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QoS Provisioning Techniques for Future Fiber-Wireless (FiWi) Access Networks

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Abstract: A plethora of enabling optical and wireless access-metro network technologies have been emerging that can be used to build future-proof bimodal fiber-wireless (FiWi) networks. Hybrid FiWi networks aim at providing wired and wireless quad-play services over the same infrastructure simultaneously and hold great promise to mitigate the digital divide and change the way we live and work by replacing commuting with teleworking. After overviewing enabling optical and wireless network technologies and their QoS provisioning techniques, we elaborate on enabling radio-over-fiber (RoF) and radio-and-fiber (R&F) technologies. We describe and investigate new QoS provisioning techniques for future FiWi networks, ranging from traffic class mapping, scheduling, and resource management to advanced aggregation techniques, congestion control, and layer-2 path selection algorithms.

Keywords: Aggregation; EPON; FiWi; LTE; QoS; RPR; scheduling; SuperMAN; WiFi; WiMAX

1. Introduction

Expecting that optical fiber paves all the way to and penetrates into the home of residential and business customers in the near to midterm, we elaborate on the final frontier of optical networks, namely, the convergence with their wireless counterparts. Due to the difficulty and prohibitive costs of supplying optical fiber to all end-user premises as well as the spectrum limitations of wireless access networks,

hybrid fiber-wireless (FiWi) access networks seem to be more attractive than relying on either stand-alone access solution. FiWi networks are realized by integrating wireless access technologies, e.g., cellular, WiMAX, and WiFi, with installed optical fiber infrastructure that has been pushed ever closer toward end-users over the last few years [1]. Optical and wireless technologies can be thought of as quite complementary and will expectedly coexist over the next decades. Future broadband access networks will be bimodal, capitalizing on the respective strengths of both technologies and smartly merging them in order to realize future-proof 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 [2].

According to the European Telecommunications Standardization Institute (ETSI), fixed mobile convergence (FMC) is concerned with developing network capabilities and supporting standards that may be used to seamlessly offer a set of consistent services via fixed or mobile access to fixed or mobile, public or private, networks, independently of the access technique [3]. FMC can be done at different levels, e.g., business or service provisioning level. Note, however, that FMC does not necessarily imply the physical convergence of networks. FiWi research focuses on the physical (PHY) and medium access control (MAC) layers with the goal to develop and investigate low-cost enabling FiWi technologies as well as layer-2 protocols and algorithms. It is important to note that the higher-layer network capabilities developed through FMC standardization efforts can be exploited on top of the PHY and MAC layers of FiWi networks. At the PHY layer, FiWi research inquires new methods of optical radio frequency (RF) generation exploiting fiber nonlinearities and various modulation techniques. It also includes the study of different remodulation schemes for the design of colorless (*i.e.*, wavelength-independent) remote antenna units (RAUs). While significant progress has been made at the PHY layer of FiWi and in particular radio-over-fiber (RoF) transmission systems, FiWi networking research on layer-2 related issues has begun only very recently. Among others, FiWi layer-2 research includes the joint optimization of performance-enhancing MAC mechanisms separately used in the wireless and optical network segments, e.g., wireless frame aggregation and optical burst assembly, hybrid access control protocols, integrated path selection algorithms, as well as advanced resilience techniques. Layer-2 networking research is crucial to unleash the full potential of quality-of-service (QoS)-aware future FiWi networks [4].

QoS and quality-of-experience (QoE) play a key role in providing various multimedia applications and services over hybrid FiWi networks. From a networking point of view, both QoS and QoE represent challenging issues in heterogeneous networks, especially for streaming media applications [5]. More specifically, while QoS support is achievable by managing the networking layers, QoE requires improvements at the end-user application level. For instance, to provide high-quality mobile IPTV services, key QoS metrics, such as packet loss, bandwidth, delay, jitter, and packet-error ratio, are important [6]. Different techniques might be used for the design of hybrid FiWi networks to deliver QoS-enabled services for mobile end-users, including traffic engineering and service differentiation, optimized buffering, and error-correction at the end-user. Moreover, QoE might be provided by using resource-aware mobile services, such as tuning the transmission rate according to the experience of an end-user. The variability of wireless channel conditions and mobility of wireless end-users might change the qual-

ity of received services which requires quick response times. In this paper, we focus on layer-2 QoS which largely depends on the performance of routing and resource management algorithms, including bandwidth allocation and channel assignment algorithms, with absolute or relative QoS assurances.

The remainder of this paper is structured as follows. Sections 2 and 3 review enabling optical and wireless access-metro network technologies and their underlying QoS provisioning techniques, respectively. In Section 4, we elaborate on enabling FiWi technologies and FiWi network architectures. We also describe new QoS provisioning techniques for future FiWi networks. In Section 5, we study the performance of our proposed QoS provisioning techniques. Section 6 concludes the paper.

2. Optical Access-Metro Networks

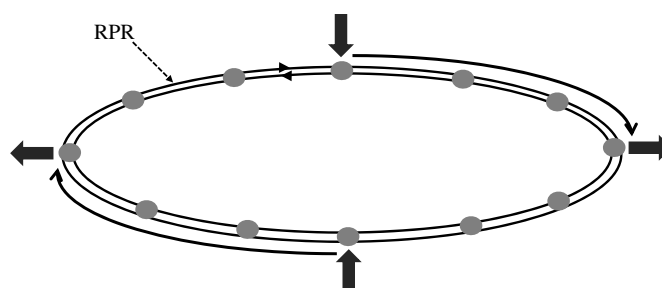
In this section, we review enabling optical access-metro technologies and their QoS provisioning techniques.

2.1. Enabling Optical Technologies

Resilient Packet Ring (RPR)

The resilient packet ring (RPR) [7] architecture and functionality is fully described in the IEEE 802.17 standard. RPR is a packet switched ring-based architecture consisting of two counterdirectional optical fiber ringlets with all nodes performing optical-electronic-optical (OEO) conversion. RPR combines the benefits of SONET/SDH legacy networks, *i.e.*, fast recovery and support of legacy time division multiplexing (TDM) traffic with a high level of QoS, with Ethernet's low equipment cost, statistical multiplexing gain, and simplicity. Spatial reuse is deployed in RPR to improve the bandwidth efficiency by means of destination stripping, which enables the destination node to remove packets from the ring, thus allowing simultaneous communications between nodes on different ring segments, as shown in Fig. 1. Unicast traffic is typically sent on the ringlet spanning the shortest path to the destination. Multicast traffic is realized by means of unidirectional or bidirectional flooding. RPR deploys a topology discovery protocol, which allows each node to maintain information about the number and order of nodes as well as the status of each link. A distributed fairness control protocol is deployed which provides fairness among the nodes [8]. Due to its dual-fiber ring topology, RPR is able to recover from a single link or node failure within 50 ms. Failure recovery is performed by means of wrapping and/or steering [9].

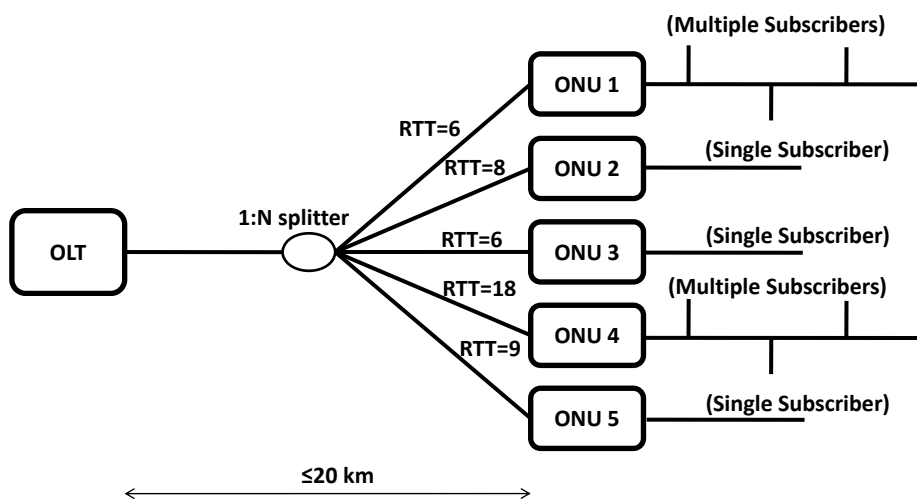
Figure 1. Destination stripping and spatial reuse in RPR.



Ethernet Passive Optical Network (EPON)

Typically, an EPON has a physical tree topology with the central office located at the root and the subscribers connected to the leaf nodes of the tree. In general, the round-trip time (RTT) between OLT and each ONU is different, as illustrated in Fig. 2. An EPON connects the optical line terminal (OLT) located at the central office to multiple ONUs (the customer premises equipment) through a 1 : N optical splitter/combiner at the remote node (RN). Each ONU can serve a single or multiple residential and business subscribers. EPON uses one wavelength for upstream and another wavelength for downstream transmissions. Due to the directional property of the optical splitter/combiner, the OLT is able to broadcast data to all ONUs in the point-to-multipoint (PMP) downstream direction. In the upstream direction, however, ONUs cannot communicate directly with one another. Instead, each ONU is able to send data only to the OLT (multipoint-to-point). TDM allows all ONUs to share either wavelength without channel collisions. To facilitate dynamic bandwidth allocation (DBA) and arbitrate the upstream transmissions of multiple ONUs, the so-called multipoint control protocol (MPCP) specified in IEEE 802.3ah is deployed in EPON. In addition to auto-discovery and registration, MPCP uses two polling messages (*i.e.*, REPORT and GATE) to facilitate arbitration. The REPORT message is used by each ONU to report bandwidth requirements of up to eight priority queues to the OLT. The GATE message is generated by the OLT and contains up to four transmission grants per ONU. Note that no specific DBA algorithm is specified in IEEE 802.3ah [10].

Figure 2. Network architecture of an EPON with one OLT and N = 5 ONUs, each with a different RTT.



2.2. Optical QoS Provisioning Techniques and Mechanisms

In this section, we describe the QoS provisioning techniques and mechanisms proposed for RPR and EPON networks.

Traffic Classes

RPR supports three different traffic classes: (i) **Class A** assures high priority, low latency and jitter service with guaranteed bandwidth (e.g., voice); (ii) **Class B** traffic offers medium priority with predictable latency and jitter service (e.g., video); and (iii) **Class C** offers low priority and best-effort service (e.g., web browsing). Traffic classes A and B are divided into two subclasses, *i.e.*, A0, A1, B-CIR (committed information rate), and B-EIR (excess information rate), respectively. Bandwidth is pre-allocated for classes A0, A1, and B-CIR. A0 bandwidth is called *reserved* and each RPR node informs the amount of required bandwidth by means of the topology discovery protocol. The reserved A0 bandwidth cannot be reclaimed by another node, even if the corresponding source node does not use it. The remaining amount of bandwidth is called *unreserved*. A portion of the unreserved bandwidth, called *reclaimable bandwidth*, is pre-allocated for classes A1 and B-CIR. Unused reclaimable bandwidth and the remaining bandwidth may be used by classes B-EIR and C.

While the above-mentioned three traffic classes are typically found in metro-access technologies, eight traffic classes are defined in EPON. However, IEEE 802.1D layer-2 bridges might be used to map these traffic classes. IEEE 802.1D is the bridge standard which applies IEEE 802.1p to provide QoS support for bridged traffic [11]. The IEEE 802.1p standard defines eight traffic classes for Ethernet local area networks (LANs). More specifically, IEEE 802.1p uses 3 bits of each Ethernet frame header to specify its traffic class based on given QoS requirements.

Scheduling and Resource Management

Each RPR node may consist of one or two transit queues: a primary transit queue (PTQ) and a secondary transit queue (STQ), whereby the PTQ is mandatory and the STQ is optional. In the dual-queue mode, traffic class A is buffered in the PTQ, while the STQ stores in-transit traffic of classes B and C. Control packets and packets buffered in the PTQ and STQ are transferred according to the following access policies. In general, PTQ traffic is given priority over STQ traffic. If the PTQ is empty, local traffic is served until the STQ reaches a certain threshold; once the threshold is reached, priority is given to STQ traffic. These mechanisms, under stable conditions, assure that in-transit packets are not dropped by intermediate nodes. It is worthwhile to note that traffic class A experiences only the propagation delay and, occasionally, queuing delay due to a local packet transmission. Packets subject to fairness control belong only to B-EIR and C traffic classes, also known as fairness eligible (FE) classes. RPR nodes are not allowed to use reclaimable or reserved bandwidth for FE packets.

In EPON, different queues of an ONU store different classes of traffic with different QoS requirements. To support QoS in EPON, two scheduling methods are considered: (i) **intra-ONU scheduling**, where the scheduling is performed at a given ONU according to its priority queues, and (ii) **inter-ONU scheduling**, where the scheduling of each queue is performed at the OLT. The following two strategies were proposed to implement these two scheduling paradigms [12]:

- **Direct (single-level) scheduling:** allows the OLT to perform both inter-ONU and intra-ONU scheduling [13]. In this approach, a scheduler located in the OLT receives information from and individually schedules each queue located in the ONUs. As the information about each queue is collected in one place, the centralized scheduler can easily ensure that the required service guarantees are

preserved and that the excess bandwidth is fairly divided among backlogged queues. The OLT can generate multiple grants, each for a specific traffic class, to be sent to the ONUs using GATE messages [14]. Using a unique logical link identifier (LLID) for each queue allocated by the scheduler eliminates any need for low-level schedulers or ingress shapers in the ONU and gathers all the intelligence in the OLT.

- Hierarchical (multi-level) scheduling: allows the OLT to perform inter-ONU scheduling while each ONU performs intra-ONU scheduling [13]. In this scheme, each ONU requests the OLT to allocate bandwidth based on its buffer occupancy status. The OLT only allocates the requested bandwidth to each ONU while it has no information about the internal queue structure of each ONU. Each ONU divides the allocated bandwidth among its different service classes based on their QoS requirements and schedules the transmissions of different priority queues within the allocated transmission window. In the hierarchical EPON scheduling scheme, the OLT receives a single REPORT message from each ONU and sends a single GATE message to each one. As a result, this scheme is scalable with the number of queues.

The important task of intra-ONU scheduling in providing QoS is class-based bandwidth allocation. Class-based bandwidth allocation is achieved by collecting the REPORT messages from all ONUs before making decisions. In strict priority intra-ONU scheduling, the OLT assigns fixed bandwidth to expedited forwarding (EF) traffic [15]. The leftover bandwidth is granted to assured forwarding (AF) requests. The remaining bandwidth after serving EF and AF traffic is distributed among best effort (BE) requests. The so-called light-load penalty is the major problem of this scheme where fixed bandwidth allocation for EF traffic may penalize AF and BE traffic by increasing frame delay and long report collection time. The following two methods were proposed to solve the light-load penalty in EPONs:

1. Two-stage buffers (tandem queue at ONU): in this scheme, a priority queue and a single first-in first-out (FIFO) queue are deployed in the first and second stage, respectively. At a given time slot, each ONU transmits traffic from the second stage, while the first stage forwards traffic to the second stage in a priority order. At the end of each time slot, the ONU reports the current occupancy of the second stage buffer to the OLT [13]. Although this scheme eliminates the light-load penalty problem, two-stage buffers increase delay for higher priority classes, *i.e.*, EF traffic.
2. Credit-based slot size: in this method, the ONU predicts the amount of high-priority packets that are expected to arrive. The prediction is done for constant bitrate (CBR) flows (*i.e.*, EF traffic), where the intra-ONU scheduler increases the size of requested bandwidth in its REPORT message based on the statistical history of previous cycles [14].

In [16], the so-called DBA with multiple services (DBAM) algorithm has been proposed to accommodate various types of traffic in EPONs. DBAM applies priority queuing to store EF, AF, and BE traffic. It adopts the limited bandwidth allocation scheme to arbitrate bandwidth allocation among ONUs and employs class-based traffic prediction of frames arriving during the waiting time in order to reduce delay and queue length in addition to overcoming the light-load penalty.

3. Wireless Access-Metro Networks

In this section, we review enabling wireless access-metro technologies and their QoS provisioning techniques.

3.1. Enabling Wireless Technologies

Long Term Evolution (LTE)

LTE has been defined by the third generation partnership project (3GPP). The first amendment of LTE (release 8) provides a transmission rate of 300 Mbit/s and operates in both time division duplex (TDD) and frequency division duplex (FDD) modes. LTE aims at providing a smooth evolution from earlier 3GPP and 3GPP2 cellular networks such as wide-band code division multiple access/high-speed packet access (WCDMA/HSPA) and code division multiple access (CDMA2000) [17]. In 2008, LTE-Advanced (also known as requirements for further advancements for evolved-universal terrestrial radio access) was initiated to enhance LTE radio access in terms of system performance and capabilities [18]. To support the requirements of international mobile telephony (IMT)-Advanced [19], the following characteristics are considered for LTE [17]:

1. **Carrier aggregation**, where multiple fixed bandwidth carriers are aggregated to support huge transmission bandwidth with very high transmission rates, e.g., the 20 MHz carriers are aggregated to a bandwidth of up to 100 MHz.
2. **Relaying support**, to increase coverage and decrease deployment cost.
3. **Extended multi-antenna transmission**, to increase the number of downlink/uplink transmissions which enlarges the total transmission rate.
4. **Coordinated multipoint (CoMP) transmission/reception**, where multiple cells perform transmission/reception simultaneously to improve the performance of cell-edge nodes.
5. **Backward compatibility**, where both first LTE released end-users and LTE-Advanced end-users are able to access the network, thereby providing a cost-efficient pay-as-you-grow migration.

WiMAX

The initial IEEE 802.16 WiMAX standard was established in the frequency band of 10-66 GHz, providing up to 75 Mbit/s line-of-sight (LOS) connections in terms of both PMP and mesh modes. IEEE 802.16a provides non-LOS connections in the frequency band of 2-11 GHz (licensed and unlicensed). IEEE 802.16 is a connection-oriented standard, *i.e.*, prior to transmitting data between subscriber stations (SSs) and base station (BS), connections must be established. Each connection is identified by a 16-bit connection identifier (CID). The WiMAX MAC layer is responsible for assigning CIDs as well as allocating bandwidth to SSs. It consists of the following three sublayers: (*i*) convergence sub-layer (CS), whereby different higher-layer protocols are implemented in different CSs, e.g., ATM CS and packet CS are used for ATM and Ethernet networks, respectively; (*ii*) common part sub-layer (CPS),

which is responsible for bandwidth allocation and generating MAC protocol data units (MPDUs); and (iii) security sub-layer [20]. The IEEE 802.16e (known as Mobile WiMAX) standard offers scalability in both radio access technology and network architecture. While the spectrum allocation is applied as a radio access technology of Mobile WiMAX, its flexibility in network deployment provides various services [21].

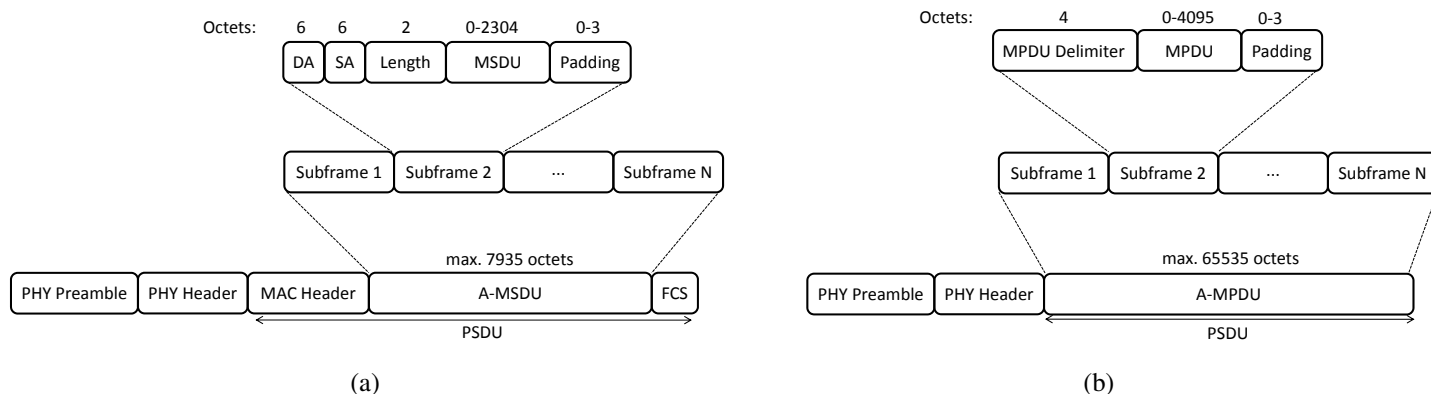
WiFi

Another wireless network standard, known as WiFi, is IEEE 802.11 [20]. Due to the use of unlicensed frequency bands (2.4 GHz with 14 distinct channels) in IEEE 802.11b/g, providing up to 11/54 Mbps data rate, WiFi networks have gained much attention.

Next-generation WLANs offer a throughput of at least 100 Mb/s measured at the MAC service access point (SAP). The IEEE 802.11n draft 5.0 provides both PHY and MAC enhancements [22]. As shown in Fig. 3, the main MAC enhancement of 802.11n is frame aggregation which comes in two flavors [23]:

- **A-MSDU:** Aggregate MAC service data unit (A-MSDU) is used to join multiple MSDU subframes (see Fig. 3(a)). Specifically, a high-throughput (HT) wireless station (STA) packs multiple MSDUs with possibly different destination addresses into one MAC protocol data unit (MPDU) and sends it to the HT access point (AP). An HT AP is allowed to pack multiple MSDUs into one MPDU, whereby all constituent MSDU subframes must be destined to the same HT STA. In either direction, all constituent MSDU subframes must have the same traffic identifier (TID) value (*i.e.*, same QoS level).
- **A-MPDU:** Aggregate MAC protocol data unit (A-MPDU) is used to join multiple MPDU subframes (see Fig. 3(b)). Specifically, multiple MPDUs with the same receiver address are packed into one PHY service data unit (PSDU).

Figure 3. Frame aggregation schemes in next-generation WLAN: (a) A-MSDU, and (b) A-MPDU.



It is important to note that both A-MSDU and A-MPDU require only a single PHY preamble and PHY header. In A-MSDU, the PSDU includes a single MAC header and frame check sequence (FCS),

as opposed to A-MPDU where each MPDU subframe contains its own MAC header and FCS. Due to the resultant lower overhead, A-MSDU is able to achieve a higher throughput than A-MPDU for error-free channels. For error-prone channels, however, the throughput of A-MSDU decreases quickly which indicates the lower robustness of A-MSDU. Thus, adaptively using A-MSDU under good channel conditions and A-MPDU under bad channel conditions yields better performance [24]. Note that A-MPDU and A-MSDU can be used separately or jointly. It was shown in [23] that joint two-level aggregation is able to achieve a higher throughput efficiency. In this approach, the maximum size of A-MSDU is restricted to 4095 octets. Finally, it is worthwhile to note that fragmentation of MSDUs and A-MSDUs with the same receiver address is allowed.

Although most deployed WLANs are based on the IEEE standard 802.11a/b/g or the emerging IEEE standard 802.11n, the recent amendment IEEE 802.11s provides mesh capability by converging the advantages of different routing protocols [25]. IEEE 802.11s, also known as wireless mesh network (WMN) defines the hybrid wireless mesh protocol (HWMP) which is inspired by a combination of on-demand and tree-based pro-active routing algorithms [26]. While ad-hoc on-demand distance vector (AODV) is used for peer-to-peer transmissions between fixed or mobile mesh nodes, called mesh points (MPs), the tree-based routing protocol is applied to provide MPs with access to the wired distribution system (DS) through fixed gateway nodes, called mesh portal points (MPPs) [27]. In WMNs, the mesh access point (MAP) is a special type of MP equipped with the additional capability of an AP to provide service to STAs. In addition to routing, WMNs face several challenges such as security and QoS, which must be considered and addressed in IEEE 802.11s [28]. Recently, IEEE 802.11s and its challenges have been discussed in greater detail in [29] and some experimental work has been reported in [30], [31], and [32].

3.2. Wireless QoS Provisioning Techniques and Mechanisms

In this section, we describe the QoS provisioning techniques and mechanisms designed for LTE, WiMAX, and WiFi networks.

Traffic Classes

While LTE is designed to support end-to-end QoS for any IP-based traffic [33], IEEE 802.16e defines the following five scheduling services to support different traffic classes:

1. **Unsolicited grant service (UGS):** it provides fixed-size interval transmission opportunities without the need for requests or grants.
2. **Real-time polling service (rtPS):** it allows the BS to offer periodic request opportunities to a specific SS in order to indicate its required bandwidth.
3. **Extended-real-time polling service (ErtPS):** it is able to offer unsolicited unicast grants, similarly to UGS, and to change the size of the bandwidth grant dynamically.
4. **Non-real-time polling service (nrtPS):** it provides fairness by means of allocating the contention and regular unicast request opportunities in the uplink bandwidth request (UL-request) of each SS.

Unicast request opportunities are offered regularly in order to ensure that the SS has a chance to request bandwidth even in a congested network environment.

5. **BE:** it is based on contention and provides non-regular unicast request opportunities.

In WiFi networks, the amendments IEEE 802.11e and IEEE 802.11n are designed to provide QoS support for mobile STAs. In IEEE 802.11e, the hybrid coordination function (HCF) is used for providing parameterized (*i.e.*, absolute) and prioritized (*i.e.*, relative) QoS. HCF uses a contention-based channel access method, known as enhanced distributed channel access (EDCA), that operates concurrently with a polling-based HCF-controlled channel access (HCCA) method [34]. HCCA uses the eight traffic classes of IEEE 802.1D, while EDCA deploys four different access categories (ACs), each associated with a different channel access priority.

Scheduling and Resource Management

The resource management and scheduling of LTE are monitored by the link layer which consists of three sublayers [33]: (*i*) packet data convergence protocol (PDCP) sublayer, which is responsible for handover, IP header compression, and ciphering; (*ii*) radio link control (RLC) sublayer, which performs data segmentation and concatenation; and (*iii*) MAC sublayer, which is responsible of resource management and scheduling. Compared to third generation (3G) cellular networks, the link layer protocols of LTE are designed to enhance QoS by increasing their reliability, security, and integrity.

In LTE networks, each end-user applies the scheduling request (SR) mechanism to send a request to access the channel. In the SR mechanism, an end-user reports the amount of data buffered in its queues, known as buffer status report (BSR). Typically, the following two mechanisms are defined to perform resource management by means of SR: (*i*) dedicated SR (D-SR), where each end-user should send its SR on a dedicated resource over the physical uplink-control channel (PUCCH) to the BS, called enhanced NodeB (eNB), and (*ii*) random access-based SR (RA-SR), where the end-user should use a four-phase contention-based random access procedure [33]. We note that RA-SR is used if no PUCCH resources for D-SR are assigned to the end-user.

Unlike conventional cellular networks, e.g., global system for mobile communications (GSM), where the channels are dedicated to high-priority QoS-enabled end-users, in LTE end-users apply a shared uplink and a shared downlink channel. In [35], a combined admission control and time-frequency domain scheduling framework was proposed to support QoS and service differentiation for the LTE uplink. It is important to note that no specific scheduling and resource assignment scheme was standardized. The deployed scheduling algorithm in the eNB is responsible to meet the QoS requirements of different traffic classes according to instantaneous channel conditions and/or fairness allocation policies [36]. The scheduler selects both the appropriate end-user and radio bearer for downstream, while in upstream, the uplink scheduling grants are assigned to end-users without specifying the radio bearer. Since the end-user sends BSRs for pre-allocated active radio bearers, the eNB ensures that users with high-priority data are given preference and obtain the assigned QoS. The scheduling grants are carried to end-users on the physical downlink-control channel (PDCCH) [33].

For deploying LTE under realistic wireless channel conditions, a two-layered retransmission scheme, called hybrid-automatic repeat request (HARQ) protocol, is proposed to handle occasional retransmis-

sion errors. The MAC and RLC sublayers deploy the HARQ protocol to provide a highly reliable selective-repeat ARQ. This protocol aims at reliably transferring traffic with low latency and low overhead [17]. Furthermore, LTE is able to perform channel-dependent scheduling in both time and frequency domains in order to synchronize itself with rapid channel-quality variations (*i.e.*, fading) [37]. For low data rate applications, e.g., voice-over-IP (VoIP), where the additional channel-dependent scheduling overhead is not efficient, LTE uses space-frequency block coding (SFBC) for transmit diversity [17].

No specific scheduling algorithm is standardized to support different types of data flows and QoS for WiMAX SSs. The requested services of each SS are first registered during the initialization phase and connections are established subsequently. If a given SS changes its services, additional connections can be established in the network. Each connection is associated with a service flow (SF). An SF is defined based on available scheduling services and includes a set of QoS parameters, an SF identifier (SFID), and a CID [21]. To implement WMNs, two scheduling types are used: (*i*) centralized and (*ii*) distributed. In the centralized scheduling mode, such as the PMP, each Mesh-SS (MSS) sends its request to the mesh-BS (MBS) that manages the network. In the distributed scheduling mode, each MSS distributes its scheduling information and one-hop neighbors to all its adjacent MSSs. A three-way handshake mechanism is deployed for bandwidth allocation. Coordinated (collision-free) and uncoordinated (non-collision-free) methods are used for distributed scheduling. The two different mesh scheduling methods can be applied together by subdividing the data part of the frame into two parts, one for centralized scheduling and another one for distributed scheduling [20]. Generally, WiMAX applies three different types of SFs: (*i*) provisioned SFs, which are represented by an SFID; (*ii*) admitted SFs, which show the admitted requests for the available resources and/or SFs; and (*iii*) active SFs which exhibit the allocated resources and/or SFs. Each SS must send an UL-request to the BS, and the BS responds with an uplink bandwidth grant (UL-grant) subsequently. The UL-grant services assign bandwidth based on the QoS parameters of that connection. Although bandwidth requests are per connection, the BS does not allow to grant the entire uplink capacity to a single SS. When an UL-grant is sent by the BS, the receiver SS cannot change or share the size of the granted bandwidth [38]. In IEEE 802.16, there are two modes of transmitting the UL-requests: (*i*) contention mode and (*ii*) contention-free mode (polling). In the contention mode, SSs send their UL-requests during the contention period, whereby contention is resolved by means of back-off. In contention-free mode, the BS polls each SS and SSs reply by sending UL-requests.

In WiFi, the so-called transmission opportunity (TXOP) is the main new MAC enhancement of HCF. In EDCA, a QoS-enhanced STA (QSTA) and, in HCCA, a QoS-enhanced access point (QAP) generate the TXOP to allow a QSTA to transmit a burst of data frames, separated only by a short inter-frame space (SIFS) from each other. In HCCA, QSTAs report their QoS requirements for each traffic class to the QAP by means of traffic specification (TSPEC) frames. A TSPEC describes the traffic characteristics and QoS requirements for a given traffic flow, also referred to as traffic stream (TS), e.g., minimum and maximum service interval, minimum data rate, and delay bound. A TID is applied by MAC clients to distinguish MAC service data units (MSDUs) for the MAC entity that supports QoS differentiation via different service classes. There are sixteen possible TID values, whereby eight identify traffic classes and eight identify parameterized TSs. The IEEE standard 802.11n does not specify any particular scheduling algorithm. Scheduling can be done in two ways: inter-QSTA scheduling and intra-QSTA scheduling.

Inter-QSTA scheduling arbitrates the transmissions of different QSTAs, while intra-QSTA scheduling arbitrates the transmissions of different traffic classes or AC queues in each QSTA. There are two possible implementation methods. Either inter-QSTA scheduling is implemented at the QAP or TXOP holder, and each QSTA performs its own intra-QSTA scheduling, or both inter-QSTA and intra-QSTA scheduling are implemented at the QAP or TXOP holder. During a TXOP, a single block acknowledgment request (BAR) frame is transmitted at the end of data transmission by the TXOP holding QSTA. The receiving STA replies with a block acknowledgment (BA) frame to confirm the frames that were correctly received. Moreover, IEEE 802.11e is able to provide direct connections between QSTAs by using the so-called direct link protocol (DLP). In a direct connection, the QAP can monitor the involved QSTAs by sending beacons periodically.

In IEEE 802.11n, HT STA and HT AP are able to provide QoS like the aforementioned QSTA and QAP in IEEE 802.11e. If an HT STA, which gains access to the channel using EDCA, runs out of frames to transmit, a TXOP holding HT STA can transmit a contention free end (CF-End) frame to truncate the TXOP and thereby improve bandwidth-efficiency. The reverse direction (RD) protocol provides bidirectional TXOP connections. More precisely, during an RD exchange sequence, the RD initiator can transmit PHY protocol data units (PPDUs) and obtain response PPDUs from the RD responder in a single TXOP. In the HT control field of an IEEE 802.11n PPDUs, the RD grant (RDG)/More PPDUs field is used to indicate the RD permission and the last transferred PPDUs. In EDCA, an RD responder must transmit the same type of AC data frames as received, while in HCCA an RD responder is allowed to transmit data frames of any TID. Bandwidth-efficiency is further improved by means of a reduced inter-frame space (RIFS) in HT greenfield deployments that cuts down the dead time between frame transmissions. In HCCA, power save multi-poll (PSMP) is one of the new MAC layer features of next-generation WLAN to improve bandwidth-efficiency. The HT AP sends a PSMP frame in order to schedule the upstream and downstream transmissions of HT STAs, also known as uplink transmission time (UTT) and downlink transmission time (DTT), respectively. In a PSMP frame, the PSMP-UTT and PSMP-DTT fields indicate the durations of uplink and downlink streams dedicated to each HT STA. The PPDUs transmitted between PSMP-UTT and PSMP-DTT are separated by SIFS, while the PPDUs transmitted within them may be separated by RIFS or SIFS [22].

4. QoS Provisioning Techniques for Future FiWi Networks

4.1. Enabling FiWi Technologies

Various optical RF generation techniques have been proposed to avoid the electronic bottleneck, such as all-optical wavelength up-conversion by means of cross-absorption modulation (XAM) in an electroabsorption modulator (EAM) or four-wave mixing (FWM) in nonlinear dispersion-shifted fiber. According to [39], external intensity and phase modulation (PM) schemes are currently the most practical solutions for all-optical RF generation due to their low cost, simplicity, and long-distance transmission performance.

For multi-user modulation support, different multiplexing techniques, such as wavelength division multiplexing (WDM) and sub-carrier multiplexing (SCM), have been considered. For instance, the joint distribution of ultra wideband (UWB) and WiMAX radio signals over PON using single- and orthogonal-

polarization multiplexing was proposed in [40]. In this approach, both UWB and WiMAX signals are modulated by an external orthogonal frequency division multiplexing (OFDM) modulator, while they are jointly transmitted by means of polarization multiplexing. The reported results illustrate the feasibility of polarization multiplexing over a 25 km single-mode fiber (SMF) PON with tolerable error vector magnitude (EVM) penalties.

To provide a low-cost flexible optical backhaul for FiWi networks, remote modulation techniques might be used, where a central light source is used at the central office (CO) to generate a downlink wavelength that is reused at RAUs for upstream transmission by means of remote modulation. It is important to note that by using remote modulation techniques, there is no need for an additional light source at each RAU. Different remodulation schemes were experimentally studied in [39], such as PM for downstream/directly modulated semiconductor optical amplifier (SOA) for upstream, where an optical carrier is combined with an RF signal, generated by means of PM, and sent downstream using a fiber Bragg grating (FBG) at the RAU to reflect the optical carrier and pass the RF signal. The reflected optical carrier is amplified and directly modulated with upstream data using an SOA.

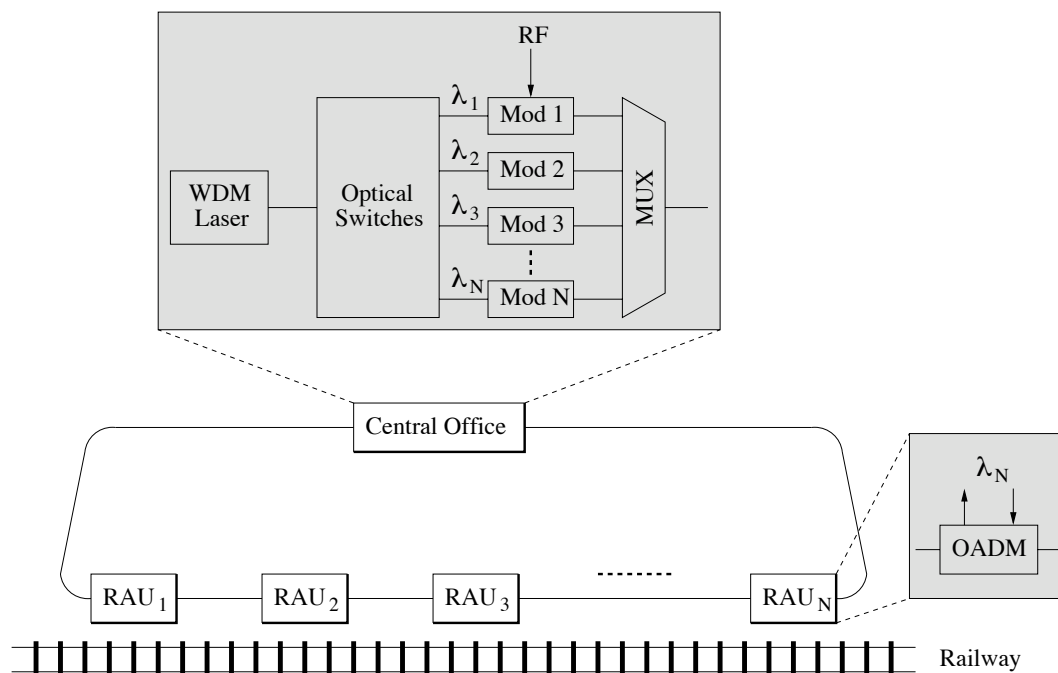
In FiWi networks, different enabling optical and wireless technologies may be used. Among others, RPR and EPON are expected to play an important role in the design of a flexible and cost-effective optical backhaul. Other key FiWi technologies are tunable transceivers, burst-mode laser drivers and receivers, and colorless ONUs [41]. Moreover, emerging broadband wireless access technologies (*i.e.*, LTE, WiMAX, and WiFi) might be considered for triple-play QoS support of cellular and wireless end-users over a flexible and user-friendly platform.

4.2. FiWi Architectures

Recently, various FiWi network architectures were surveyed in [42]. In this section, we briefly review the state-of-the-art of FiWi network architectures, including FiWi network design proposals not covered in [42].

Typically, cellular networks (such as LTE) are used for fast moving users, *e.g.*, train passengers. They suffer from frequent hand-overs when hopping from one BS to another one. The frequent hand-overs may cause numerous packet losses, resulting in a significantly decreased network throughput. An interesting approach to avoid hand-overs in cellular networks for train passengers is the use of an optical fiber WDM ring-based FiWi network installed along the rail tracks in combination with the moving cell concept, as recently proposed in [43]. Fig. 4 depicts the moving cell-based FiWi network architecture using an optical fiber WDM ring to interconnect the RAUs with the CO, where all processing is performed. Each RAU deploys an optical add-drop multiplexer (OADM) fixed tuned to a separate wavelength channel. At the CO, a WDM laser generates the desired wavelengths, which are optically switched and passed to an array of RF modulators, one for each RAU. The modulated wavelengths are multiplexed onto the optical fiber WDM ring and received by each addressed RAU on its assigned wavelength. An RAU retrieves the RF signal and transmits it to the antennas of a passing train. In the upstream direction, the RAU receives all RF signals and sends them to the CO for processing. By processing the received RF signals, the CO is able to keep track of the train location and identifying the RAU closest to the moving train. It then assigns downstream RF signals to the corresponding RAU such that the train and moving cells move along in a synchronous fashion.

Figure 4. Moving cell-based RoF network architecture for train passengers [43].



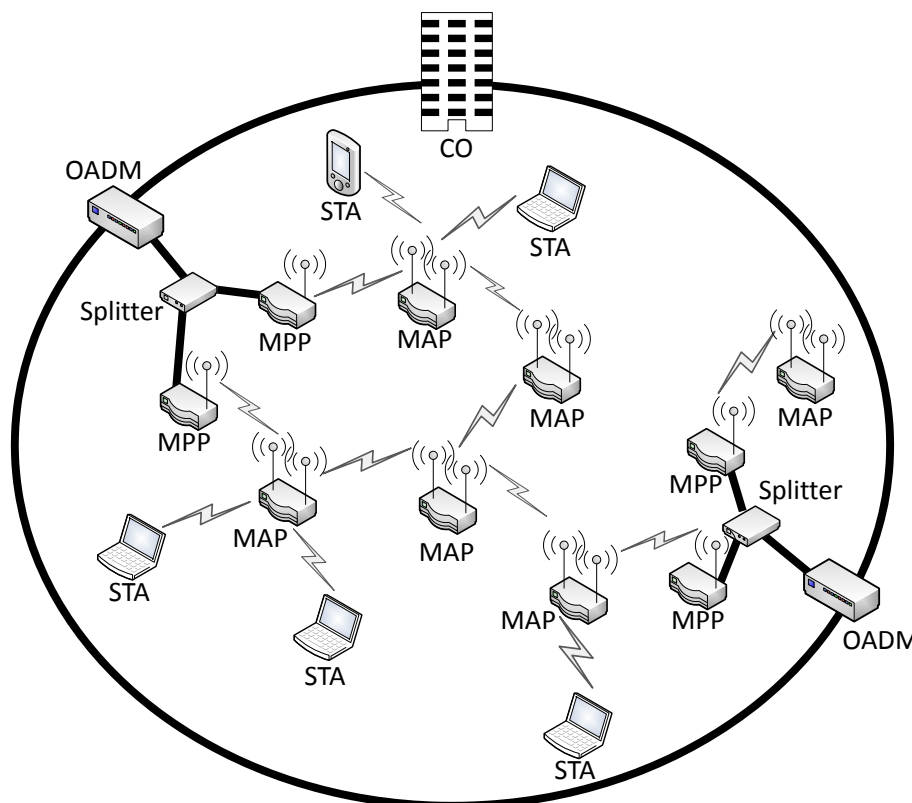
To provide connectivity for movement of end-users in any possible direction, the *moving extended cell* concept was proposed in [44]. A hybrid frequency division multiplexing (FDM)/WDM network architecture was used to support the delivery of multiple RF channels in the 60 GHz frequency band over the same wavelength. The extended cell involves the current user’s cell and the surrounding cells ensuring connectivity for any random direction. It is adaptively restructured when the user enters a new cell. It was shown that the proposed concept can provide zero packet loss and call dropping probability in high-rate wireless services for a wide range of mobile speeds of up to 40 m/sec, independently of the fiber link distances.

As mentioned above, both EPON (and PON in general) and WiMAX networks have a PMP topology with a central control station (OLT in EPON and BS in WiMAX) performing DBA by means of centralized polling and scheduling. These similarities give rise to interesting convergence problems whose optimization is expected to lead to an improved FiWi network performance. According to [45], the integration of EPON and WiMAX access networks can be done in several ways, ranging from independent and unified connection-oriented to microwave-over-fiber architectures.

The FiWi network proposed in [46] consists of an optical WDM backhaul ring with multiple single-channel or multi-channel PONs attached to it, as shown in Fig. 5. More precisely, an OADM is used to connect the OLT of each PON (located at the CO) to the WDM ring. In this figure, MPPs are used to bridge PONs and WMN. In the downstream direction, data packets are routed from the CO to the MPPs through the optical backhaul and are then forwarded to the STAs by MAPs. In the upstream direction, MAPs forward data packets to one of the MPPs, where they are subsequently transmitted to the CO on one of the wavelength channels of the optical backhaul WDM ring, as each PON operates on a separate dynamically allocated wavelength channel. Since the optical backhaul and WMN use different technologies, an interface is defined between each ONU and the corresponding MPP in order to monitor

the WMN and perform route computation taking the state of wireless links and average traffic rates into account. When the traffic demands surpass the available PON capacity, some of the TDM PONs may be upgraded to WDM PONs. If some PONs are heavily loaded and others have less traffic, some heavy-loaded ONUs may be assigned to a lightly-loaded PON by tuning their optical transceivers to the wavelength assigned to the lightly-loaded PON.

Figure 5. Unidirectional ring/PON architecture integrated with a WiFi-based WMN [46].

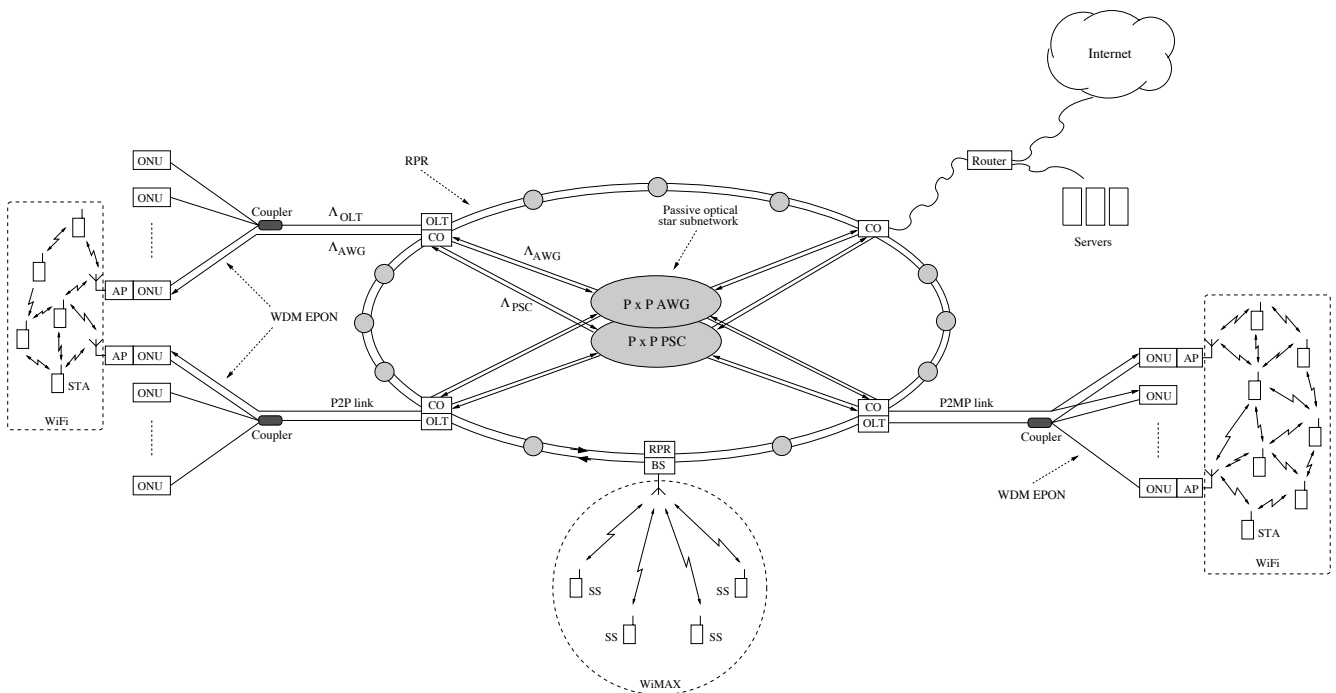


In [2], the proposed SuperMAN architecture leverages on the similarities of EPON and WiMAX in that the two technologies are more likely to target the same network segment rather than being cascaded to cover different network segments. In other words, SuperMAN provides the network operators with the ability to make a choice between EPON and WiMAX depending on a number of factors, e.g., right-of-way and techno-economic justification [47]. It seems somewhat impractical to deploy a metropolitan-reach wireless technology such as WiMAX for realizing wireless drop lines of rather short length to or inside offices and homes. Instead, using next-generation low-cost WiFi technologies in conjunction with WDM-enhanced EPON access networks while integrating WiMAX with RPR appears to be a more promising approach.

Fig. 6 depicts the network architecture of SuperMAN [2]. It builds on an all-optically integrated Ethernet-based access-metro network, described at length in [48], extended by optical-wireless interfaces with next-generation WiFi and WiMAX networks. More specifically, the optical part of SuperMAN consists of an RPR metro network that interconnects multiple WDM EPON access networks attached to a subset of RPR nodes. Each of the attached WDM EPONs has a tree topology with the OLT at the root tree being collocated with one of the COs. No particular WDM architecture is imposed on the

ONUs, thus allowing the decision to be dictated by economics, state-of-the-art transceiver manufacturing technology, traffic demands, and service provider preferences. The recommended WDM extensions to the IEEE 802.3ah MPCP, described in greater detail in [49], guarantee backward compatibility with legacy TDM EPONs and enable the OLT to schedule transmissions to and receptions from ONUs on any supported wavelength channel. 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 collocated OLTs/COs with a passive optical star subnetwork whose hub consists of an athermal wavelength-routing $P \times P$ arrayed waveguide grating (AWG) in parallel with a wavelength-broadcasting $P \times P$ passive star coupler (PSC). The aforementioned optical part of SuperMAN interfaces with next-generation WiFi and WiMAX networks, as shown in Fig. 6.

Figure 6. SuperMAN architecture: integrating next-generation WiFi technologies with WDM EPON and next-generation WiMAX technologies with RPR.



4.3. FiWi QoS Provisioning Techniques and Mechanisms

Traffic Class Mapping, Scheduling, and Resource Management

In [50], centralized and distributed scheduling approaches were proposed for the integration of EPON and WiMAX. The simulation results demonstrate the improvement of network throughput and end-to-end delay for different QoS demands. The integrated QoS-aware DBA scheme proposed in [51] supports bandwidth fairness at the ONU-BS interface, while the WiMAX SSs perform class-of-service bandwidth assignment. The reported results show the improvement of network throughput, delay, and bandwidth utilization.

Figure 7. Optical-wireless interface between RPR and WiMAX networks.

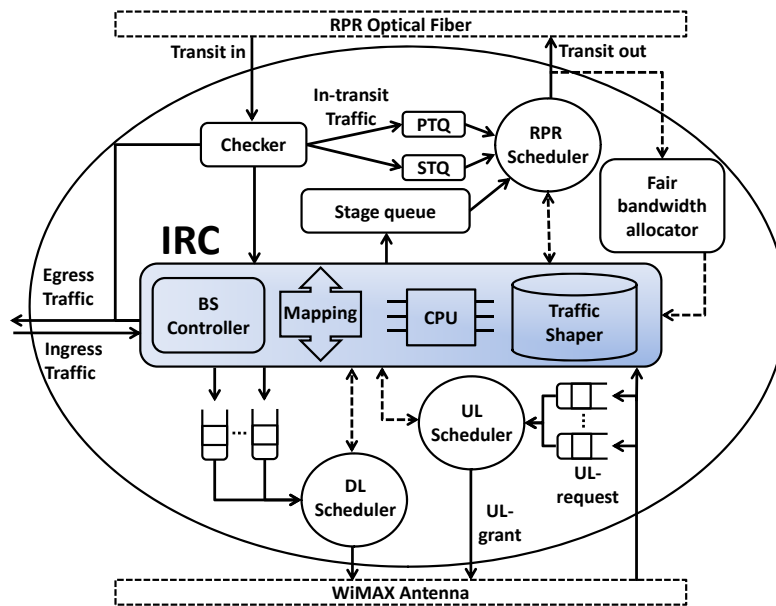


Figure 8. Hierarchical WiMAX scheduling algorithm of an RPR/WiMAX interface node.

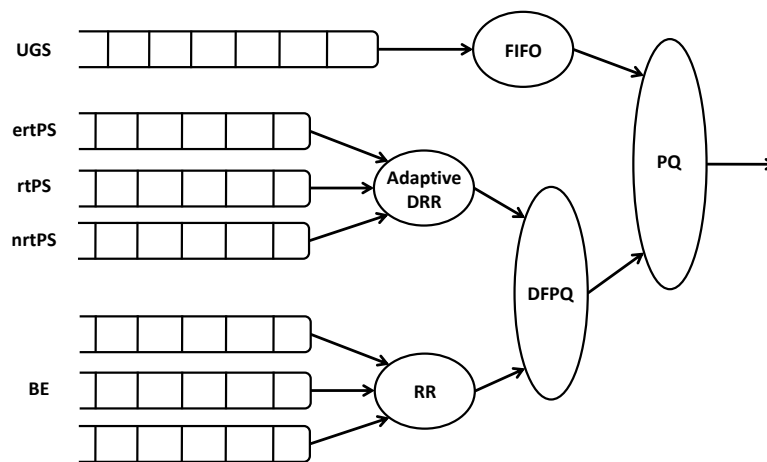


Fig. 7 depicts the optical-wireless interface between an RPR metro edge ring and a WiMAX access network, where the so-called integrated rate controller (IRC) plays a key role in integrating the two networks [52]. It comprises a BS controller, a traffic class mapping unit, a central processing unit (CPU), and a traffic shaper. The IRC is used to seamlessly integrate both networks and jointly optimize the RPR scheduler and WiMAX downlink (DL) and uplink (UL) schedulers. The BS controller is responsible for handling incoming and outgoing WiMAX traffic, besides providing hand-over for SSs between different interface nodes. The traffic class mapping unit is able to translate the different WiMAX and RPR traffic classes bidirectionally. The traffic shaper checks 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. As mentioned

in Section 2, RPR specifies traffic classes A, B, and C, while WiMAX specifies UGS, ErtPS, rtPS, nrtPS, and BE scheduling services. According to the aforementioned properties of RPR traffic classes and WiMAX scheduling services, bidirectional traffic classes are mapped as shown in Table 1.

Table 1. Bidirectional mapping of RPR traffic classes and WiMAX scheduling services.

RPR Traffic Classes	WiMAX Scheduling Services	Applications
A0: Low latency and jitter, pre-allocated reserved bandwidth	UGS: Unsolicited grant service, reserved fixed-size grants	Real-time fixed-size data packets on a periodic basis, without silence suppression (VoIP, T1, and E1 voice service)
A1: Low latency and jitter, pre-allocated unreserved reclaimable bandwidth	ErtPS: Extended real-time, efficiency of both UGS and rtPS polling service, dynamic size allocations	Delay-sensitive real-time flows, variable-size data packets on a periodic basis (VoIP with activity detection)
B-CIR: Committed information rate, predictable latency and jitter, pre-allocated unreserved reclaimable bandwidth	rtPS: Real-time polling service, real-time unicast request opportunities	Real-time flows of variable-size data packets on a periodic basis (streaming audio-video, MPEG)
B-EIR: Excess information rate, predictable latency and jitter, unallocated unreserved bandwidth	nrtPS: Non real-time polling service, unicast assurance polling on a regular basis	Delay tolerant data services with a minimum required data rate (FTP)
C: Unpredictable latency and jitter, unallocated unreserved bandwidth	BE: Best-effort service	Delay and jitter tolerant data services (Web browsing, E-mail, data transfer)

Fig. 8 shows the novel hierarchical scheduling algorithm proposed to provide end-to-end QoS in SuperMAN [52]. The proposed hierarchical scheduling algorithm deploys the following different queuing methods:

- **FIFO:** Typically, UGS 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 performance of real-time traffic. The adaptive scheduler operates according to the traffic status, *i.e.*, non-burst mode or burst mode.
- **RR:** Due to the delay insensitivity of BE SFs, a simple round robin (RR) scheduler is applied for scheduling them.
- **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) arranges the SF queues according to their priority classes. It then calculates the quantum of each non-empty queue based on the required bandwidth in a scheduling cycle. The higher priority packets are scheduled

first, until the deficit counter of their traffic classes become smaller than a pre-selected 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.

Recall that the CPU (see Fig. 7) monitors and controls all the schedulers directly. Upon reception of UL-requests, the optical-wireless 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 optical and wireless segments is crucial to provide end-to-end QoS connectivity for the reserved (UGS/A0) and real-time traffic classes over SuperMAN.

Aggregation Techniques

Bandwidth provisioning plays an important role to support QoS especially for wireless end-users of FiWi networks. In [53], we proposed and investigated advanced aggregation techniques for both next-generation WLAN and EPON networks. We note that the IEEE standard 802.3ah does not specify any aggregation method for EPON. We introduced a novel integrated EPON-WLAN FiWi network architecture which consists of different ONU structures that enable existent EPON networks to evolve in a pay-as-you-grow manner while providing backward compatibility with legacy infrastructure and protecting previous investments.

Figure 9. Functional block diagram of CO and ONU-HT AP.

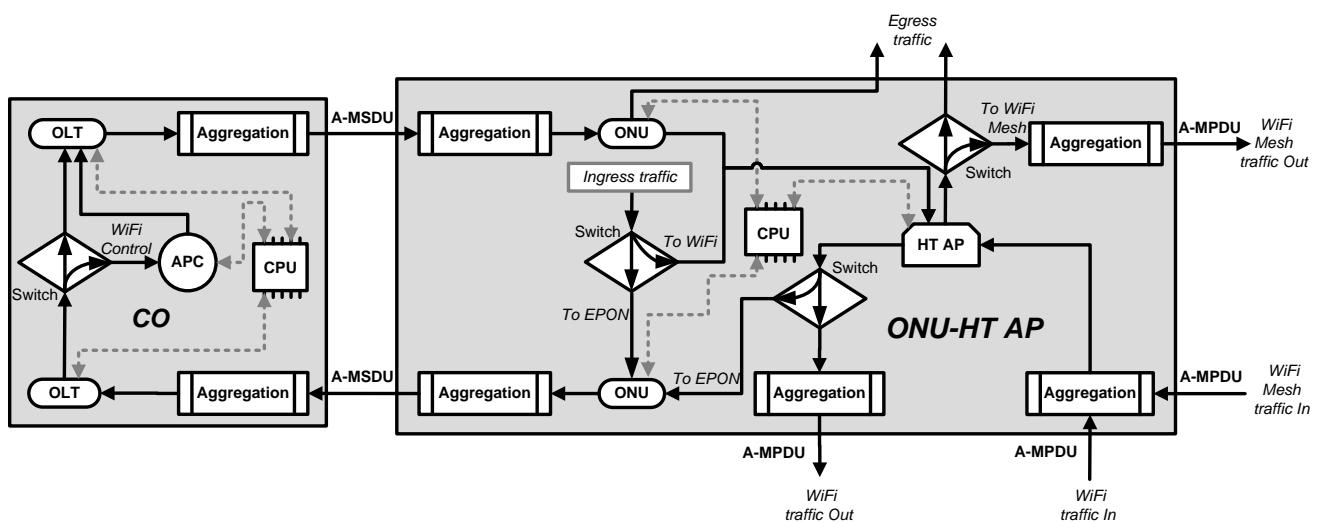


Fig. 9 depicts the functional block diagram of the CO and ONU-HT AP components. In this diagram, all depicted blocks are intended to be logical. For instance, the two logical OLT blocks are part of a single physical OLT. An ONU-HT AP provides the optical-wireless interface in our proposed FiWi network.

It includes a software and hardware upgrade for aggregation and wireless extension, respectively. More specifically, it determines the type of aggregation (*i.e.*, A-MSDU, A-MPDU, or two-level aggregation) for both optical and wireless segments. The ingress and egress traffic of the ONU-HT AP comes from and goes to optical subscribers. In the logical branch on the left-hand side, incoming optical traffic is first aggregated by the aggregation module and broadcast to the connected ONUs. The destination ONU-HT AP de-aggregates the received traffic, as shown in Fig. 9. The incoming packets are injected to the ONU and are subsequently divided into egress and WiFi traffic. The WiFi traffic in addition to the ingress traffic destined to WiFi are forwarded to the AP. The ingress traffic destined to EPON in addition to the traffic routed by the AP and WiFi control traffic are injected to the ONU and transferred by using aggregation. The WiFi control traffic consists of status updates of connected HT STAs and ONU-HT APs. The optical traffic and WiFi control traffic are received by the OLT, whereby a switch separates and forwards them to the AP Controller (APC). The APC controls, monitors, and configures the ONU-HT APs to facilitate their wireless operations, such as hand-over of high-speed mobile STAs. Moreover, it performs load balancing between the optical and wireless network segments. Specifically, an APC is able to mitigate traffic congestion at ONU-HT APs by means of WMN between them. The APC periodically monitors ONU-HT APs and establishes WMN links to decrease the optical traffic load, especially for delay-sensitive traffic. On the right-hand logical branch of Fig. 9, incoming and outgoing wireless traffic destined to another ONU-HT AP is received and transferred by using the aggregation unit. Note that while both EPON and next-generation WLAN in HCCA mode use the same eight traffic classes, the HT AP unit of ONU-HT AP performs traffic class mapping for the EDCA mode. The role of the CPU at the ONU-HT AP is to monitor and synchronize all the operational processes at the AP and ONU, including alarm management for congested traffic. The CPU at the CO monitors the OLT and APC to avoid traffic congestion. According to the pros and cons of single- and two-level aggregation schemes, we proposed and investigated various advanced aggregation techniques for our FiWi network. We applied A-MSDU in the optical segment since A-MSDU is able to achieve a higher throughput than A-MPDU for error-free channels [24]. A-MPDU is considered for the wireless network segment. For optical downstream traffic destined to HT STAs, two-level aggregation techniques are used to improve the throughput-delay performance. In EPON, the maximum size of an MSDU is restricted to 1500 octets. For the optical traffic, we set the maximum size of an A-MSDU frame to 7935 octets. Since ONU-HT APs use two-level aggregation techniques for optical traffic destined to HT STAs, we set the A-MSDU frame to 4095 octets due to the maximum MPDU length limitation for an A-MPDU data frame (see Fig. 3).

Congestion Control and Layer-2 Path Selection Algorithms

The design and use of a suitable routing algorithm is another means to improve QoS support in FiWi networks. Routing algorithms play a key role in load balancing and congestion control of both optical and wireless links in future FiWi networks. In [54], a novel integrated routing algorithm with load balancing was proposed for the unidirectional ring/PON architecture to improve the network throughput-delay performance. Moreover, different routing algorithms have been proposed for the wireless segment of FiWi networks [55]: 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.

In the integrated EPON and next-generation WLAN network proposed in [53], the OLT gathers information about its connected ONUs during the discovery and registration phase. Specifically, the OLT recognizes the configuration of connected ONUs (*i.e.*, ONU and ONU-HT AP) in addition to their MAC addresses and LLIDs. Each ONU-HT AP reports the information about its connected HT STAs. This information is mapped into the reserved fields of the REGISTER_REQ MPCP protocol data unit (PDU). The OLT creates a routing table which contains the information about all ONUs. This table is used by the DBA algorithm in use when assigning transmission grants to ONUs. A copy of this information is broadcast by the OLT to all ONUs. The ONU-HT APs use this information for routing their upstream traffic, *i.e.*, making a decision between forwarding the traffic to the OLT or using the WMN. More precisely, the APC and each ONU-HT AP create the following routing tables: (i) **Optical Routing Table** which contains the information broadcast by the OLT, and (ii) **Wireless Routing Table** which comprises the information of connected local HT STAs. We note that the wireless routing table consists of the list of ONU-HT APs connected to the WMN and their associated HT STAs. The wireless mesh routing information is updated using either reactive or proactive wireless routing algorithms. The above-mentioned routing tables may be used to deploy different path selection algorithms. We proposed a novel integrated dynamic path selection scheme concurrently used by the APC and ONU-HT APs to mitigate traffic congestion at ONU-HT APs via the WMN. This path selection algorithm uses the above-mentioned routing tables and buffer status of each ONU-HT AP to minimize the number of hops required to traverse and to maximize network load balancing. More specifically, the proposed path selection algorithm selects a suitable path for each incoming traffic based on the load of ONU-HT APs to avoid traffic congestion.

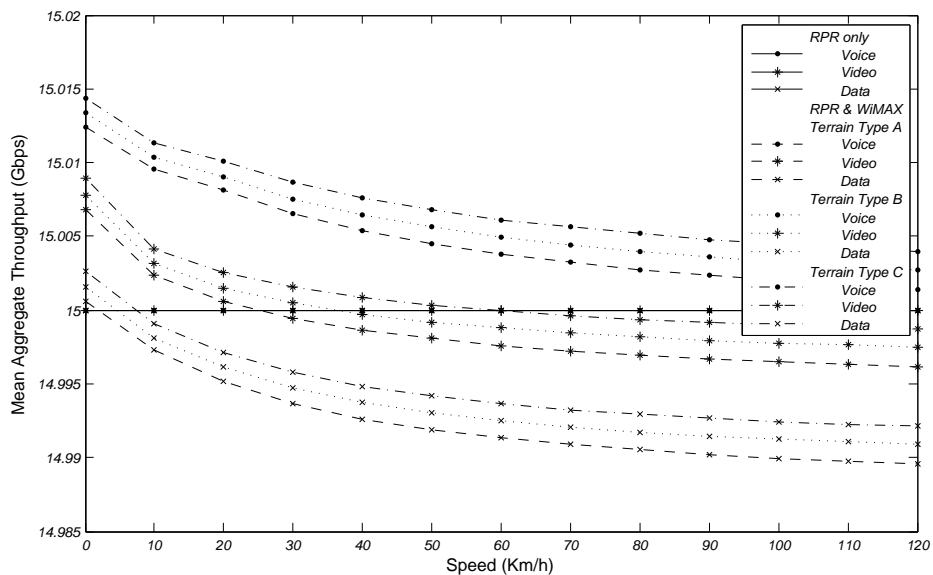
5. Numerical Results

5.1. Integration of RPR and WiMAX

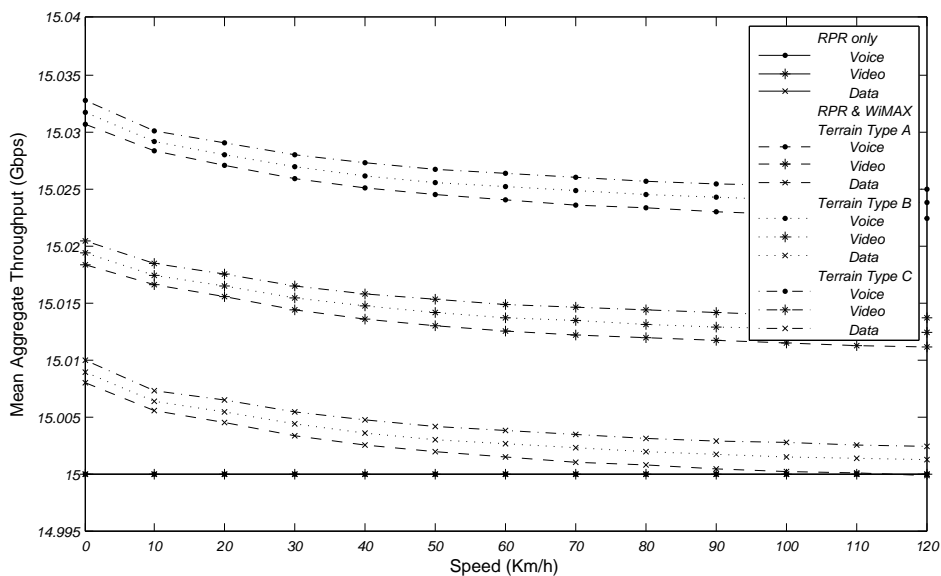
Fig. 10 depicts the mean aggregate throughput of SuperMAN versus the speed of the SS (given in km/h) for RPR background traffic only (no SSs) and RPR background traffic in conjunction with WiMAX traffic coming from and going to 25 attached mobile SSs for different terrain types A, B, and C, where type A describes an urban environment with maximum path loss, type B specifies a suburban environment with intermediate path loss, and type C describes a rural environment with minimum path loss. The considered RPR ring consists of 8 RPR nodes with 2.5 Gb/s line rate for each ringlet with an RPR RTT set to 0.5 ms. For RPR background traffic only, the mean aggregate throughput equals 15 Gb/s for each of the three traffic classes (voice, video, and data) independent of speed and wireless channel conditions. As shown in Fig. 10, for increasing speed the mean aggregate throughput decreases rapidly. This is due to the fact that for an increasing packet error rate, the number of required packet retransmissions increases, which in turn reduces the mean aggregate throughput of SuperMAN. This figure shows that deploying the proposed novel hierarchical scheduler at each RPR/WiMAX interface node improves the performance of SuperMAN in terms of mean aggregate throughput and mean delay for voice, video, and data traffic. The results shown in Fig. 10 prove 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 all three traffic classes than a conventional weighted fair queuing (WFQ) scheduler for fixed users and mobile users with a speed of up to 120 km/h, under realistic wireless channel conditions. In the WFQ scheduler, the weights assigned to UGS (equivalent to A0 in RPR), rtPS (equivalent to B-CIR in RPR), and BE (equivalent to C in RPR) traffic are set to 50%, 30%, and 20%, respectively. For a more detailed discussion of Fig. 10 and the hierarchical scheduler, the interested reader is referred to [52].

Figure 10. Mean aggregate throughput versus mobile SS speed with 25 attached mobile WiMAX SSs and 15 Gbps RPR background traffic for different terrain types using: (a) WFQ scheduler and (b) hierarchical WiMAX scheduler.



(a)



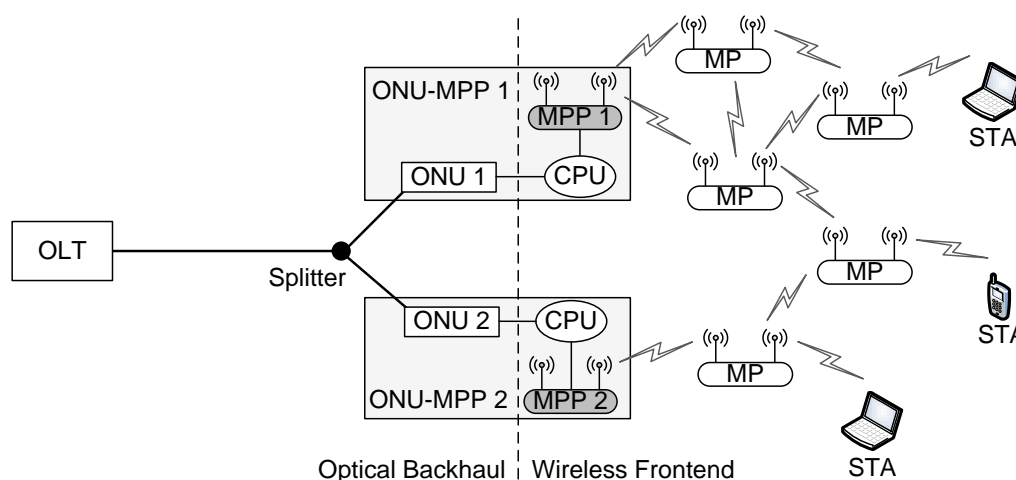
(b)

5.2. Integration of EPON and WLAN

Advanced Aggregation Techniques

Fig. 11 shows the considered FiWi network interface consisting of a tree-based EPON and next-generation WLAN-based single-channel WMN. In this figure, the optical-wireless interface consists of the following three components: (i) ONU—this component contains a MAC enhanced legacy ONU which is backward compatible to legacy TDM EPON ONUs and performs aggregation and de-aggregation operations for incoming and outgoing EPON traffic, (ii) MPP—this unit includes the wireless equipment of a next-generation WLAN-based WMN, and (iii) CPU—this component synchronizes the two aforementioned units and controls both optical and wireless network segments by monitoring their operation. We note that the WMN provides multihop communications to forward traffic en route to and from MPPs by using intermediate MPs.

Figure 11. FiWi network interface: integrated EPON and next-generation WLAN-based WMN.



In our simulations, we consider uniform unicast traffic where a given node (*i.e.*, OLT, 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 2 ONU-MPPs are connected to the OLT, whereby the distance between ONUs and OLT is set to 20 km. The optical line rate is set to 1 Gb/s. We evaluate the proposed FiWi network performance in terms of throughput, delay, overhead, and packet loss, whereby 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. First, 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 addition, we consider triple-play traffic (*i.e.*, voice, video, and data). 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. In our simulations, the two voice and video codecs are used simultaneously, each encoding 50% of the generated traffic. Moreover, we assume Poisson traffic with different packet sizes as background data traffic which uses 20% of the network capacity. In our simulations, we use the limited-service interleaved polling with adaptive cycle time (IPACT) with the maximum grant size of $G_{max}=15$ kbytes as EPON DBA algorithm [56]. In the limited-service granting approach, the transmission grant size per ONU is set to the reported queue size up to a maximum grant size of this ONU. Three STAs are located at a range of 2 km of the associated MAPs, while the distance between a connected pair of MP and MPP is set to 2 km. In our simulations, the bit error rate (BER) of the wireless channel is set to 10^{-5} .

Fig. 12 shows the beneficial impact of our proposed advanced aggregation techniques on the network performance for a 54 Mb/s WMN under voice, video, and data traffic. We observe that the proposed aggregation techniques improve both network throughput and delay. The throughput increases for increasing load, whereby the voice traffic achieves higher throughput than others using the proposed aggregation techniques.

Fig. 13 shows the impact of our proposed aggregation techniques on the performance of the FiWi network 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 aggregation techniques improve the mean throughput and to a lesser extent also the mean delay. Note that in Figs. 12 and 13 the 95% confidence intervals exhibit an error of less than 10% from the mean values.

Integrated Path Selection Scheme

In this section, we examine different path selection schemes to improve the performance of the integrated EPON-WLAN FiWi network by means of wireless mesh networking between ONU-HT APs, considering not only throughput and delay but also overhead and packet loss. In our simulations, we consider uniform unicast traffic where a given node sends a generated packet to any other node with equal probability $1/(N-1)$ and N denotes the number of OLT, ONU-HT APs, and HT STAs. We assume that 16 TDM ONUs and 16 ONU-HT APs are connected to the CO, whereby the distance between the ONUs and CO is set to 20 km. The optical line rate is set to 1 Gb/s. Each ONU-HT AP has three 10-Mbyte buffers for the EPON, WiFi, and wireless mesh segments. The wireless channel bandwidth and data rate are set to 20 MHz and 100 Mbit/s, respectively. Two HT STAs are located at a range of 2 km of the associated ONU-HT AP, while ONU-HT APs are located 2 km from each other. In our simulations, the BER of the wireless channel is set to 10^{-5} . We use the aforementioned traffic model to generate voice, video, and data packets at each ONU-HT AP and HT STA, while the OLT and each ONU are assumed to generate the same amount of traffic and a packet generated at a given node is equally destined to any of the remaining nodes. We note that layer-3 (*i.e.*, routing based on IP addresses) might be used in our integrated dynamic path selection scheme due to the single-hop WMN connections between the ONU-HT APs.

Figure 12. Impact of advanced aggregation techniques on integrated EPON-WLAN network performance for a 54 Mb/s WMN under voice, video, and data traffic.

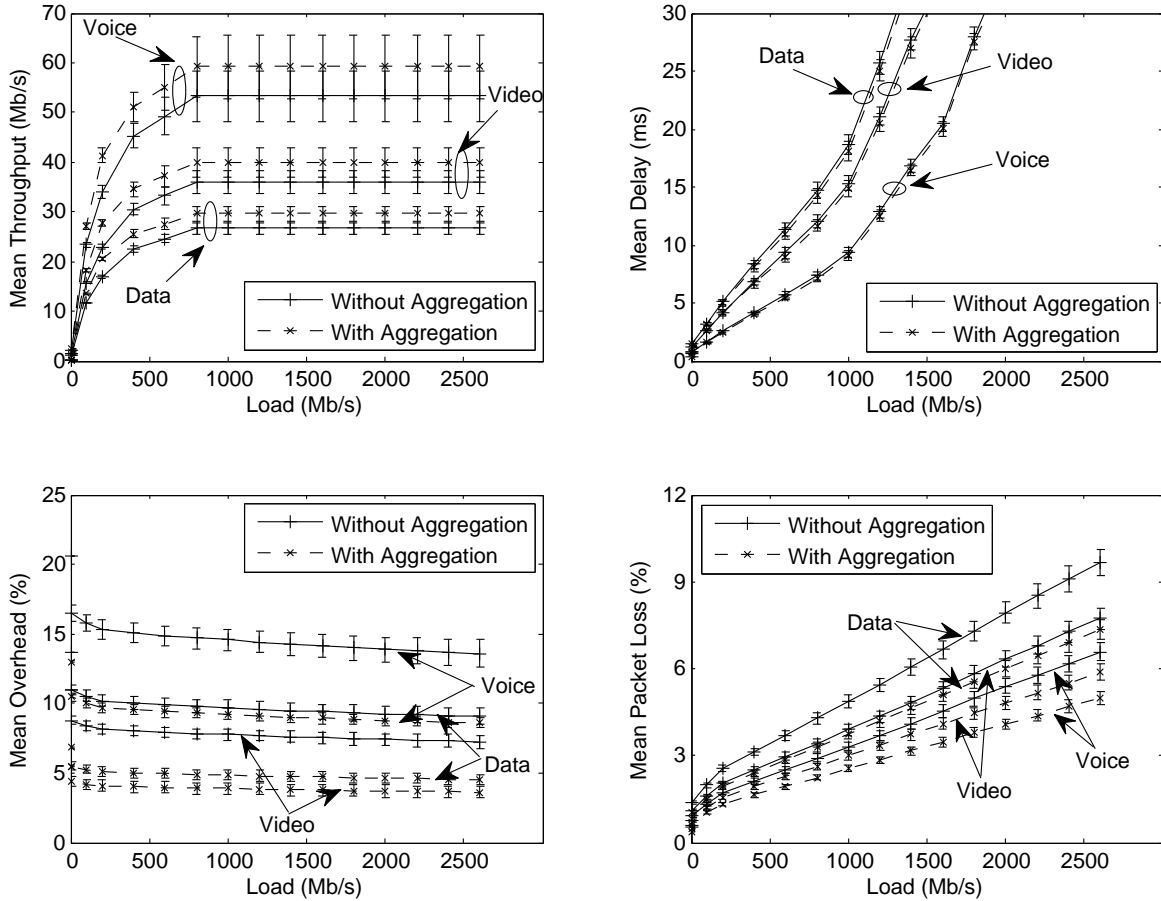


Figure 13. Impact of advanced aggregation techniques on integrated EPON-WLAN network performance for various WMN data rates under triple-play traffic.

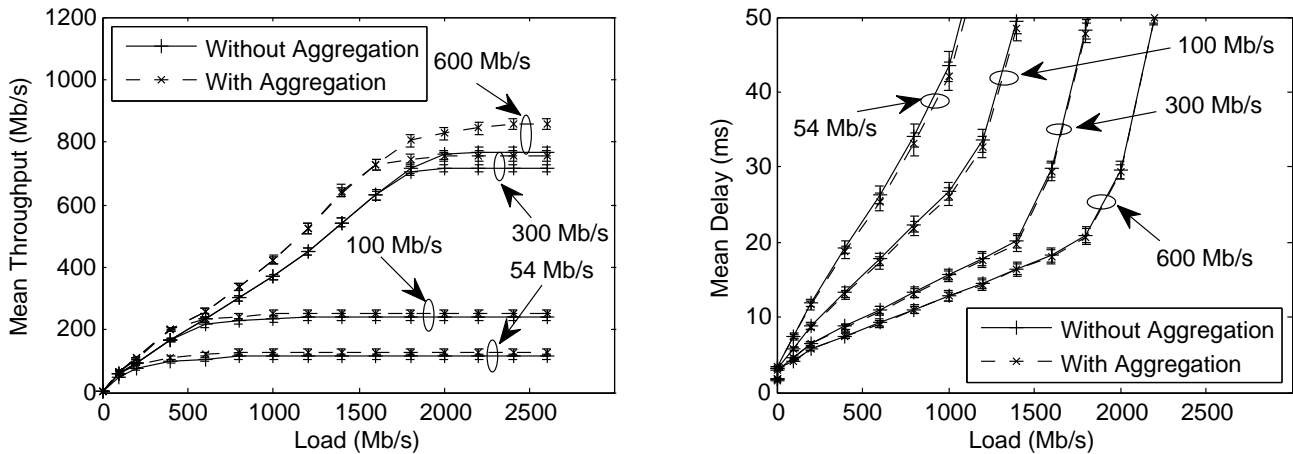
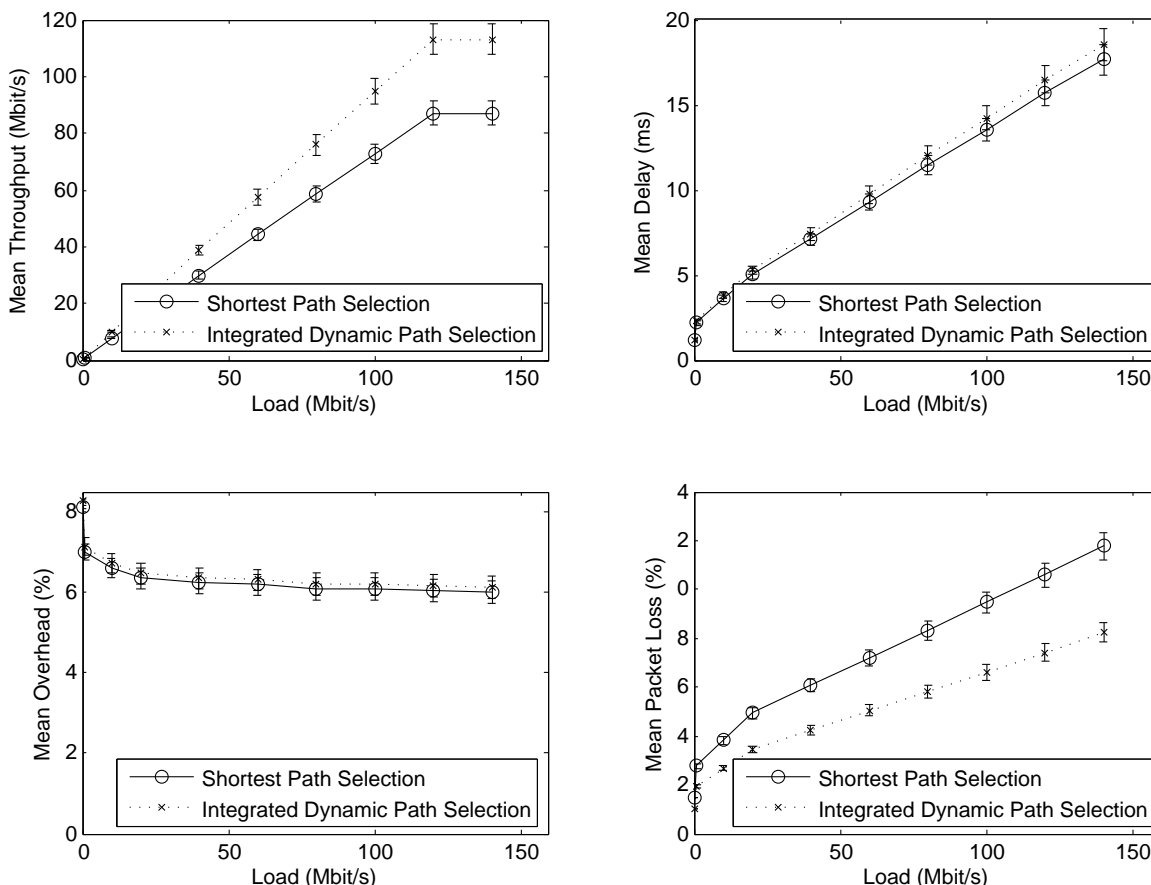


Fig. 14 shows the beneficial impact of using our integrated dynamic path selection scheme on the FiWi network using both advanced aggregation techniques and wireless mesh networking. In our sim-

Figure 14. Impact of path selection schemes on FiWi network performance using advanced aggregation techniques and wireless mesh networking.



ulations, delay denotes the time interval between packet arrival at the source node and packet reception at the destination node which includes the time required for path selection process. We observe that the dynamic path selection scheme improves throughput and packet loss, without increasing delay and overhead significantly. Note that in Fig. 14 the 95% confidence intervals exhibit an error of less than 10% from the mean values.

6. Conclusions

Hybrid optical-wireless FiWi networks form a powerful future-proof platform that provides a number of advantages. Introducing optical fiber into broadband wireless access networks helps relieve emerging bandwidth bottlenecks in today's wireless backhaul due to increasing traffic loads generated by new applications, e.g., iPhone. By simultaneously providing wired and wireless services over the same infrastructure, FiWi networks are able to consolidate (optical) wired and wireless access networks that are usually run independently of each other, thus potentially leading to major cost savings.

In this paper, We briefly reviewed enabling optical and wireless access-metro network technologies and their QoS provisioning techniques. We elaborated on enabling FiWi technologies and introduced new QoS provisioning techniques for future FiWi networks. The focus of this paper was on a novel FiWi

access-metro network architecture, called SuperMAN, that integrates next-generation WiFi and WiMAX networks with EPON and RPR networks. We described a novel integrated hierarchical scheduler that provides end-to-end QoS connectivity and satisfies the QoS requirements of different traffic classes and scheduling services for both wired and wireless end-users of integrated RPR and WiMAX networks. The obtained results show that deploying our proposed hierarchical scheduler at each RPR-WiMAX interface node improves the performance of the considered FiWi network in terms of mean aggregate throughput and mean delay for voice, video, and data traffic.

Furthermore, we have shown that exploiting both advanced aggregation techniques and wireless mesh networking improves the performance of integrated EPON and next-generation high-throughput WLAN networks significantly. We presented a novel integrated dynamic path selection algorithm to enhance the throughput of integrated EPON and next-generation WLAN-based WMN using optical-wireless load balancing. The obtained results show that deploying our advanced aggregation techniques and integrated dynamic path selection algorithm improves the performance of SuperMAN in terms of not only throughput and delay but also overhead and packet loss.

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