QoS-Aware Radio-and-Fiber (R&F) Access-Metro Networks

(Invited Paper)

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***Abstract*—Future bimodal fiber-wireless (FiWi) access-metro networks may deploy both radio-over-fiber (RoF) and radio-and-fiber (R&F) technologies. RoF networks are rapidly becoming mature, but they fall short of interworking with distributed wireless MAC protocols such as DCF in widely deployed IEEE 802.11 WLANs. While R&F networks are able to avoid this limitation by means of protocol translation at the optical-wireless interface, recent testbed activities demonstrated that their multimedia QoS performance is far from acceptable, giving rise to various open R&F networking issues. In this paper, we report on our ongoing research activities on providing improved QoS support in R&F access-metro networks by means of (i) hierarchical scheduling and hybrid access control in integrated RPR/WiMAX metro networks, and (ii) hierarchical frame aggregation in integrated EPON/next-generation WLAN-based mesh access networks.**

I. Introduction

Future broadband access networks will be bimodal, capitalizing on the respective strengths of both optical and wireless technologies and smartly merging them in order to realize future-proof fiber-wireless (FiWi) networks that strengthen our information society while avoiding its digital divide. By combining the capacity of optical fiber networks with the ubiquity and mobility of wireless networks, FiWi networks form a powerful platform for the support and creation of emerging as well as future unforeseen applications and services, e.g., telepresence [1].

Radio-over-fiber (RoF) networks have been studied for many years as an approach to integrate optical fiber and wireless networks. In RoF networks, radio frequencies (RFs) are carried over optical fiber links between the central office (CO) and multiple low-cost remote antenna units (RAUs) in support of a variety of wireless applications, e.g., microcellular radio systems [2]. It was experimentally demonstrated that RoF networks can have an optical fiber range of up to 50 km [3]. However, inserting an optical distribution system in wireless networks may have a detrimental impact on the performance of medium access control (MAC) protocols [4]. The additional propagation delay may exceed certain timeouts of wireless MAC protocols, resulting in a deteriorated network performance. More precisely, MAC protocols based on centralized polling and scheduling, e.g., IEEE 802.16 WiMAX, are less affected by increased propagation delays due to their ability to take longer walk times between the CO and wireless subscriber stations (SSs) into account by means of interleaved polling and scheduling of upstream transmissions originating from different SSs. However, in distributed MAC protocols, e.g., the widely deployed distributed coordination function (DCF) in IEEE 802.11a/b/g WLANs, the additional propagation delay between wireless stations (STAs) and access point (AP) poses severe challenges. Due to the acknowledgment (ACK) timeout optical fiber can be deployed in a standard 802.11b WLAN-based RoF network with a default ACK timeout value of 20 μs only up to a maximum length of 1948 meters to ensure the proper operation of DCF [5].

The aforementioned limitations of WLAN-based RoF networks can be avoided in so-called *radio-and-fiber (R&F)* networks [6]. While RoF networks use optical fiber as an analog transmission medium between the CO and one or more RAUs with the CO being in charge of controlling access to both optical and wireless media, in R&F networks access to the optical and wireless media is controlled separately from each other by using in general two different MAC protocols in the optical and wireless media, with protocol translation taking place at their interface. As a consequence, wireless MAC frames do not have to travel along the optical fiber to be processed at the CO, but simply traverse their associated AP and remain in the WLAN, thus avoiding the negative impact of fiber propagation delay on the network performance.

In general, FiWi networks may deploy both RoF and R&F technologies. While significant progress has been made at the PHY layer of FiWi and in particular RoF transmission systems, FiWi networking research on layer-2 related issues has begun only very recently, addressing key challenges such as integrated channel assignment and bandwidth allocation, integrated path selection, hierarchical optical burst assembly and wireless frame aggregation, as well as flow and congestion control [7]. Another important challenge is quality-of-service (QoS) which plays a key role in running various multimedia applications and services over FiWi networks. In this paper, we study an Ethernet-based R&F access-metro network, referred to as SuperMAN, which integrates next-generation WiFi and WiMAX networks with optical access and metro networks. Our focus is on layer-2 QoS provisioning which largely depends on the performance of routing and resource management algorithms, including bandwidth allocation and channel assignment algorithms, with absolute and relative QoS assurances.

The remainder of this paper is structured as follows. Section II briefly reviews the state-of-the-art of FiWi networks and QoS provisioning techniques. In Section III, we elaborate on our SuperMAN network architecture and describe new QoS provisioning techniques. The performance of our proposed QoS provisioning techniques is investigated by means of simulation in Section IV. Section V concludes the paper.

II. FiWi Networks

Various FiWi network architectures were recently surveyed in [8]. In this section, we briefly describe two state-of-the-art FiWi network testbeds and outline their technological maturity.

A. State-of-the-Art

1) RoF Testbed: The Georgia Institute of Technology RoF testbed was designed for the field trial demonstration of 270 Mb/s standard definition (SD) and 1.485 Gb/s high definition (HD) real-time video stream delivery using 2.4 GHz and 60 GHz millimeter (mm)-wave transmissions over 2.5 km SMF between the Centergy building (transmitter) and the aware home residential building (receiver) [9]. All-optical up-conversion is used at the transmitter to generate a 60 GHz mm-wave signal (by means of phase modulation) and to send the HD video signal at 1554 nm. Electrical mixing and double-sideband optical modulation techniques are used to up-convert the SD video 2.4 GHz radio signal before optical transmission at 1550 nm. PIN photodiodes are used at the receiver to perform O/E conversion of the filtered optical signals. The experimental results demonstrate a very good bit error rate (BER) performance of the received video signals.

2) R&F Testbed: The University of California (UC) Davis R&F testbed integrates two Ethernet passive optical networks (EPONs) and an IEEE 802.11g WLAN-based wireless mesh network (WMN) with a maximum transmission rate of 54 Mb/s for voice, video, and data traffic [10]. In this architecture, optical protection is provided by using full EPON duplication. Programmability is realized by using a Linux PC connected to each optical network unit (ONU) and open source firmware in each wireless gateway and router. The experimental results show that the quality of video transmissions sharply deteriorates for an increasing number of wireless hops. In fact, the video client showed a blank screen after four wireless hops. The obtained findings clearly demonstrate that running EPON and WMN networks independently from each other yields a poor network performance. A more involved investigation of advanced QoS provisioning techniques is needed to support multimedia applications and services in R&F networks.

B. QoS Provisioning Techniques

While the Georgia Institute of Technology testbed successfully demonstrates the maturity of RoF networks, the UC Davis R&F testbed suffers from its wireless mesh frontend and fails to provide multimedia services. Recently, various QoS provisioning techniques were developed for R&F networks. In [11], centralized and distributed scheduling approaches were examined for the integration of EPON and WiMAX. The simulation results demonstrate an improved network throughput and end-to-end delay for different QoS demands. The integrated QoS-aware dynamic bandwidth allocation (DBA) scheme proposed in [12] supports bandwidth fairness at the ONU-BS (base station) interface which sends optical bandwidth requests to the optical line terminal (OLT) based on the status of its queues. The reported results show improved network throughput, delay, and bandwidth utilization.

The design of suitable routing algorithms is another means to improve QoS support in R&F networks. Routing algorithms play a key role in load balancing and congestion control of optical and wireless R&F network links. In [13], a novel integrated routing algorithm with load balancing was proposed for an optical unidirectional ring/PON based R&F architecture to improve the network throughput-delay performance. Moreover, different routing algorithms were investigated for the wireless segment of R&F networks [14]: minimum-hop routing algorithm (MHRA), shortest path routing algorithm (SPRA), predictive-throughput routing algorithm (PTRA), delay-aware routing algorithm (DARA), and risk-and-delay-aware routing algorithm (RADAR). Among the aforementioned routing algorithms, RADAR shows the best performance in terms of delay, throughput, and load balancing under both high and low traffic loads, besides providing risk awareness.

III. SuperMAN

The considered SuperMAN architecture builds on an all-optical Ethernet-based access-metro network, described at length in [1], extended with optical-wireless interfaces to next-generation WiFi and WiMAX networks. SuperMAN is a QoS-aware R&F access-metro network whose optical part consists of a resilient packet ring (RPR) metro network that interconnects multiple wavelength division multiplexing (WDM) upgraded EPON access networks. Each WDM EPON has a tree topology, with the OLT at the tree root being collocated with one of the RPR ring nodes. The optical access-metro network lets low-cost PON technologies follow low-cost Ethernet technologies from access networks into metro networks by interconnecting the P OLTs with a passive optical WDM star subnetwork whose hub consists of a passive athermal wavelength-routing $P \times P$ arrayed waveguide grating (AWG) in parallel with a wavelength-broadcasting $P \times P$ passive star coupler (PSC). The two types of optical-wireless interface in SuperMAN involve the integration of (i) RPR with WiMAX and (ii) EPON with next-generation WiFi, as explained in greater detail in the following.

A. Integration of RPR and WiMAX

1) Traffic Mapping: Fig. 1 depicts the optical-wireless interface between an RPR metro ring node and a WiMAX access network, where the so-called integrated rate controller (IRC) (shaded in Fig. 1) plays a key role in integrating the two networks [15]. It comprises a BS controller, a traffic class mapping unit, central processing unit (CPU), and traffic shaper. The IRC is used to seamlessly integrate both networks and

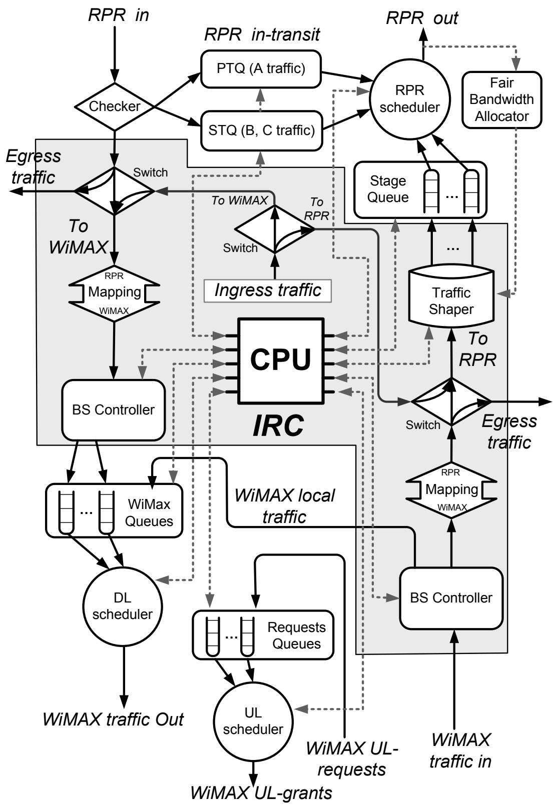

Fig. 1. Optical-wireless interface between RPR and WiMAX networks.

jointly optimize the RPR scheduler and WiMAX downlink (DL)/uplink (UL) schedulers. The BS controller is responsible for handling incoming and outgoing WiMAX traffic, besides providing hand-over for SSs between different ring nodes. The traffic class mapping unit is able to translate the different WiMAX scheduling services and RPR traffic classes bidirectionally. The traffic shaper monitors the control rates of RPR traffic and performs traffic shaping according to RPR's fairness policies. The CPU synchronizes the aforementioned units and controls the RPR and WiMAX schedulers. More specifically, the CPU estimates the load of incoming traffic from different domains and synchronizes the schedulers based on traffic monitoring. RPR specifies the five traffic classes A0, A1, B-CIR, B-EIR, and C, while WiMAX specifies the following five scheduling services: unsolicited grant service (UGS), extended-real-time polling service (ErtPS), real-time polling service (rtPS), non-real-time polling service (nrtPS), and best effort (BE). RPR traffic classes and WiMAX scheduling services are mapped to each other in the order they are listed above.

2) Hierarchical Scheduling and Hybrid Access Control Algorithm: Fig. 2 shows a novel hierarchical scheduling algorithm for integrating RPR and WiMAX networks [15]. The hierarchical scheduling algorithm deploys the following different queuing methods:

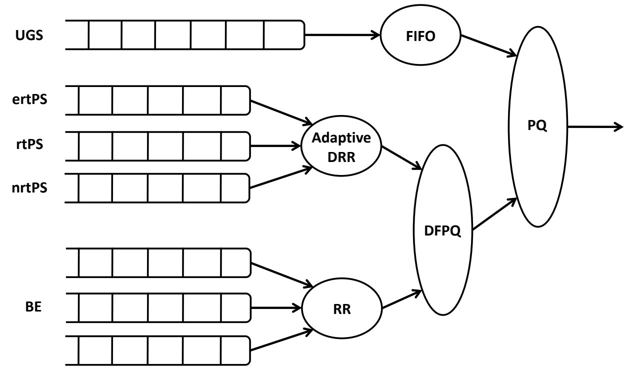

Fig. 2. Hierarchical scheduling algorithm for WiMAX/RPR interface.

- **FIFO:** Typically, UGS service flows (SFs) consist of fixed-size packets at a constant data rate. FIFO queuing is used for UGS SFs due to its ability to provide in-order packet queuing for high-priority packets.
- **Adaptive DRR:** To schedule ertPS, rtPS, and nrtPS SFs, an adaptive deficit round robin (DRR) scheduler is used to satisfy both delay and fairness requirements of real-time traffic. The adaptive scheduler operates in burst or non-burst mode according to given traffic loads.
- **RR:** Due to the delay insensitivity of BE SFs, a simple round robin (RR) scheduler is applied.
- **DFPQ:** This scheduling scheme is deployed in order to improve the fairness between the outputs of the adaptive DRR and RR schedulers. Deficit fair priority queuing (DFPQ) serves the SF queues according to their priority. It then calculates the quantum of each non-empty queue based on the required bandwidth in each scheduling cycle. Higher priority packets are scheduled first, until the deficit counter of their traffic classes is smaller than a preselected threshold. Subsequently, lower priority packets are scheduled.
- **PQ:** Priority queuing (PQ) is applied to distinct traffic classes with various QoS requirements. The straightforward slot allocation of PQ is suitable for higher priority queues. PQ is used at the outputs of the FIFO and DFPQ schedulers in order to provide service differentiation of higher and lower priority SFs.

The CPU in Fig. 1 monitors and controls the aforementioned schedulers. Upon reception of UL-requests, the RPR/WiMAX interface node is able to change the reserved bandwidth of traffic class A0 based on the requested bandwidth for UGS SFs. Also, once an RPR node receives A1 and B-CIR packets, the CPU informs the DFPQ scheduler to dynamically adjust its threshold for ertPS and rtPS. This adaptive interaction between the optical and wireless segments is crucial to provide end-to-end QoS connectivity for guaranteed and real-time traffic classes.

B. Integration of EPON and Next-Generation WiFi

Fig. 3 depicts the network architecture and node structures of an integrated EPON and next-generation WLAN-based

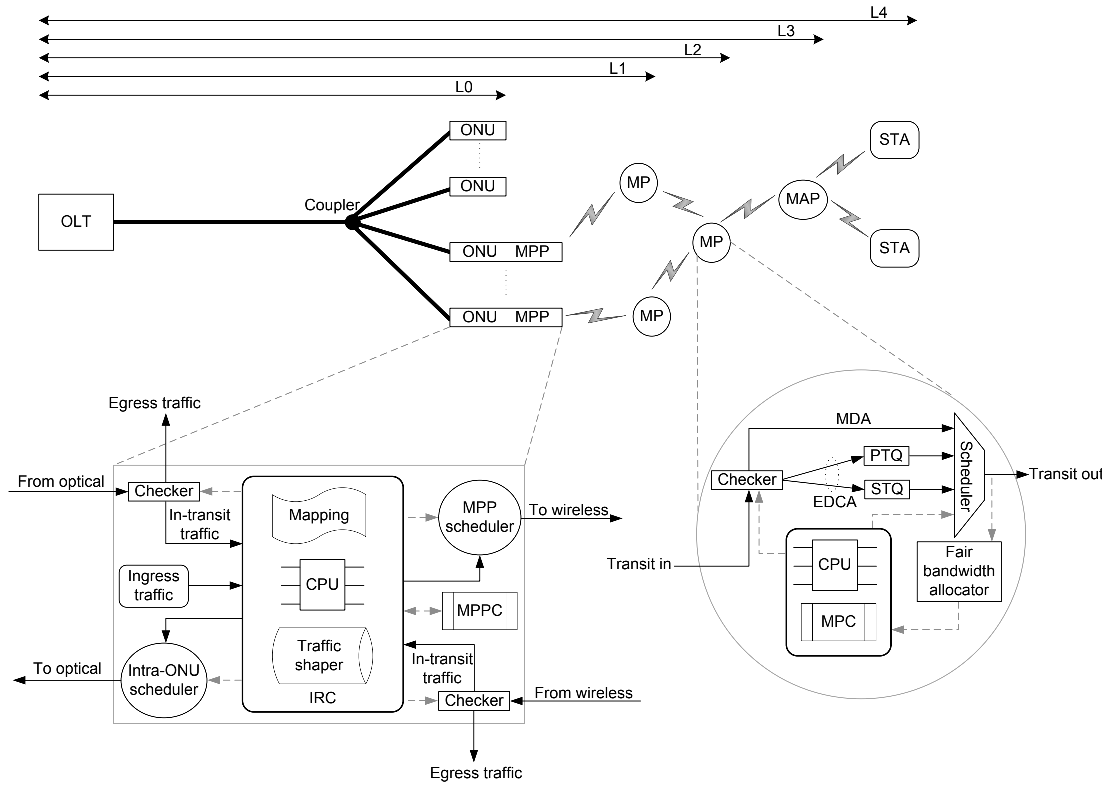

Fig. 3. Integration of EPON and next-generation WLAN-based mesh network.

WMN network, which was not described and investigated in [15]. In this figure, an ONU represents a conventional ONU with or without WDM upgrades. Some of the ONUs are integrated with a mesh portal (MPP) to interface with the WMN, as described in greater detail in the following.

1) ONU MPP: An integrated ONU MPP node consists of the following four main modules: intra-ONU scheduler, MPP scheduler, MPP controller (MPPC), and IRC. The intra-ONU and MPP schedulers are used to transmit local and forward in-transit traffic to the EPON and WMN, respectively. The ingress traffic and egress traffic denote the traffic generated by and destined to the local ONU, respectively. The IRC plays a key role in integrating the ONU and MPP. It comprises a traffic class mapping unit, CPU, and traffic shaper. It is used to seamlessly integrate both technologies and jointly optimize the intra-ONU and MPP schedulers. The traffic class mapping unit is able to translate the different EPON and wireless enhanced distributed channel access (EDCA)/mesh deterministic access (MDA) traffic classes bidirectionally [16]. The traffic shaper checks the load of each scheduler and performs traffic shaping and hierarchical aggregation/de-aggregation, as described in greater detail shortly. The CPU synchronizes the aforementioned units and controls the intra-ONU and MPP schedulers. More precisely, the role of the CPU is twofold: (i) synchronizing all the operational processes occurring at different modules of the IRC, including alarm management, and (ii) monitoring and tuning the traffic shaper and schedulers dynamically in order to optimize QoS-aware packet delivery. Moreover, the CPU monitors the load of incoming traffic from different domains and synchronizes the schedulers based on traffic monitoring information. For instance, in case of wireless network congestion, the CPU generates a congestion control message and sends it to the transmitter MP to perform load balancing. We note that the dashed lines in Fig. 3 represent the monitoring functions executed by the CPU. The MPPC is responsible for handling incoming and outgoing wireless traffic, besides establishing and monitoring wireless links.

2) MP: The wireless mesh point (MP) node structure comprises the following four main modules: MP scheduler, MP controller (MPC), fair bandwidth allocator, and CPU which is used to monitor the aforementioned components. The MP scheduler is used to forward in-transit traffic to other wireless nodes. Incoming in-transit frames are transferred to the checker and are subsequently switched to the scheduler or transit queues based on their type of access, i.e., MDA or EDCA. The primary transit queue (PTQ) and secondary transit queue (STQ) are defined for prioritized transmission of EDCA packets. Note that MDA and EDCA provide absolute and relative QoS in the WMN, respectively. MDA in-transit frames pass the MP without de-aggregation. However, EDCA frames can be de-aggregated and reordered based on the priority of the transit queues. The fair bandwidth allocator module monitors the assigned bandwidth and processes control congestion packets. The CPU synchronizes the aforementioned units and controls the MP scheduler and checker. MPC is responsible for handling incoming and outgoing traffic through wireless mesh links, besides avoiding local congestion. The MAP node structure is similar to the MP node structure, but additionally provides service to STAs.

3) Hierarchical Frame Aggregation: The major MAC performance enhancement of IEEE 802.11n next-generation WLANs is frame aggregation, which comes in two flavors: aggregate MAC service data unit (A-MSDU) and aggregate MAC protocol data unit (A-MPDU) [17]. We apply A-MSDU in the optical segment since for an error-free media such as optical fiber A-MSDU achieves a higher throughput than A-MPDU [18]. A-MPDU is used in the error-prone WMN. As shown in Fig. 3, our proposed hierarchical frame aggregation include the following five different aggregation layers L0-L4:

- **L0:** This layer applies only the optical frame aggregation technique (i.e., A-MSDU) for traffic between the OLT and ONUs.
- **L1:** This layer performs a two-level hop-by-hop aggregation (i.e., A-MSDU and A-MPDU) for traffic between the OLT and first-hop MPs. More specifically, A-MSDU is used for traffic between the OLT and ONU MPPs (and ONUs), whereby an ONU MPP additionally applies A-MPDU for the first wireless hop.
- **L2:** This layer deploys A-MSDU and A-MPDU jointly for aggregation of traffic between the OLT and a so-called virtual root MP (VRMP). A VRMP is a special MP with the additional capability of reordering and aggregating packets destined to a given receiver.
- **L3:** This layer performs a two-level aggregation by combining L2 aggregation (between OLT and VRMP) with A-MPDU on the wireless link between each pair of MAP and VRMP.
- **L4:** This layer is designed for end-to-end aggregation of traffic between the OLT and STAs. Each STA deploys A-MPDU to reach its associated MAP which in turn performs L3 aggregation for communication to and from the OLT.

Furthermore, we deploy an integrated dynamic path selection scheme which uses the routing tables of MPs and ONU MPPs as well as their buffer status with the objective to minimize the required number of wireless hops and maximize WMN load balancing. The proposed path selection scheme is used for intra-mesh traffic to mitigate congestion at ONU MPPs.

IV. Results

A. RPR/WiMAX Interface

The results in [15] show that the proposed hierarchical scheduler with its multiple stages puts less backpressure on the RPR metro ring network and thereby achieves a higher mean aggregate throughput for voice, video, and data traffic than a conventional weighted fair queuing (WFQ) scheduler for both fixed and mobile users with a speed of up to 120 km/h under realistic wireless channel conditions. For a more detailed performance evaluation of the hierarchical scheduler we refer the interested reader to [15].

B. EPON/Next-Generation WiFi Interface

In our simulations, we consider uniform unicast traffic where a given node (i.e., OLT, ONU, ONU MPP, or STA) sends a generated packet to any other node with equal probability $1/(N-1)$ and N denotes the number of nodes. We assume that 16 ONUs and 16 ONU MPPs are connected to the OLT, whereby the distance between ONUs/ONU MPPs and OLT is set to 20 km. The EPON data rate is set to 1 Gb/s. We consider voice and video. For the generation of voice traffic, we use the voice codec standard ITU-T G.711 where a packet of 160 bytes is generated every 20 ms without compression, translating into a CBR source rate of 64 kb/s. The fixed-size CBR voice packets contain 12, 8, and 20 bytes of RTP, UDP, and IP headers, respectively. Further, we assume that there is no silence suppression. For the generation of video traffic, we deploy MPEG-4 to encode 600-byte packets at a data rate of 768 kb/s which generates UDP CBR traffic, including 8 bytes and 20 bytes of UDP and IP headers, respectively. The two voice and video codecs are used simultaneously, each encoding 50% of the generated traffic. In addition, we consider Poisson data traffic with different packet sizes. The size of a generated data packet is equal to 40, 552, and 1500 bytes according to a distribution of 50%, 30%, and 20%, respectively. The generated data packets are transmitted with an additional 20-byte TCP header and 20-byte IP header. In our simulations, we use the limited-service interleaved polling with adaptive cycle time (IPACT) with a maximum grant size of G_{max}=15 kbytes as EPON DBA algorithm [19]. In the limited-service granting approach, the transmission grant size per ONU is set to the reported queue size up to the maximum grant size. Five STAs are located at a range of 200 m of the associated MAPs, while the distance between a pair of adjacent MAP, MP, and ONU MPP is set to 2 km. Each STA is connected to an ONU MPP via an MAP and two intermediate MPs, whereby the MP two hops from the STA plays the role of a VRMP. The bit error rate (BER) of the wireless channel is set to 10^{-5}. We evaluate the network performance in terms of throughput and delay, where throughput denotes the number of successfully transmitted packets and delay denotes the time interval between packet arrival at the source node and packet reception at the destination node in steady state.

Fig. 4 shows the beneficial impact of our proposed hierarchical frame aggregation on the network performance for a 54 Mb/s WMN under voice, video, and data traffic. We observe that the proposed frame aggregation technique improves both network throughput and delay. The throughput increases for increasing load, whereby the video traffic achieves higher improvement than others using the proposed hierarchical frame aggregation.

Fig. 5 shows the throughput-delay performance of the hierarchical frame aggregation for various WMN data rates 54 Mb/s, 100 Mb/s, 300 Mb/s, and 600 Mb/s under triple-play traffic. In this figure, the results are averaged over all three traffic types. We observe that the proposed frame aggregation technique improves the mean throughput and to a lesser extent

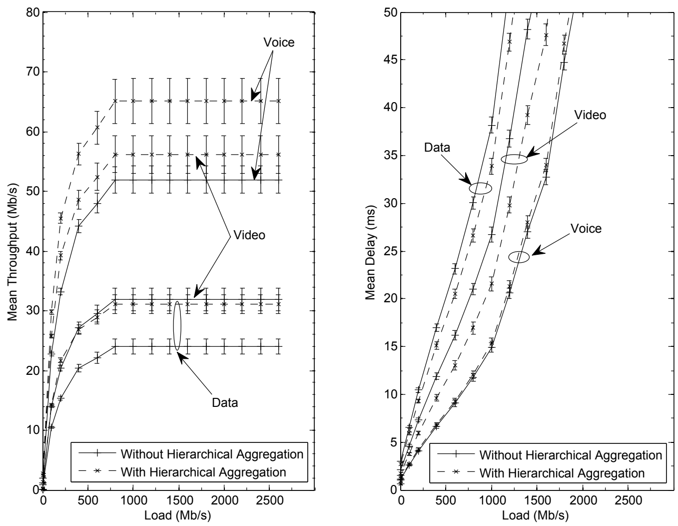

Fig. 4. Impact of hierarchical frame aggregation on integrated EPON-WLAN network performance for a 54 Mb/s WMN under triple-play (voice, video, and data) traffic.

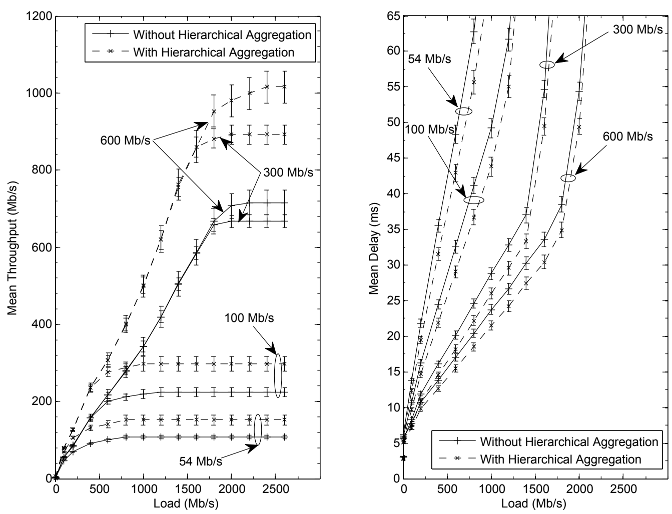

Fig. 5. Impact of hierarchical frame aggregation on integrated EPON-WLAN network performance for various WMN data rates under triple-play traffic.

also the mean delay. Note that in Figs. 4 and 5 the 95% confidence intervals exhibit an error of less than 10% from the mean values.

V. Conclusions

FiWi networking research on layer-2 related issues has begun only very recently. Among others, important research challenges include integrated channel assignment and bandwidth allocation, integrated path selection, hierarchical optical burst assembly and wireless frame aggregation, flow and congestion control, as well as end-to-end QoS support. In contrast to RoF networks, a more involved investigation of advanced QoS provisioning techniques is needed to support multimedia applications and services in R&F networks. We reported on our ongoing research activities on providing improved QoS support in our proposed Ethernet-based SuperMAN access-metro R&F network with optical-wireless interfaces between RPR and WiMAX networks as well as EPON and next-generation WLAN-based mesh networks. Our results show that deploying hierarchical frame aggregation across EPON and wireless mesh networks significantly improves the throughput-delay performance under triple-play traffic.

References

[1] M. Maier, N. Ghazisaidi, and M. Reisslein, "The Audacity of Fiber-Wireless (FiWi) Networks (Invited Paper)," in *Proc., ICST ACCESSNETS*, Las Vegas, NV, USA, Oct. 2008.

[2] T.-S. Chu and M. J. Gans, "Fiber Optic Microcellular Radio," *IEEE Transactions on Vehicular Technology*, vol. 40, no. 3, pp. 599-606, Aug. 1991.

[3] C.-T. Lin *et al.*, "Hybrid Optical Access Network Integrating Fiber-to-the-Home and Radio-Over Fiber Systems," *IEEE Photonics Technology Letters*, vol. 19, no. 8, pp. 610–612, Apr. 2007.

[4] B. L. Dang and I. Niemegeers, "Analysis of IEEE 802.11 in Radio over Fiber Home Networks," in *Proc., IEEE Conference on Local Computer Networks*, Nov. 2005, pp. 744-747.

[5] B. Kalantarisabet and J. E. Mitchell, "MAC Constraints on the Distribution of 802.11 using Optical Fibre," in *Proc., European Conference on Wireless Technology*, Sept. 2006, pp. 238-240.

[6] P. S. Henry, "Integrated Optical/Wireless Alternatives for the Metropolitan Environment," *IEEE Communications Society Webinar*, Apr. 2007.

[7] N. Ghazisaidi and M. Maier, "Fiber-Wireless (FiWi) Networks: Challenges and Opportunities," *IEEE Network*, to appear.

[8] N. Ghazisaidi, M. Maier, and C. M. Assi, "Fiber-Wireless (FiWi) Access Networks: A Survey," *IEEE Communications Magazine*, vol. 47, no. 2, pp. 160–167, Feb. 2009.

[9] A. Chowdhury *et al.*, "Advanced System Technologies and Field Demonstration for In-Building Optical-Wireless Network With Integrated Broadband Services," *IEEE/OSA Journal of Lightwave Technology*, vol. 27, no. 12, pp. 1920–1927, June 2009.

[10] P. Chowdhury *et al.*, "Hybrid Wireless-Optical Broadband Access Network (WOBAN): Prototype Development and Research Challenges," *IEEE Network*, vol. 23, no. 3, pp. 41–48, May/June 2009.

[11] Y. Luo *et al.*, "QoS-Aware Scheduling over Hybrid Optical Wireless Networks," in *Proc., OFC/NFOEC*, Anaheim, CA, USA, Mar. 2007, pp. 1–7.

[12] K. Yang *et al.*, "Convergence of Ethernet PON and IEEE 802.16 Broadband Access Networks and its QoS-Aware Dynamic Bandwidth Allocation Scheme," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 2, pp. 101–116, Feb. 2009.

[13] W.-T. Shaw *et al.*, "Reconfigurable Optical Backhaul and Integrated Routing Algorithm for Load Balancing in Hybrid Optical-Wireless Access Networks," in *Proc., IEEE ICC*, Beijing, China, May 2008, pp. 5697–5701.

[14] S. Sarkar, S. Dixit, and B. Mukherjee, "Hybrid Wireless-Optical Broadband-Access Network (WOBAN): A Review of Relevant Challenges," *IEEE/OSA Journal of Lightwave Technology*, vol. 25, no. 11, pp. 3329–3340, Nov. 2007.

[15] N. Ghazisaidi, F. Paolucci, and M. Maier, "SuperMAN: Optical-Wireless Integration of RPR and WiMAX," *OSA Journal of Optical Networking*, vol. 8, no. 3, pp. 249–271, Mar. 2009.

[16] G. R. Hiertz *et al.*, "IEEE 802.11s - Mesh Deterministic Access," in *Proc., European Wireless Conference*, Prague, Czech Republic, June 2008, pp.1-8.

[17] D. Skordoulis *et al.*, "IEEE 802.11n MAC Frame Aggregation Mechanisms for Next-Generation High-Throughput WLANs," *IEEE Wireless Communications*, vol. 15, no. 1, pp. 40-47, Feb. 2008.

[18] Y. Lin and V. W. S. Wong, "Frame Aggregation and Optimal Frame Size Adaptation for IEEE 802.11n WLANs," in *Proc. IEEE GLOBECOM*, pp. 1-6, San Francisco, CA, USA, Nov.-Dec. 2006.

[19] G. Kramer, B. Mukherjee, and G. Pesavento, "IPACT: A Dynamic Protocol for an Ethernet PON (EPON)," *IEEE Communications Magazine*, vol. 40, no. 2, pp. 74-80, Feb. 2002.