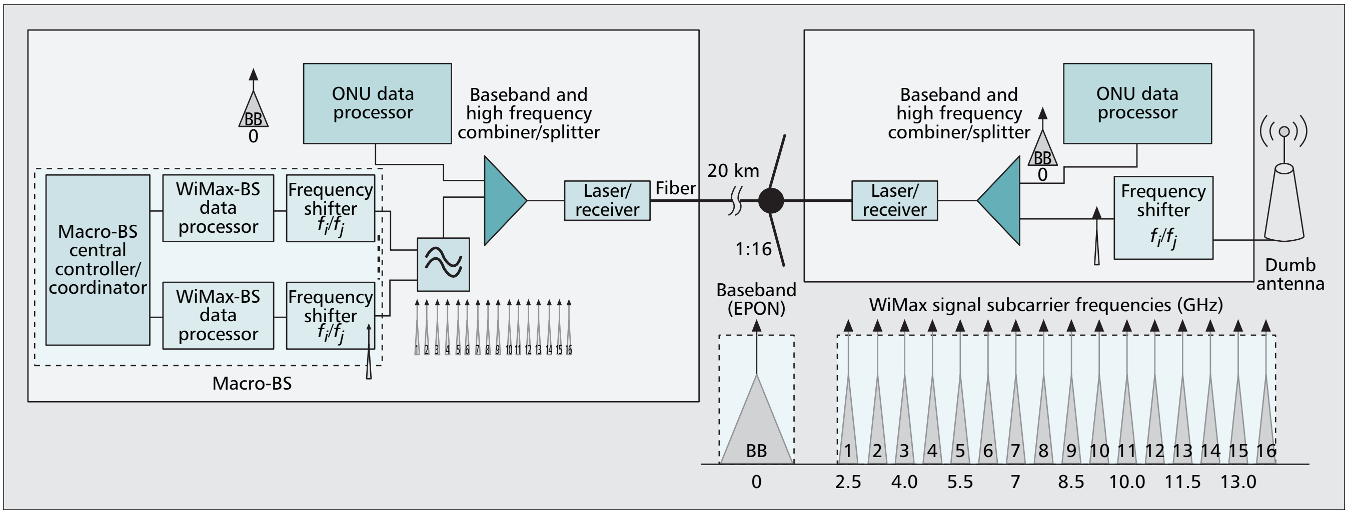

Figure 5. *Microwave-over-fiber integration architecture for EPON and WiMAX, and subcarrier signal spectrum layout in the MOF integrated system.*

large number of SSs subscribed to the system. In real physical systems, because of nonlinear effects, the crosstalk among the optical subcarriers that modulate a common active semiconductor component (e.g., laser or external modulator) at the central office can be a challenging issue. In addition, optical beat interference (OBI) between upstream optical subcarrier signals can be another challenging issue. For this, separate wavelengths may be required for each ONU, which leads to the next-generation PON systems, wavelength-division multiplexing (WDM) PONs.

DESIGN AND OPERATION

ADDRESSING AND PACKET FORWARDING

In integrated systems, each SS uses the DHCP protocol to obtain an IP address from a DHCP server [5], which can be attached to a central OLT or a remote ONU-BS. For IP packet forwarding, particularly between local SSs that belong to a common integrated access system, several forwarding mechanisms can be applied in the network and MAC layers, as shown in Fig. 6.

Figure 6a illustrates an example of employing an IP access router (AR) to forward IP packets. IP packets are first sent from SSs by encapsulating IP packets into Ethernet frames (we assume that the CS of WiMAX is operated under the mode of IP/Ethernet/WiMAX MAC PDU [6]), through the integrated access network to the OLT. The OLT then forwards the IP packets to its attached AR asking for further forwarding, either to the public or back to local SSs in the same access network. In this packet forwarding process, the intermediate devices, including the ONU-BS and OLT, are assumed to have no capability of switching Ethernet frames based on their MAC addresses like an Ethernet bridge. The advantages of this forwarding mode include simpler node architectures of OLT and ONU-BS as no MAC layer switching capability is required, and better security for each SS as all the packets must pass a router that generally possesses higher security than a layer 2 switch. However, the disadvantages of the mode fall into the bandwidth waste of local traffic forwarding for the meaningless loopback, as shown in Fig. 6a (i.e., packets from SS1 to SS3 need to pass a long round-trip loop), and the AR can become a bottleneck of the whole system as it needs to process all the packets, local or public.

To avoid the above local traffic loopback, another forwarding mechanism based on layer 2 switching can be proposed. Specifically, to each ONU-BS as well as the OLT, a layer 2 Ethernet bridge is attached, which allows the node to have the capability of switching Ethernet frames based on their MAC addresses. The IEEE 802.3D Spanning Tree Protocol (STP) [9] can be directly employed for this purpose, and the integrated access network essentially forms a simple tree with the Ethernet bridge attached to the OLT as a root node. As shown in Fig. 6b, packets exchanged between SSs within a common microcell or between microcells can always be intercepted by a bridge to avoid a long round-trip as in the previous AR mode. For example, IP packets from SS1 to SS3 can be switched by a bridge attached to an ONU-BS through Ethernet frames that encapsulates the packets. This also applies to the packets exchanged between different microcells: the bridge attached to the OLT switches these packets to avoid the access to the border AR.

In Fig. 6 we use independent boxes to represent each ONU-BS, bridge, and AR in a remote node. They can be integrated in a single device box for cost saving. So is the central node. The advantages of bridge-based forwarding mode include avoiding bandwidth waste due to the loopback of packet forwarding between SSs within the same integrated access network, and reducing the burden on the border AR, which now needs to forward the packets to the public only. The forwarding mode, however, shows the disadvantages of higher cost of each node box (both central and remote boxes), as extra layer 2 switching capability is required, and all SSs are sharing a common layer 2 network for local packet forwarding, which shows lower-level security than when all the packets pass an AR. Thus, for better user security, an extra AR can be attached to an ONU-BS node, as shown in Fig.

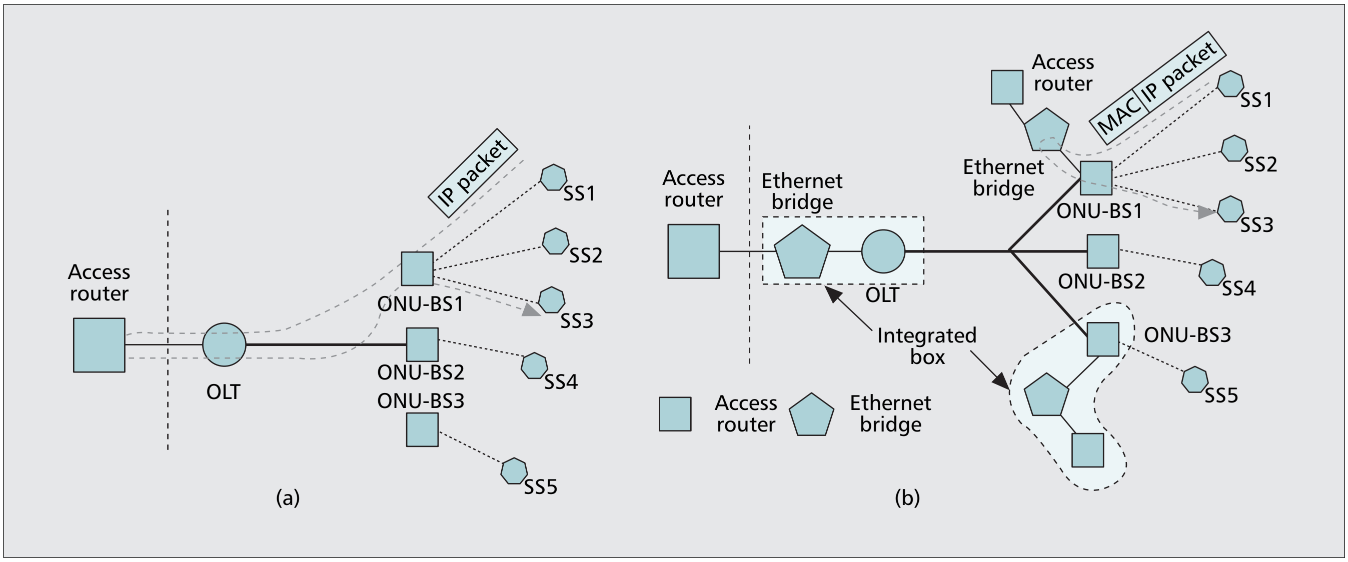

Figure 6. *Packet/frame forwarding in integrated access networks: a) network layer IP packet forwarding; b) link layer Ethernet frame switching.*

6b to offer a packet forwarding option for users that require better security. In addition, the virtual LAN (VLAN) (IEEE 802.3Q) technique [10] can be another option for better security under the bridge-based forwarding mode.

BANDWIDTH ALLOCATION AND QOS SUPPORT

For both EPON and WiMAX, it is a challenging issue to efficiently allocate upstream bandwidth to users. Both EPON and WiMAX employs a generic poll/request/grant mechanism; that is, a central station (OLT or WiMAX BS) polls a remote station (ONU or SS) on bandwidth requests, the latter responds with requests for bandwidth, and the central station then grants bandwidth. The poll/request/grant control information is usually exchanged through a dedicated control channel or by piggybacking data packets. Unsolicited bandwidth grants can also be made periodically to support delay-sensitive services or to poll each remote station to enable it to send a request.

Based on a generic poll/request/grant mechanism, EPON and WiMAX share much similarity in bandwidth allocation and QoS support. First, EPON requests bandwidth on a per-priority-queue basis, but allocates bandwidth on a per-ONU basis. Upon a granted bandwidth, each ONU makes local decisions to allocate the bandwidth and schedules packet transmission for each priority queue. WiMAX requests bandwidth on a per-connection basis, but allocates bandwidth on a per-SS basis. Upon being granted bandwidth, each SS makes local decisions to allocate the bandwidth and schedules packet transmission for each service connection. Second, both EPON and WiMAX support two types of bandwidth allocation modes: *unsolicited* and *upon request*. They show good similarity in supporting services with different QoS levels, including delay-sensitive services, bandwidth guaranteed services, and best effort services. Third, both EPON and WiMAX classify data traffic in a differentiated services (DiffServ) mode. EPON has up to eight different priority queues in each ONU, while WiMAX classifies the data traffic into five QoS levels ranging from unsolicited grant service (UGS) to best effort (BE).

The above similarity facilitates the integration of bandwidth allocation and QoS support in the integrated access architectures (not including the independent architecture). First, the integration of dynamic bandwidth allocation can be done in integrated architectures based on the generic poll/request/grant mechanism. On the EPON side, an ONU fully understands the bandwidth grant information in a WiMAX BS, which helps to request bandwidth from an OLT more efficiently. On the WiMAX side, once an ONU is granted bandwidth, the WiMAX BS fully understands how much bandwidth it can allocate for each type of service, and thus can make an optimal bandwidth allocation among all the service flows. Second, to enable more efficient integration, an effective mapping mechanism is required between EPON priority queues and WiMAX service connections. Specifically, the mapping needs to know which WiMAX flow should be stored in which EPON priority queue for equivalent QoS. EPON supports QoS in a DiffServ mode, under which packets are classified and stored in different priority queues. In contrast, although the services of WiMAX are classified to support different levels of QoS, WiMAX is a connection-oriented technology, which essentially follows an integrated service (IntServ) mode. Thus, for integration, an interesting problem is how to make efficient conversions between DiffServ and IntServ services. In addition, it is also interesting to see how the end-to-end QoS can be supported after these two systems are integrated.

HANDOVER

To support user mobility, it is important to consider handover when a user is crossing the boundary of two WiMAX cells. The integrated architectures are expected to provide simpler handover operation. As shown in Fig. 1, an OLT

The current integration architectures consider only the fundamental EPON and WiMAX systems. For future even higher access bandwidth, the architectures can be extended to employ more advanced technologies, such as WDM in PON systems and MIMO and AAS in WiMAX systems.

can function as a coordinator to fully handle user handover as the OLT can overlook all the microcells connected to the EPON. In particular, for the independent and hybrid architectures, sitting by the OLT, a handover coordinator can be deployed to control the handover operation over relevant microcells. To fulfill that, a dedicated control channel should be reserved to ensure that the handover central controller can exchange information with the WiMAX BS at each remote node in real time, which instructs an old WiMAX BS to clear a connection with a mobile user, and a new BS to initiate a new connection with the user.

Compared to the first three integrated architectures, the MOF architecture is even simpler in user handover operation. Because all user traffic is processed in a central WiMAX macro-BS, no dedicated control channels are required for communications between a central controller and individual WiMAX micro-BSs as in the other integrated architectures. For user handover, the WiMAX macro-BS can keep on monitoring user packets to find from which dumb antenna (correspondingly, over which optical subcarrier frequency) the user traffic is forwarded. If the user traffic is forwarded over the same subcarrier frequency as before, no handover is required; otherwise, if the user traffic is received from a different optical subcarrier, it means that the user has moved to a new microcell and a handover operation is required. In the future, when the macro-BS sends data to the user, the macro-BS must use the new optical subcarrier frequency such that the data can be forwarded to the new microcell in which the user is located.

CONCLUSIONS AND FUTURE PERSPECTIVES

It is a good match in bandwidth hierarchy to use an EPON as a backhaul to connect multiple disperse WiMAX BSs. In this article we propose four architectures for the integration of EPON and WiMAX. The control and operation of these architectures are discussed. We found that the integration of EPON and WiMAX can help realize fixed mobile convergence and provide a number of attractive features. First, integration enables efficient strategies for bandwidth allocation and packet scheduling that help to achieve better capacity utilization and support of QoS. Second, integration can simplify network operation (e.g., handover operation). Third, integration enables a single passive optical network to simultaneously carry two different types of access networks, and provide both wired and wireless broadband access services. Ultimately, the integration of EPON and WiMAX is expected to save design and operational costs for new-generation broadband access networks.

The current integration architectures consider only the fundamental EPON and WiMAX systems. For future even higher access bandwidth, the architectures can be extended to employ more advanced technologies, such as WDM in PON systems, and multiple input multiple output and adaptive antenna systems in WiMAX systems. Finally, although we chose EPON as a representative technique for passive access networks, the proposed integration architectures and related operation principles are also applicable to other PON techniques such as GPON.

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REFERENCES

[1] IEEE 802.3ah, "Ethernet in the First Mile," June 2004.

[2] G. Kramer, B. Mukherjee, and G. Pesavento, "IPACT: A Dynamic Protocol for an Ethernet PON (EPON)," *IEEE Commun. Mag.*, Feb. 2002, pp. 74–80.

[3] C. M. Assi *et al.*, "Dynamic Bandwidth Allocation for Quality-of-Service over Ethernet PONs," *IEEE JSAC*, vol. 3, no. 9, Nov. 2003, pp.1467–77.

[4] IEEE 802.16e/D12, "Air Interface for Fixed and Mobile Broadband Wireless Access Systems," Feb. 2005.

[5] G. Nair *et al.*, "IEEE 802.16 Medium Access Control and Service Provisioning," *Intel Tech. J.*, vol. 8, no. 3, Aug. 2004, pp. 213–28.

[6] WiMAX Forum, "Mobile WiMAX — Part I: a Technical Overview and Performance Evaluation," Aug. 2006.

[7] M. Vrdoljak, S. I. Vrdojak, and G. Skugor, "Fixed-Mobile Convergence Strategy: Technologies and Market Opportunities," *IEEE Commun. Mag.*, Feb. 2007, pp. 116–21.

[8] A. Nirmalathas *et al.*, "Wavelength Reuse in the WDM Optical Interface of a Millimetre-Wave Wireless-Wireless Antenna Base Station," *IEEE Trans. Microwave Theory*, vol. 49, no. 10, Oct. 2001, pp. 2006–12.

[9] IEEE 802.1D, "Media Access Control (MAC) Bridges," June 2004.

[10] IEEE 802.1Q, "Virtual Bridged Local Area Networks," May 2006.

BIOGRAPHIES

GANGXIANG SHEN (g.shen@ee.unimelb.edu.au) is a research fellow with ARC Special Research Centre for Ultra-Broadband Information Networks, Department of Electrical Engineering, University of Melbourne, Australia. He received his Ph.D. from the Department of Electrical and Computer Engineering, University of Alberta, Canada, in January 2006. He received his M.Sc. from Nanyang Technological University in Singapore and B.Eng. from Zhejiang University in P. R. China. His research interests are in optical networks, network survivability, and wireless mesh networks. In particular, his Ph.D. work was mainly focused on p-Cycle-based Protected Working Capacity Envelope (PWCE), flow p-Cycles, and translucent optical networks. He has authored and co-authored more than 30 technical papers.

RODNEY S. TUCKER [F'90] (r.tucker@ee.unimelb.edu.au) is a laureate professor at the University of Melbourne, Australia. He is research director of the Australian Research Council Special Research Centre for Ultra-Broadband Information Networks in the University of Melbourne's Department of Electrical and Electronic Engineering. He has held positions at the University of Queensland, the University of California, Berkeley, Cornell University, Plessey Research, AT&T Bell Laboratories, Hewlett Packard Laboratories, and Agilent Technologies. He is a Fellow of the Australian Academy of Science, the Australian Academy of Technological Sciences and Engineering, and the Optical Society of America. He received B.E. and Ph.D. degrees from the University of Melbourne in 1969 and 1975, respectively. In 1997 he was awarded the Australia Prize for his contributions to telecommunications.

CHANG-JOON CHAE'S (thomas.chae@nicta.com.au) biography was not available at the time of publication.