VMP: A MAC Protocol for EPON-Based Video-Dominated FiWi Access Networks

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***Abstract*—Optical and wireless network technologies are expected to converge in the near to midterm, giving rise to bimodal *fiber-wireless (FiWi)* broadband access networks. In triple-play (voice, video, and data) service scenarios for such FiWi access networks, video traffic will likely dominate due to the widely predicted increase in video network services and the high traffic volume of compressed video compared to voice and data services. In this paper, we introduce and evaluate a comprehensive *video MAC protocol (VMP)* to efficiently deliver prerecorded video downstream to wireless consumers over a FiWi network in the presence of voice and data upstream and downstream traffic. VMP consists of three main novel components: *(i)* frame fragmentation in conjunction with hierarchical frame aggregation for efficient MAC frame transport over the integrated optical and wireless network segments, *(ii)* multi-polling medium access control for upstream voice and data packets and acknowledgements for downstream video packets, and *(iii)* prefetching of video frames over the optical and wireless network segments in conjunction with hybrid reservation/contention-based medium access. Our simulation results indicate that VMP achieves significant improvements in throughput-delay performance for all three traffic types as well as reductions in the playback starvation probability for video traffic compared to existing state-of-the-art MAC mechanisms.**

***Index Terms*—EPON, FiWi, H.264 SVC, MAC layer protocol, prefetching, video streaming, wireless mesh network.**

I. INTRODUCTION

A. Background

RECENTLY, passive optical networks (PONs) have received renewed attention due to their ability of providing the lowest energy consuming solution for broadband access, apart from offering high capacity, small attenuation, low operational expenditures, and longevity. The results reported in [1] show that PONs consume less energy per bit than hybrid fiber-copper based access technologies, e.g., fiber-to-the-node (FTTN), and wireless access solutions, e.g., WiMAX. In [2], it was shown that PONs are also more energy efficient than fiber-to-the-home (FTTH) network technologies such as point-to-point and active optical access networks. This property assures future PON deployments in response to concerns about the greenhouse impact of the Internet. Another important recent observation made by the 2009 Cisco Visual Networking Index is the fact that the sum of all forms of video, i.e., Internet video, TV, video on demand (VoD), and peer-to-peer (P2P), is expected to account for over 91% of global consumer traffic by 2013, whereby over 60% of all consumer Internet traffic will be Internet video. Consequently, it is expected that video applications play a key role in the design of future broadband access networks that benefit from the huge capacity and low power consumption of PON-based infrastructures.

A key requirement for providing flexible networked video services [3] is to deliver the video frames in a timely manner so that the receiver can continuously play back the video. This timely video frame delivery is made challenging by the highly varying (bursty) video traffic bit rates [4]–[8] produced by the efficient video coding standards, especially the H.264 Scalable Video Coding (SVC) standard [9], [10].

To provide quad-play services (i.e., voice, video, data, and mobility) on the same network infrastructure, bimodal *fiber-wireless (FiWi)* networks hold great promise as future-proof broadband solutions by deploying PONs as wireless backhauls and capitalizing on the respective strengths of both optical and wireless technologies and judiciously merging them [11], [12]. FiWi networks are categorized into: *(i)* radio-over-fiber (RoF) and *(ii)* radio-and-fiber (R&F) networks. RoF networks use optical fiber as an analog transmission medium between the central office (CO) and multiple remote antenna units (RAUs), with the CO being in charge of controlling access to both optical and wireless media. Conversely, in R&F networks, access to the optical and wireless media is controlled separately from each other by using, in general, two different medium access control (MAC) protocols in the optical and wireless media, with protocol translation taking place at their interface. To better understand the rationale behind R&F networks, note that the additional fiber propagation delay in FiWi networks may exceed certain timeouts of distributed wireless MAC protocols, such as the widely deployed distributed coordination function (DCF) of IEEE 802.11a/b/g wireless local area networks (WLANs), resulting in a deteriorated network performance. By means of protocol translation at the optical-wireless interface, R&F networks are well suited to build WLAN-based FiWi networks of extended coverage without imposing stringent limits on the size of the optical backhaul, as opposed to RoF networks that limit the length of deployed fibers to a couple of kilometers [13].

Recently, the University of California (UC) Davis has reported on an R&F prototype which integrates two Ethernet PONs (EPONs) and an IEEE 802.11g WLAN-based wireless

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mesh network (WMN) [14]. The experimental results show that the quality of video transmissions sharply deteriorates for an increasing number of wireless hops. After four wireless hops the video client showed a blank screen, which clearly indicates the technological immaturity of current WLAN-based R&F networks and the need for advanced novel networking mechanisms for FiWi networks transporting video streams.

B. *Contributions of This Article*

In this paper, we propose and evaluate an advanced MAC protocol, called *video MAC protocol (VMP)*, for future EPON-based R&F FiWi networks dominated by downstream video traffic. In our VMP protocol, we introduce three main MAC enhancement techniques to improve the quality of received video streams at the end-users, namely: *(i)* We examine MAC frame fragmentation in conjunction with two-level (hierarchical) frame aggregation, whereas previous research has only considered frame fragmentation with one-level frame aggregation or two-level aggregation without frame fragmentation, as detailed in Section I-C. *(ii)* We introduce hybrid wireless channel access control consisting of reservation-based periods, non-polling contention-based periods, and polling contention-free periods. We achieve polling contention-free channel access through multi-polling medium access control over the integrated fiber-wireless network segments, whereas existing polling-based access control mechanisms consider only one network segment in isolation. *(iii)* We introduce prefetching of video frames in conjunction with hybrid reservation/contention-based MAC over the integrated fiber-wireless network segments, whereas existing state-of-the-art MAC mechanisms consider video delivery over an isolated wireless network segment with hybrid reservation/contention-based MAC without prefetching [15], [16].

By means of extensive simulations we examine our VMP protocol for a triple-play mix of up- and downstream voice traffic, downstream video traffic, as well as up- and downstream data traffic. The obtained results show a significantly improved throughput-delay performance of hybrid WLAN-EPON networks for voice, video, and data traffic by using our proposed VMP protocol. We focus in particular on the performance for the video streams and find that the novel mechanisms in VMP significantly reduce the playback starvation probability. For instance, the prefetching mechanism reduces the starvation probability by close to an order of magnitude compared to hybrid reservation/contention based MAC without prefetching. To the best of our knowledge, this paper is the first to introduce and investigate a comprehensive video MAC protocol for integrated EPON-WLAN based FiWi networks.

The remainder of the paper is structured as follows. Section I-C discusses related work. Section II briefly reviews the considered FiWi network architecture and basic operating principles. Section III introduces our proposed MAC protocol for integrated next-generation WLAN-based WMN and EPON networks. The performance of the proposed MAC protocol is evaluated in Section IV. Section V concludes the paper.

C. *Related Work*

1) Frame Fragmentation and Aggregation: Hierarchical (two-level) MAC frame aggregation has been studied for an isolated WLAN in [17]. Furthermore, hierarchical frame aggregation for a FiWi network has been examined in [18]. Noting that all aggregated frames need to be retransmitted if errors occur, one-level aggregation with fragment retransmission using a specific acknowledgement technique has been proposed in [19]. The proposed fragmentation strategy retransmits only the corrupted fragments. The fragment size plays a key role for efficient fragmentation and we follow the guidelines of [19] for the fragment size settings in our study. Building on these existing techniques, we introduce hierarchical (two-level) frame aggregation with frame fragmentation in this article and study this novel approach in the context of a FiWi network.

2) Wireless Channel Access Control: A plethora of MAC enhancement techniques for single-hop WLANs as well as WLAN-based wireless mesh networks that combine contention with reservations have recently been proposed, see for instance [20], [21]. Most relevant for our study are MAC techniques that exploit IEEE 802.11n frame aggregation, such as multi-user polling controlled channel access (MCCA), which has been introduced in [22] for an isolated next-generation WLAN. MCCA divides the channel access time into two periods: *(i)* non-polling period and *(ii)* polling period. The access point (AP) gathers the channel access requests of stations (STAs) and broadcasts a multi-polling packet, which indicates the polling schedule of each STA. In this article, we extend the multi-polling strategy to an integrated FiWi network.

Furthermore, studies that examine video transport in conjunction with enhanced MAC techniques are closely related to our article. A hybrid contention/reservation MAC protocol has been studied in the context of a single-hop wireless network in [15], [16]. We combine hybrid contention/reservation MAC with prefetch scheduling of video frames in this article.

3) Video Traffic Scheduling: The collaborative prefetch scheduling of a multitude of prerecorded video streams by a central controller to a set of receivers has been investigated for networks with a wired bottleneck link in several studies, see for instance [23]–[26]. Similarly, centralized prefetch scheduling for wireless networks with dedicated wireless channels has been studied, see for instance [27]–[29]. In contrast, in this article, we investigate centralized prefetch scheduling over an integrated FiWi network with hybrid contention/reservation MAC.

Video transmission over optical access networks has been investigated relatively little to date. Video delivery over hybrid fiber-coax access networks with a focus on traffic prediction and the DOCSIS medium access control and physical layer specifications is studied in [30]. Techniques based on multi- and broadcast that periodically transmit segments of popular videos in optical access networks are studied in [31], [32]. In the recent studies [33], [34], these periodic transmission schemes are *(i)* extended with patching mechanisms that allow a receiver to quickly start video playback from a patch stream while storing the next video segments from the periodic transmissions, and *(ii)* refined with a range of performance enhancing mechanisms, such as downloading popular movies during night hours. These

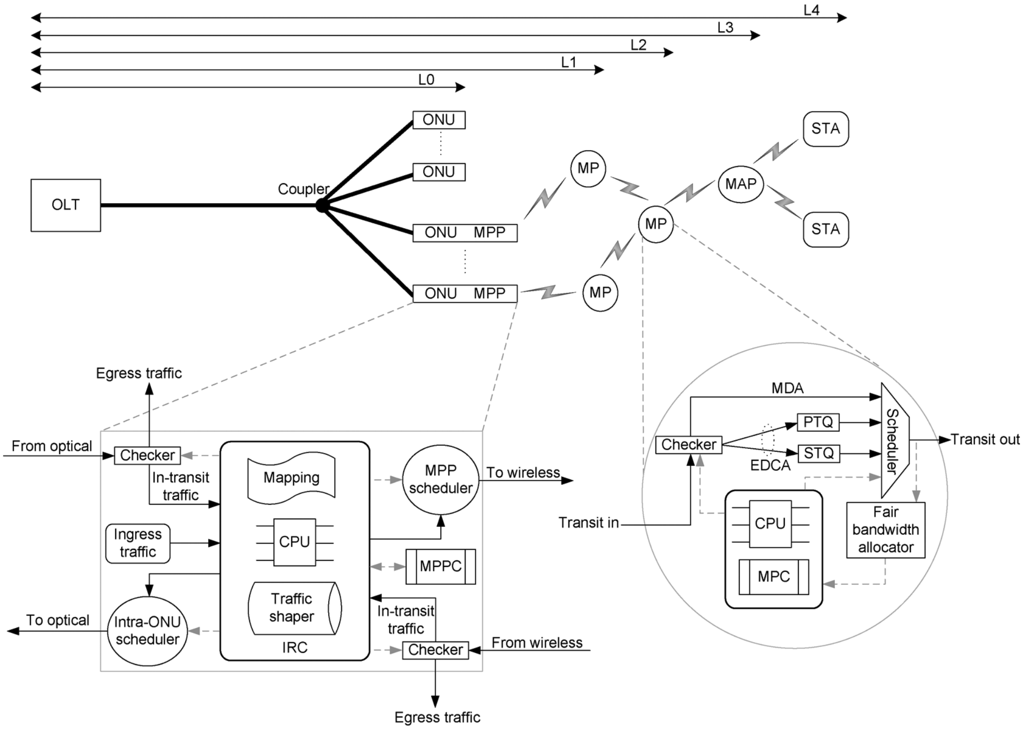


Fig. 1. Network architecture and node structures of integrated next-generation WLAN-based WMN and EPON. The arrows at the top illustrate the ranges of the hierarchical frame aggregation levels L0–L4 [18].

existing studies have in common that they do not consider the variable frame sizes of rate-distortion (RD)-efficient video codecs; instead, they approximate (or bound) the video bit rate as a constant bit rate. In contrast, we consider the highly variable bit rates of H.264 SVC encoded video and examine video frame scheduling mechanisms that efficiently deliver the variable-sized video frames for timely playback.

Video streaming in wireless mesh networks has been intensely researched, whereby exploiting the path diversity has typically received the most attention, see for instance [35]–[38]. We also note that multicast techniques in conjunction with a specific multiple description video coding mechanism are studied in [39] for an integrated EPON-WiMAX access network. To the best of our knowledge no prior studies have examined the complementary issue of prefetching variable-size video frames in wireless mesh networks, nor integrated FiWi networks.

II. INTEGRATION OF EPON AND NEXT-GENERATION WLAN-BASED WMN

In this section, we briefly describe the considered FiWi network architecture and the standard operation principles for the optical and wireless network segments. We refer to [18] for more details on the network architecture and to the applicable standards IEEE 802.3ah and IEEE 802.11n and 802.11s for more details on the operating principles.

A. Network Architecture

Fig. 1 shows the network architecture and node structures of our integrated EPON and next-generation WLAN-based WMN. In this figure, an optical network unit (ONU) represents a conventional EPON ONU which connects to the optical line terminal (OLT) via a passive fiber tree network. Some of the ONUs, e.g., ONUs with suitable traffic demands, are upgraded with the so-called mesh portal point (MPP) to interface with the WMN. An integrated ONU MPP node mainly consists of intra-ONU scheduler, MPP scheduler, MPP controller (MPPC), and integrated rate controller (IRC). The IRC comprises a traffic class mapping unit, central processing unit (CPU), and traffic shaper and is used to seamlessly integrate both optical and wireless technologies and facilitate joint optimization of the intra-ONU and MPP schedulers.

In the WMN, we deploy IEEE 802.11s which combines the advantages of the basic service set (BSS) and independent basic service set (IBSS) by capitalizing on the relaying functionality of wireless mesh points (MPs). As illustrated in Fig. 1, the wireless MP node structure comprises four main modules, namely MP scheduler, MP controller (MPC), fair bandwidth allocator, and CPU. Note that IEEE 802.11s introduces a contention-free medium reservation access mechanism, called mesh deterministic access (MDA), to provide end-to-end QoS for delay-sensitive traffic [40]. In the MP node structure of Fig. 1, 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., enhanced distributed channel access (EDCA) or MDA. As explained in greater detail in Section III, the primary transit queue (PTQ) is dedicated to high-priority traffic and the secondary transit queue (STQ) is used by other types of traffic. The mesh access point (MAP) is a special type of MP that has the additional capability of an AP.

We denote N for the total number of ONUs, ONU MPPs, and STAs attached to the OLT. We consider streaming prerecorded video from the OLT to these N nodes. In addition, these N nodes and the OLT generate and receive voice and data traffic.

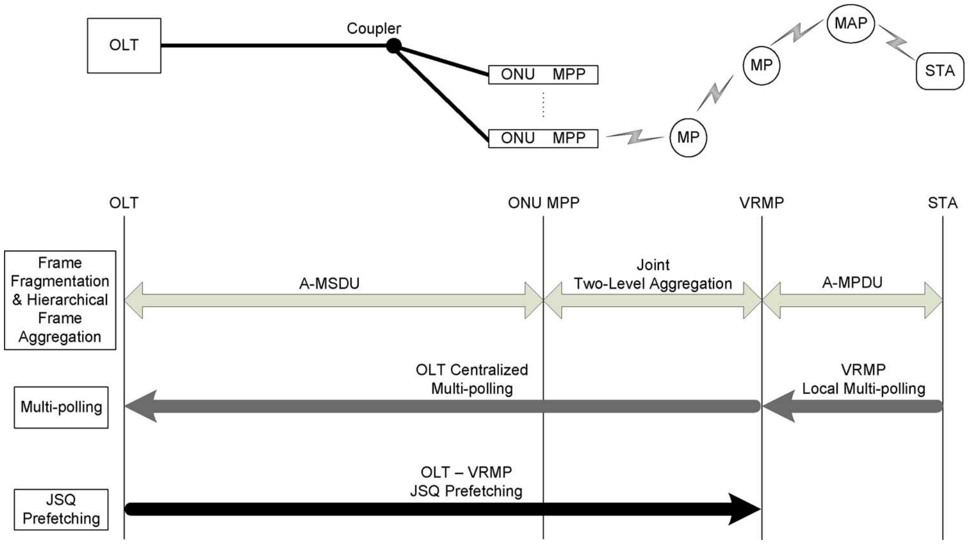


Fig. 2. Our performance enhancing MAC protocol mechanisms are employed across the optical and wireless network segments to improve down- and upstream packet delivery (frame fragmentation and aggregation), upstream packet and acknowledgement delivery (multi-polling), and video streaming in the downstream direction (prefetching).

We denote R [in bit/s] for the downstream bottleneck bandwidth of the optical and wireless network segments [41].

B. Network Operation

The fiber infrastructure carries a single upstream wavelength channel (from ONUs to OLT) and a single downstream wavelength channel (from OLT to ONUs). To let ONUs share up- and downstream bandwidth without collisions, time division multiplexing (TDM) is deployed, whereby the so-called multipoint control protocol (MPCP), specified in IEEE 802.3ah, is used to facilitate dynamic bandwidth allocation (DBA) and arbitrate the upstream transmissions of ONUs by means of polling. MPCP uses the two polling messages REPORT and GATE. The REPORT message is used by each ONU to report bandwidth requirements of up to eight priority queues to the OLT. Each GATE message contains up to four transmission grants for an ONU, with each grant specifying the start time and length of a separate upstream transmission window.

In the wireless segment of the considered FiWi network architecture, we apply IEEE 802.11n, Draft 9.0, Part 11. In IEEE 802.11n, frame aggregation has been introduced as the major MAC enhancement technique for next-generation WLANs to offer a significantly increased throughput of 100 Mb/s or higher at the MAC service access point (SAP). Two methods were specified for frame aggregation: *(i)* aggregate MAC service data unit (A-MSDU), which is used to join multiple MAC service data units (MSDUs), and *(ii)* aggregate MAC protocol data unit (A-MPDU), which is used to join multiple MAC protocol data units (MPDUs). Note that A-MSDU and A-MPDU can be used separately or jointly. Hierarchical frame aggregation techniques which involve five different aggregation layers L0–L4, as shown in Fig. 1, were introduced in [18]. By default, all MPs are involved in relaying in-transit frames, but in our architecture, we permit only a subset of MPs to perform de-aggregation, re-ordering, and aggregation of in-transit frames. We refer to these special MPs as *virtual root MPs (VRMPs)*. A VRMP carries out two-level de-aggregation, re-ordering, and single-level A-MPDU aggregation of frames destined to the same MAP (L2).

In the MDA mode of the WMN, MPs reserve the wireless medium for so-called MDA opportunities (MDAOPs) using two types of time periods: *(i) neighborhood MDAOP times*—the transmitting/receiving (TX/RX) time periods of a given MP during which the MP and its neighboring MPs are either a transmitter or receiver of the corresponding MDAOPs, and *(ii) MDAOP interfering times*—MDAOP times of neighboring MPs, which the MP is aware of and during which it is not involved as a transmitter nor receiver. A new MDAOP can be set up between a pair of MPs if there is no overlap of both MPs' neighborhood MDAOP and MDAOP interfering times [40].

III. VMP: A MAC PROTOCOL FOR FUTURE VIDEO-DOMINATED FIWI ACCESS NETWORKS

Fig. 2 illustrates where we employ our performance enhancing MAC protocol mechanisms in the FiWi network. We employ joint frame fragmentation and hierarchical aggregation to improve performance for both down- and upstream traffic. Multi-polling is primarily designed to improve upstream traffic performance while prefetching improves the downstream video delivery.

A. Frame Fragmentation and Hierarchical Frame Aggregation

In VMP, we apply A-MSDU in the optical segment since for an error-free medium, such as optical fiber, A-MSDU achieves a higher throughput than A-MPDU [42]. We study joint frame fragmentation and hierarchical frame aggregation to improve bandwidth efficiency and network reliability in integrated EPON and WLAN-based multihop WMNs. In contrast, both MCCA [22] and AFR [19] applied A-MPDU only for single-hop WLAN networks.

Fig. 3(a) shows the data frame format of VMP. Following [19], we limit the maximum fragment size to 256 octets. The

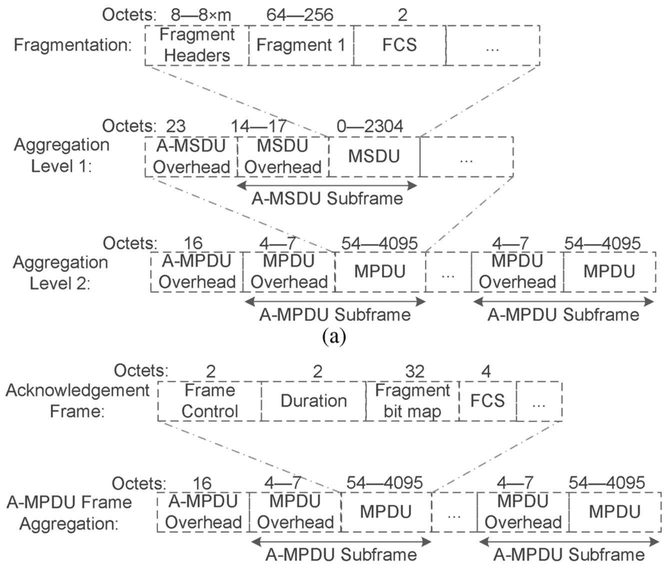


Fig. 3. Data and acknowledgment (ACK) frame formats for joint frame fragmentation and hierarchical (two-level) frame aggregation in VMP. (a) VMP frame fragmentation with m fragments and hierarchical frame aggregation; (b) VMP aggregation of ACK frames.

results in [19] demonstrate that the maximum fragment size of 256 octets robustly achieves close to maximum throughput for a wide range of practically relevant bit error rates, including the range 10^{-6} to 10^{-4} (whereby our study considers a bit error rate of 10^{-5}). As shown in Fig. 3(a), we add a fragment header and frame check sequence (FCS) to the payload of each fragment. We aggregate the fragments with their headers subject to the maximum MSDU size (i.e., 2304 octets). Note that for each fragment an 8-octet fragment header is added which consists of packet ID, packet length, starting fragment bit, position of fragment in the original packet, and 1-octet FCS to protect the header against bit errors.

In Fig. 3(a), the MSDU overhead consists of the destination address, source address, and padding. The A-MSDU overhead includes the rest of the MAC header/trailer overhead. To apply A-MPDU as the second-level hierarchical frame aggregation, we limit the maximum size of aggregated A-MSDU fragments (including the A-MSDU headers) to 4095 octets. The MPDU overhead accounts for the MPDU delimiter and padding added to each MPDU. The A-MPDU overhead includes the PHY header and PHY preamble. In IEEE 802.11n, 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 FCS, as opposed to A-MPDU where each MPDU contains its own MAC header and FCS.

In the downstream direction of Fig. 1, the OLT performs only A-MSDU frame aggregation for traffic destined to the ONUs. In contrast, for traffic destined to wireless STAs the OLT performs frame fragmentation and A-MSDU frame aggregation (L0). The ONU MPP encapsulates received A-MSDUs destined to the same VRMP into A-MPDUs [i.e., joint two-level aggregation (L2)]. In the upstream direction, STAs perform frame fragmentation and hierarchical frame aggregation. Note that the receiving VRMP and ONU MPP are able to de-fragment in-transit traffic, reorder the packets, and perform two-level and A-MSDU frame aggregation before forwarding traffic to the OLT.

In VMP, the wireless packet acknowledgment plays a more important role than in EDCA due to the joint use of hierarchical frame aggregation and multi-polling schemes. In VMP, each node is allowed to transmit the acknowledgment request (AR) and ACK packets in the polling period specified by the controller. Note that the AR and ACK can be combined and aggregated with the data frame. Similar to [19], we add an 8-octet fragment bitmap to each acknowledgment frame, where each bit is assigned to one fragment. Additionally, as illustrated in Fig. 3(b), we aggregate the ACK frames using A-MPDU, which was not considered in [19].

B. *Multi-Polling Channel Access*

In order to achieve low network overhead and high bandwidth efficiency we combine the frame fragmentation and hierarchical aggregation techniques of the preceding section with novel channel access techniques involving multi-polling. More specifically, we define three wireless channel access periods: *(i)* polling contention-free period coordinated with multi-polling, *(ii)* MDA reservation-based period, and *(iii)* non-polling contention-based period. The MDA reservation-based period and the non-polling contention-based period follow the standard IEEE 802.11 mechanisms. We allocate each wireless station s, $s = 1, \ldots, S$, a reservation-based period corresponding to a downstream bit rate of $r_r(s)$ [in bit/s], with $\sum_{s=1}^{S} r_r(s) \leq R$. For the remainder of this section, we focus on the novel multi-polling approach.

In VMP, we introduce a multi-polling mechanism to arbitrate the upstream transmissions of both wired and wireless end-users. Multi-polling also helps the wireless end-users and intermediate nodes to increase or decrease their reserved bandwidth. Our multi-polling approach combines concepts from: *(i)* MPCP in EPON, and *(ii)* point coordination function (PCF) of legacy WLANs in centralized mode, where the AP polls each STA in a round-robin fashion. In our multi-polling approach, the OLT uses extended REPORT and GATE polling messages to simultaneously synchronize and schedule multiple associated VRMP nodes. In addition, each VRMP node schedules and reserves bandwidth for its associated wireless nodes with a local multi-polling mechanism.

As shown in Fig. 4, for upstream channel/bandwidth multi-polling, the VRMP sends the REPORT message to the OLT for its incoming packets destined to the OLT through the ONU MPP. The in-path MPs forward the REPORT packet to the ONU MPP which forms the extended REPORT message sent to the OLT. The OLT applies a joint dynamic channel assignment/dynamic bandwidth allocation (DCA/DBA) algorithm and transmits a multi-polling packet to the considered ONU MPP. The OLT is able to perform fair resource allocation since it is aware of the status of all VRMP nodes. Each traversed ONU MPP sets the channel and bandwidth according to the received multi-polling packet and forwards the information to the VRMP. The VRMP receiving the multi-polling packet updates its network allocation vector (NAV) accordingly. The VRMP locally broadcasts the NAV in order to avoid packet collisions on the wireless channel by the local nodes.

In addition, the OLT incorporates the upstream traffic amount arriving from the VRMP's local nodes in the DBA decision for the optical segment. This adaptive interaction between optical and wireless segments is helpful in improving network performance. For backward compatibility with legacy WLAN equipment, we employ the lowest transmission rate over a pre-specified wireless channel for control and polling message transmissions.

Both downstream and upstream wireless local traffic flows are monitored and controlled by the associated VRMP. Each VRMP applies the MCCA multi-polling mechanism, which we employ over multiple wireless hops (MCCA [22] employs multi-polling only over a single wireless hop). Each VRMP has access to the channel with higher priority than other nodes using the PCF inter-frame space (PIFS), which is shorter than the DCF inter-frame space (DIFS) and arbitration inter-frame space (AIFS) intervals. Since the VRMP prioritizes and schedules the channel access of polled nodes, the associated nodes can apply DIFS instead of AIFS as the minimum idle period before the contention period.

Similar to EPON, our MAC protocol is not restricted to any specific DBA or scheduling algorithm. The applied DBA algorithm should set the polling periods properly to avoid channel access starvation of IEEE 802.11 WLAN legacy nodes.

1) Implementation Details: In the extended REPORT frame format, we make use of the reserved bits of the standard IEEE 802.3ah TDM EPON REPORT message. The VRMP node reports the status of the PTQ and the wireless channels to its associated ONU MPP, see rightmost REPORT message in Fig. 4. We use the reserved 39 octets of the standard REPORT message to carry the information of up to three VRMPs attached to each ONU MPP, see middle Extended REPORT message in Fig. 4, to the OLT. More specifically, we use three octets to indicate up to three lightly loaded wireless channels of each VRMP. Moreover, the ONU MPP uses two octets to report the contention-free polling-based traffic status (i.e., PTQ) of each VRMP, whereby each VRMP is identified by its 6-octet MAC address. (We leave six of the 39 reserved octets unused; these six octets can be used for future enhancements, or could be used to report two additional wireless channels for each VRMP.) Similarly, we use the reserved 39 octets of the standard IEEE 802.3ah EPON GATE message in the extended GATE frame to transfer the scheduling information to up to three VRMPs. The OLT uses six octets to schedule each attached VRMP by means of the assigned 4-octet transmission opportunity (TXOP) grant and 2-octet start time. Moreover, three octets are used by the OLT to indicate the status of the wireless channels of three VRMPs (one octet for each VRMP), as illustrated in the left part of Fig. 4. If more than three VRMPs are attached to an ONU MPP, then the VRMP can take turns in the reporting and granting cycle, e.g., with six VRMPs, three VRMPs participate in one cycle, then the other three VRMPs in the next cycle, and so on.

C. Prefetching for VBR Video Streams

1) Overview: The VMP protocol focuses on delivering downstream pre-recorded video to the ONUs (including the ONU MPPs) and the wireless stations (STAs). For brevity of the presentation we concentrate in the following on the streaming from the OLT to the wireless stations $s,\ s = 1, \ldots, S$. Each station may receive one or several video streams. We denote J for the total number of video streams serviced by the OLT and $\mathcal{S}_s$ for the set of streams received by station s. We define $s(j)$ to identify the station s receiving stream j.

Generally, a prefetching mechanism strives to build up reserves of prefetched video frames in the buffers of the wireless stations. The prefetched reserves help to overcome delays due to large video frames and outages of the wireless channels. A prefetch policy that transmits video frames for the stream $j,\ j = 1, \ldots, J$, with the shortest prefetched video segment p_j [in seconds] achieves generally minimal video playback starvation probabilities [26]. In order to determine the shortest prefetched video segment, the OLT needs to track the lengths of the prefetched video segments $p_j,\ j = 1, \ldots, J$, for the individual streams.

A key consideration for designing a video prefetching mechanism for a FiWi network with its multiple heterogeneous network segments is the timely downstream delivery of a video frame from the OLT to the wireless station and the timely return of an acknowledgement for an intact frame delivery. Clearly, for the transmission over the optical network segment and for the transmission over the wireless network segment during the reservation-based period, losses are highly unlikely. On the other hand, transmissions over the wireless network segment during contention-based periods may occasionally suffer losses or large delays. In our multi-polling approach, the OLT reserves for each node receiving video traffic periodically recurring (e.g., every few msec) slots for transmitting video frame acknowledgements upstream over the wireless and optical network segments.

The design of a prefetching mechanism for FiWi networks involves tradeoffs between transmitting future frames that increase the length of the prefetched segments p_j, re-transmitting video frames that are not acknowledged within a timeout period (and can still be received by their playback deadline), and the complexity of the scheduling and decision process. We approach these tradeoffs by exploiting the GoP frame structure of H.264 SVC encoded video [9], [10]. We define intra-coded (I) frames, forward predictive encoded (P) frames, and bidirectionally predicted (B) frames up to a prescribed level $l,\ l = 0, 1, \ldots, \log_2(g + 1)$, (with g B frames between successive I and P frames) in the hierarchical B frame prediction structure as high priority frames. High priority frames are transmitted primarily over the reservation-based period in the wireless network segment and are retransmitted if not acknowledged within a timeout period Δ_o. On the other hand, we define B frames from levels higher than l as low priority frames that are primarily transmitted during the contention-based period of the wireless network segment and are not retransmitted. In addition to frame prioritization according to the position of a frame in the GoP structure, other video-specific enhancement techniques, such as interleaving of video frames or parts thereof [43], [44], or general forward error correction techniques can be employed. With frame interleaving, the playout deadlines of the frames after de-interleaving need to be considered when verifying the playout deadline constraint, see Section III-C2b.

An additional important consideration in the design of the prefetching mechanisms is the assignment of prefetching tasks to the nodes in our FiWi network architecture illustrated in

Fig. 1. Our architecture envisions the OLT and the VRMP as the two main nodes responsible for protocol execution and control of the FiWi network. For instance, we envision that the VRMP functions as a local media gateway that serves media streams to its associated wireless stations and performs local adaptations (such as transcoding). In keeping with this architectural vision, we place the responsibilities for controlling the prefetching on the OLT and VRMP. The intermediate nodes between OLT and VRMP, i.e., the ONU MPP and any intermediate MPs, as well as the intermediate nodes between VRMP and wireless station simply forward the in-transit video frame packets. In the following we develop in detail the individual components of the prefetching mechanism executed at the OLT and VRMP.

2) Prefetching Mechanisms at OLT: The OLT performs three main functions for the prefetching. First, the OLT tracks the lengths of the prefetched segments p_j for the individual streams. Based on these segment lengths p_j, the OLT selects the video frames to be transmitted. Then, the OLT prioritizes the transmissions of the selected frames.

a) Tracking prefetch segment length p_j: For each ongoing stream $j,\ j = 1,\ldots,J$, the OLT tracks the length of the prefetched segment p_j [in seconds] and the prefetch buffer content b_j [in bit] as follows. When a video frame of size x_j is scheduled for transmission for stream j, the OLT makes the updates $p_j \leftarrow p_j + 1/T$ and $b_j \leftarrow b_j + x_j$, whereby T denotes the frame period (display time of one video frame) in seconds. The OLT tracks the removal of a frame of size x_j from the prefetch buffer for stream j through the updates $p_j \leftarrow [p_j - 1/T]^+$ and $b_j \leftarrow [b_j - x_j]^+$, whereby $[y]^+ = \max(0, y)$ at the instant of retrieval of the frame for playback.

Note that in case of loss or excessive delay of a transmitted frame, the tracking variables p_j and b_j may overestimate the actual prefetched video segment in the wireless client. In order to keep these overestimates small (and thus keep their impact on the scheduling negligible) the wireless client updates the OLT periodically, e.g., a few times per second, about its actual prefetched segment.

b) JSQ-based frame selection: VMP may employ any prefetch frame selection policy, such as policies from [23], [24], [26]. Without loss of generality, we explain here the use of the discrete-time join-the-shortest-queue (JSQ) prefetch policy, which has low complexity while achieving relatively good performance [26], [45], in the context of our FiWi network. The JSQ policy operates in rounds, whereby a round is equal to the duration of the video frame period T. Let π_j denote the length of the video segment [in seconds] selected for transmission for stream $j,\ j = 1,\ldots,J$, in the present round and let β_j denote the size [in bit] of the selected frames for stream j in the present round. At the beginning of each round, all π_j and β_j are set to zero.

To select the next frame for transmission, the OLT considers the next frame from the stream j^* with the shortest prefetched segment, i.e.,

$$j^* = \arg\min_{j=1,\ldots,J} \pi_j + p_j \tag{1}$$

and checks whether this frame meets bandwidth, buffer, and playout deadline constraints. We denote x_{j^*} for the size of the considered frame [in bit].

Toward verifying the bandwidth constraints, we introduce the following notation to characterize the bandwidth in terms of the number of bits that can be transmitted in a frame period of duration T. Specifically, we denote $\rho_t = R \cdot T$ [in bit] for the bottleneck bandwidth and $\rho_r(s) = r_r(s) \cdot T$ for the reserved bandwidth for station s. We denote $\rho_p = \rho_t - \sum_{s=1}^{S} \rho_r(s)$ for the pool of unreserved bandwidth. A considered frame of size x_{j^*} meets the overall bandwidth constraint if

$$x_{j^*} + \sum_{j=1}^{J} \beta_j \leq \rho_t. \tag{2}$$

In addition, the frame needs to meet the bandwidth constraint for station s, which can utilize its reserved bandwidth and the unused portion of the unreserved bandwidth pool. The other stations $s \neq s(j^*), s = 1,\ldots,S$, utilize

$$\rho_o = \sum_{s \neq s(j^*), s=1,\ldots,S} \left(\sum_{j \in \mathcal{S}_s} \beta_j \right) - \rho_r(s) \tag{3}$$

bits of the unreserved bandwidth pool, leaving $\rho_p - \rho_o$ for station $s(j^*)$. Hence, the considered frame meets the station bandwidth constraint if

$$x_{j^*} + \sum_{j \in \mathcal{S}_{s(j^*)}} \beta_j \leq \rho_r(s) + \rho_p - \rho_o. \tag{4}$$

The buffer constraint is satisfied if the considered frame fits into the prefetch buffer for stream j, i.e., if

$$x_{j^*} + \beta_j + b_j \leq B_j, \tag{5}$$

whereby B_j denotes the prefetch buffer capacity for stream j. The playback deadline constraint is satisfied if the frame arrives by its playout deadline if successfully transmitted in the current round. If all conditions are satisfied, the frame is selected for transmission and we update

$$\pi_{j^*} \leftarrow \pi_{j^*} + \frac{1}{T} \quad \beta_{j^*} \leftarrow \beta_{j^*} + x_{j^*}. \tag{6}$$

If the frame violates any of the constraints (2), (4), or (5), then stream j is removed from consideration for the remainder of this round. If the frame violates the playout deadline constraint, it is permanently removed from consideration. This frame selection process continues by considering the frame from the stream with the smallest $\pi_j + p_j$ until all J streams have been removed from consideration. If all frames for a stream have been prefetched, the stream is not further considered in the scheduling; the receiver plays the frames from its prefetch buffer until the end of the video is reached.

c) Transmission prioritization: The selected video frames are packetized according to the packetization policies applicable on the network and prioritized as follows along with the downstream voice and data packets. First, the packets carrying the high-priority video frames selected for station s are scheduled in the reserved bandwidth for station s. High-priority frame packets that do not fit into the reserved bandwidth for the round $\rho_r(s)$ are scheduled for transmission during the contention-based period. If after scheduling all high priority frame packets there is remaining reserved bandwidth, then the voice packets followed by low-priority video frame packets are

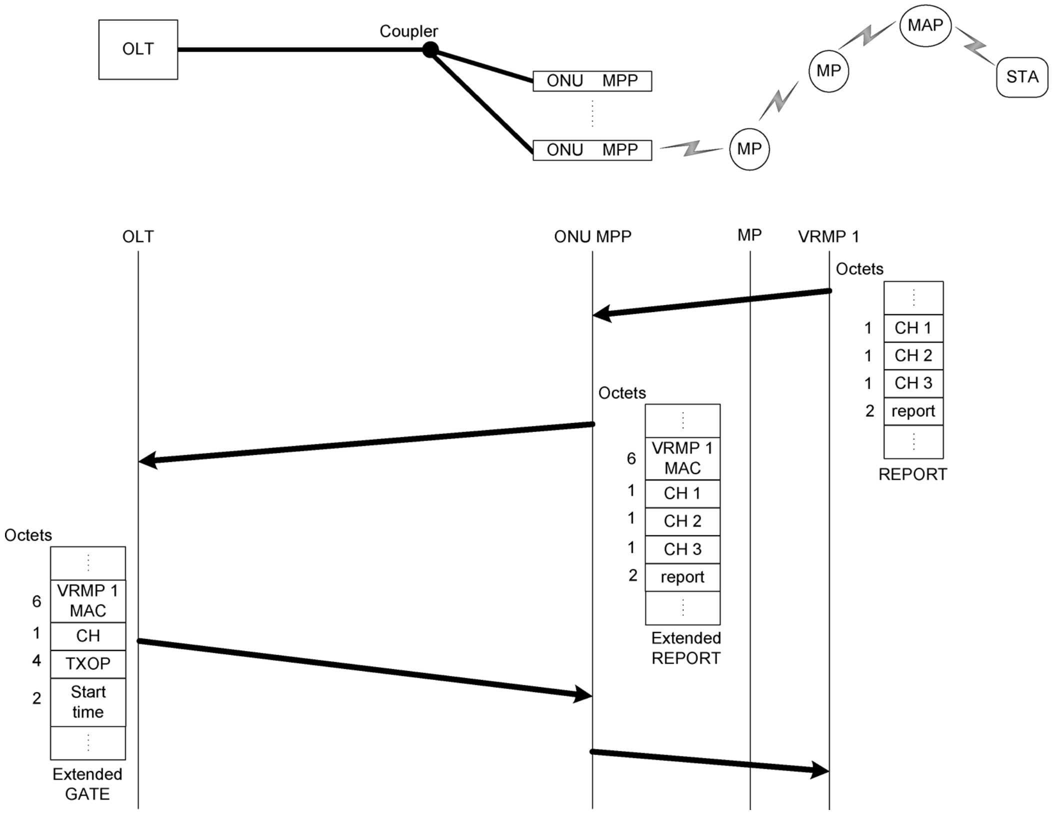


Fig. 4. Wireless channel and bandwidth multi-polling using PCF at the OLT.

scheduled to fill the reservation-based period. Data packets are scheduled for the contention-based period after all video and voice packets have been scheduled.

3) Wireless Error Recovery and Channel Probing: We consider two approaches for addressing the effects of wireless channel errors and excessive contention which may lead to losses or excessive delays of video packets (and acknowledgements). The retransmission approach retransmits high-priority frames that are not acknowledged within the timeout period Δ_o. In particular, such frames are considered first (before considering frames selected according to the $\min_j \pi_j + p_j$ rule) in the next scheduling round.

In contrast, with the channel probing approach, the OLT avoids transmissions to the affected station until a small probing packet is successfully acknowledged. With this channel probing approach, the VMP protocol takes both the status of the prefetch buffers of the individual streams as well as the status of the wireless links leading to the individual stations into consideration. Thus, channel probing ensures that the OLT does not schedule frames that would very likely be lost on the wireless network segment. Instead, with JSQ prefetching with channel probing, the OLT focuses on transmitting video frames to the stations with currently favorable wireless channel conditions.

IV. EVALUATION RESULTS

A. Simulation Set-Up

In our simulation, we consider an urban deployment scenario, where the EPON brings the fiber to the curb and ONU MPPs are used to provide wireless networking to end-users within company or university campuses, residential apartment complexes, or neighborhood area networks. We consider a FiWi network with 16 ONUs and 16 ONU MPPs connected to the OLT, whereby the distance between ONUs/ONU MPPs and OLT is set to 20 km. Five STAs are located at a range of 100 m of the associated MAPs, while the distance between a pair of adjacent MAP, MP, and ONU MPP is 200 m. Each STA is connected to an ONU MPP via an MAP and two intermediate MPs, whereby the MP located at two hops from the STA plays the role of a VRMP. We assume that the prefetch buffer size in each node is sufficiently large to avoid overflows. We set the EPON data rate to 1 Gb/s, while the data rate of a WLAN channel is set to 100 Mb/s. For these rates and the considered network topology, the wireless network segment has a capacity of 1.2 Gbps due to spatial channel reuse [41]; thus, the optical network segment is the downstream bottleneck, i.e., $R = 1\ \mathrm{Gbps}$.

In the simulation of the optical networking segment, we consider limited-service interleaved polling with adaptive cycle time (IPACT) with a maximum grant size of 15 kBytes as EPON DBA algorithm [46].

Our simulator is based on Omnet++ [47] and C++ and is an aggregation of simulation modules for the different network components and protocol aspects that form the considered VMP evaluation scenario. Each simulation module has been validated in isolation in prior work. For instance, the module for the underlying MPCP protocol and DBA on the EPON has been validated in [48] through comparisons with mathematical analysis. Similarly, the module for the wireless mesh network has been validated in [41] and the module for the frame aggregation in the integrated FiWi network has been validated in [49].

TABLE I
I AND B FRAMES STATISTICS OF FOUR SINGLE-LAYER H.264 SVC VIDEO TRACES

	Tokyo Olympics (74 min)	Silence of the Lambs (30 min)	Star Wars IV (30 min)	NBC News (30 min)
Mean I Frame Bit Rate (Mb/s)	3.40	2.42	2.54	5.53
Peak I Bit Rate (Mb/s)	11.98	10.91	6.41	11.31
CoV of I Frame Sizes	0.57	0.70	0.44	0.32
Mean B Frame Bit Rate (Mb/s)	0.400	0.149	0.161	0.672
Peak B Bit Rate (Mb/s)	6.27	6.16	3.69	6.70
CoV of B Frame Sizes	1.34	2.12	1.48	1.02

1) Triple-Play Scenario: We consider a triple-play scenario and a video-only scenario. In the triple-play scenario, we consider uniform unicast voice and data traffic, where any of the given $N+1$ nodes, i.e., OLT, ONU, ONU MPP, or STA, sends a generated packet to any other node with equal probability $1/N$. Also, ONUs, ONU MPPs, and STAs are receivers of downstream video. We employ traces of four CIF-format videos (see overview in Table I) encoded with H.264 SVC into a single layer with a quantization parameter of 24 to simulate the video streams [5], [50]. The videos cover a wide spectrum of genres and consist of many scenes with a wide range of levels of motion activity and texture detail. For each ongoing video stream, we select uniformly randomly one of the four video traces as well as a uniform random starting phase into the selected trace. The lifetime (duration) of a video stream is geometrically distributed; initially with a mean of 25 minutes. The video playback at the receiving node commences after a start-up delay of three rounds of scheduling and transmissions at the OLT. The generated video packets are transmitted using 8 octets and 20 octets of UDP and IP headers, respectively. We consider the group of pictures (GoP) structure with one I frame and $g = 15$ hierarchical B frames per GoP due to its very good RD efficiency [5]. We consider the I frames as high-priority frames and all B frames as low-priority frames. For the generation of voice traffic, we consider the voice codec standard ITU-T G.711, where a packet of 160 octets is generated every 20 msec without compression, translating into a CBR source rate of 64 kb/s. The fixed-size CBR voice packets contain 12, 8, and 20 octets of RTP, UDP, and IP headers, respectively. Further, we assume that there is no silence suppression. For a given traffic load level we use the same number of ongoing voice streams and video streams.

For the data traffic, which accounts for 20% of the total traffic load in the triple-play scenario, we consider Poisson packet traffic with packet sizes of 40, 552, and 1500 bytes with probabilities 0.5, 0.3, and 0.2, respectively. The generated data packets are transmitted with an additional 20-byte TCP header and 20-byte IP header.

For the triple-play scenario, we set the bit error rate of the wireless channel to 10^{-5} and evaluate the network performance in terms of throughput and delay as a function of load. Throughput [in bit/s] measures the long-run average bit rate due to successfully transmitted packets reaching their final destination. We include the headers directly associated with network and higher layers, i.e., IP, UDP, TCP, and RTP headers, in the throughput; whereas, all headers and overhead associated with the physical and MAC layers, such as Ethernet header and preamble as well as EPON REPORT and GATE messages, are not included in the throughput measure. The delay [in seconds] denotes the time interval from the instant a packet is generated at the source node to the instant the packet is completely received at the destination node in steady state. Throughout, we present the means and 90% confidence intervals obtained from statistically independent replications of the simulations. The load [in bit/s] is the long-run average bit rate of generated packets (and the network and higher layer headers) in the network.

2) Video-Only Scenario: In the video-only scenario there is only downstream video as specified in the preceding section, but no voice or data traffic. In order to examine the interplay between the time-sensitive video streaming traffic and wireless errors in closer detail, we consider the Gilbert-Elliot two-state wireless channel model [51]–[55]. Following [27], [56]–[58], we set the channel error probabilities of the good and bad states to 0.05 and 1, respectively, while the steady-state probability of being in the good and bad states are 0.99 and 0.01 and the average sojourn time in the bad channel state is 1 second. We evaluate the performance by measuring the starvation probability as a function of the bandwidth efficiency in our simulations. The starvation probability is defined as the long-run fraction of encoded video bits that miss their playback deadline at the receiver. When at least one of the packets carrying a frame misses its playback deadline, we consider all bits of the frame as lost. The bandwidth efficiency normalizes the sum of the average bit rates of the J ongoing video streams by the bottleneck bandwidth R.

B. Frame Fragmentation and Hierarchical Frame Aggregation

Fig. 5 compares the proposed joint frame fragmentation and hierarchical frame aggregation in the integrated FiWi network with independent network operation, and with an integrated FiWi network with only hierarchical frame aggregation (and no frame fragmentation), as studied in [18]. Throughout, the integrated FiWi networks employ our multi-polling approach. With independent network operation, EPON and WLAN-based WMN operate independently and both the optical and wireless segments are controlled separately. The independent network does not employ frame fragmentation, nor frame aggregation. We consider a single-channel WMN and the triple-play scenario in this comparison. The video traffic is transmitted using the hybrid reservation/contention based approach [15] so as to examine only the impact of the proposed joint frame fragmentation and hierarchical frame aggregation.

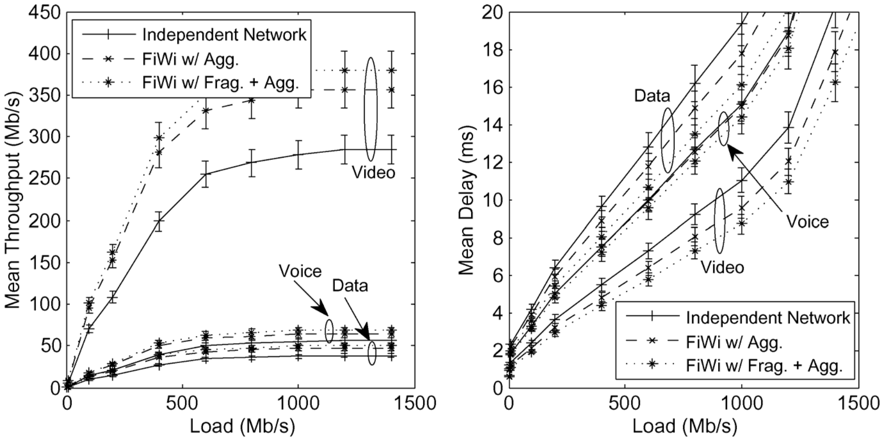


Fig. 5. Impact of frame fragmentation and hierarchical frame aggregation on integrated EPON-WLAN network performance for single-channel WMN under triple-play (voice, video, and data) traffic.

We observe from Fig. 5 that the joint frame fragmentation and hierarchical frame aggregation in the integrated multi-polling FiWi network improves both network throughput and delay. Our results confirm the throughput-delay improvement of hierarchical frame aggregation in FiWi networks, which has been previously observed in isolated WLANs [17]. Moreover, we observe the added benefit of using frame fragmentation, which was not considered in [18]. Overall, the high-volume video traffic achieves a large throughput increase of up to 46% with joint frame fragmentation and aggregation.

C. VMP Video Traffic Performance

Fig. 6 shows the impact of the reserved bandwidth r_r, which we set to the same value for all nodes receiving video, on the starvation probability for the video-only scenario with a fixed bandwidth efficiency of 95%. The independent network employs the hybrid reservation/contention-based MAC protocol [15] in the wireless network segment, while standard polling-based IPACT [46] is employed in the optical network segment. The integrated FiWi with VMP networks employ all components of our VMP protocol, i.e., joint frame fragmentation and hierarchical frame aggregation, centralized multi-polling, and prefetching.

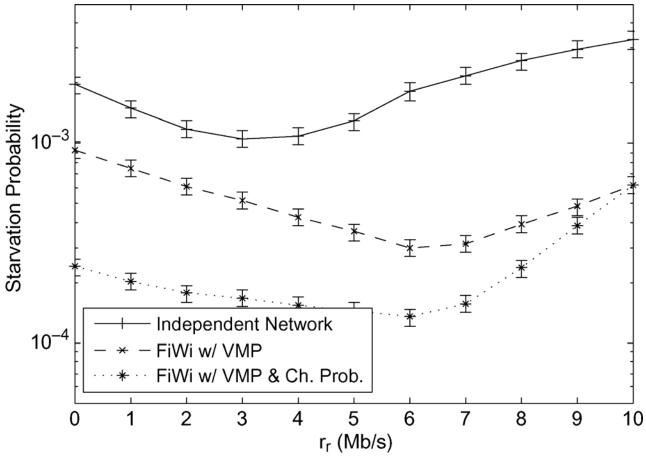


Fig. 6. Impact of reserved bandwidth r_r on starvation probability for video-only scenario.

We observe from Fig. 6 that all three considered networks exhibit the same overall trend of initially decreasing and then increasing starvation probability as the reserved bandwidth r_r increases. The explanation for this behavior is as follows. In the absence of reservations ($r_r = 0$), all video packets have to content for wireless channel access leading to a high proportion of collisions and relatively inefficient packet transport. At the other extreme, when dividing up the bottleneck bandwidth R equally among the N nodes receiving video streams and giving each receiving node a fixed bandwidth allocation $r_r = R/N$ there is no bandwidth left for contention. That is, there is effectively one "circuit" of fixed bandwidth to each receiving node and no more (global) statistical bandwidth sharing among transmissions to different nodes. As a result, only the streams destined to the same receiving node can statistically share the fixed bandwidth allocation to the node. This lack of global bandwidth sharing leads to high starvation probabilities for the streaming of the bursty video traffic without prefetching in the independent network. In particular, when all streams for a given node have relatively small frames at the same time, parts of the reserved bandwidth are not used; whereas, when the streams have relatively large frames, the reserved bandwidth is not sufficient. With prefetching, periods when the streams destined to the same receiving node have relatively small frames are utilized to transmit future frames to the node. Thus, over time, reserves of prefetched frames are built up in the receiving nodes. These reserves allow the nodes to continue playback when wireless errors occur and allow for retransmission of lost high-priority frames. The reserves also help when all streams play back relatively large frames.

The lowest starvation probabilities are achieved for moderate levels of reserved bandwidth around 3 Mb/s for the independent network and around 6 Mb/s for VMP. At these moderate levels of reservation, a basic level of the variable bit rate video traffic (especially the I frames scheduled with priority on the reserved bandwidth) benefit from the efficient contention-free fixed-bandwidth "circuit" to each receiver. The traffic exceeding the reserved bandwidth for a node contends for the globally shared remaining bandwidth pool $R - Nr_r$. As the simulation results indicate, the benefits from global statistical multiplexing of the traffic exceeding the reservations

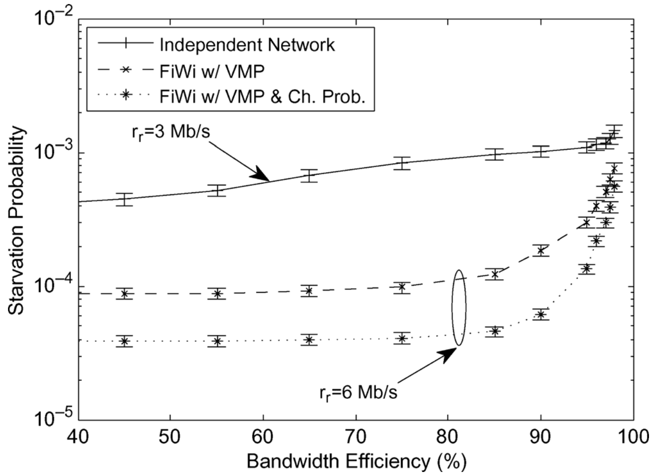


Fig. 7. Starvation probability as a function of bandwidth efficiency.

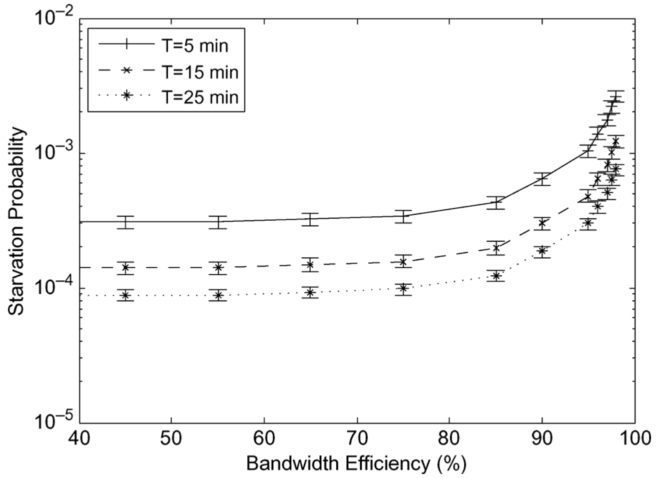


Fig. 8. Starvation probability as a function of bandwidth efficiency (normalized load) for different average video stream durations (FiWi network with VMP, no channel probing, $r_r = 6\ \mathrm{Mbps}$).

for the individual nodes outweighs the inefficiencies introduced through contention. The prefetching in VMP makes the statistical multiplexing among the streams destined to a given receiving node relatively more efficient than the transmission without prefetching in the independent network. Therefore, VMP has a tendency to give its best performance for relatively higher reserved bandwidths than the independent network.

Channel probing reduces the starvation probability significantly by avoiding transmissions to clients that are currently unreachable due to wireless outages. Instead, more frames can be prefetched for clients with favorable channel conditions, increasing in the long-run the prefetched reserves among the clients and reducing the starvation probability. This effect is particularly pronounced when the globally shared unreserved bandwidth pool is large, i.e., when r_r is small, as then the stations with favorable channel conditions can utilize the bandwidth not used by the stations in channel probing mode. Overall, Fig. 6 shows that VMP with channel probing reduces the video starvation probability by over an order of magnitude compared to the independent network for a wide range of the reserved bandwidth.

In Fig. 7, we plot the starvation probability as a function of the bandwidth efficiency. We observe that VMP achieves significantly lower starvation probabilities than the independent network. The performance improvement with VMP is especially pronounced for moderately high loads in the range from about 50–90% with VMP reducing the starvation probability by an order of magnitude or more. The combination of performance enhancing mechanisms of VMP can transport bursty video traffic over FiWi networks with small starvation probabilities when the bottleneck capacity is only about 10–15% higher than the sum of the average rates of the video streams.

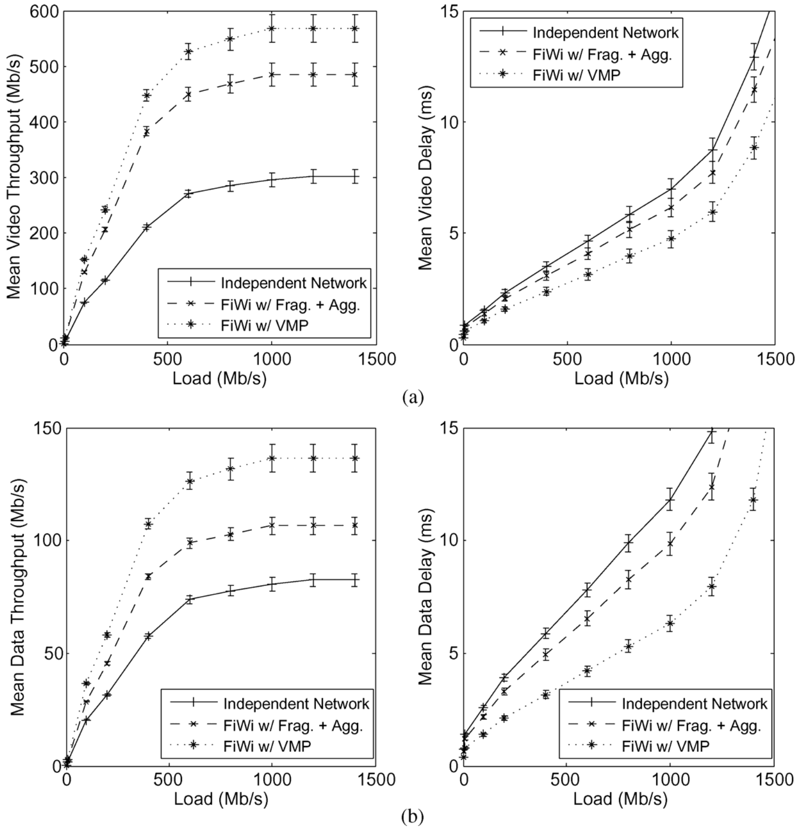
In Fig. 8, we examine the impact of the average duration of the video streams on the VMP performance. We conservatively consider VMP without channel probing. We observe that the starvation probability decreases with increasing average stream duration. This is because longer stream lifetimes give more opportunities for building up large prefetched reserves. Nevertheless, even for average stream duration as short as five minutes does VMP with prefetching achieve significant reductions of the starvation probability compared to the independent network (Fig. 7), which is essentially unaffected by the stream duration. Aside from the duration of the video streams, the performance of VMP with prefetching depends on the availability of buffer in the intermediate nodes and the receiving nodes. Many video-capable consumer devices have abundant memory that can buffer video segments on the order of tens of seconds or minutes; thus, removing the buffer constraint for most practical systems.

D. *VMP Performance for Triple-Play Traffic*

In Fig. 9, we plot the throughput and delay for video traffic and data traffic when VMP with prefetching (without channel probing) is employed in the triple-play scenario. We observe from Fig. 9(a) that video traffic benefits significantly from the combination of joint frame fragmentation and hierarchical frame aggregation combined with multi-polling and prefetching. Similarly, we observe from Fig. 9(b) that data traffic benefits from the performance enhancing mechanisms in VMP. (The results for voice traffic, which are not plotted, are similar.) Aside from benefiting from the frame fragmentation and frame aggregation as well as the multi-polling, the downstream voice and data traffic benefit from the more efficient video transport with prefetching. Data traffic is not starved despite the strategy of the JSQ prefetching to transmit as many future frames as fit fully into the total bandwidth and the station bandwidth. There is typically some unused bandwidth remaining after the JSQ policy has removed all streams from consideration because all frames have been transmitted for a stream or none of the next frames of the streams fits fully into the remaining bandwidth. Voice and data traffic, which have much lower traffic rates than the video streams, fill up the remaining bandwidth.

V. CONCLUSION

We have studied efficient medium access control (MAC) mechanisms for integrated Fiber-Wireless (FiWi) networks with substantial prerecorded video traffic in the downstream direction. We have found that the combination of *(i)* joint frame fragmentation and hierarchical frame aggregation, *(ii)*



(a)

(b)

Fig. 9. Throughput and delay performance of VMP for video traffic and data traffic in triple-play scenario. (a) Video traffic; (b) data traffic.

multi-polling, and *(iii)* prefetching in conjunction with hybrid reservation/contention-based MAC efficiently supports triple-play (data, voice, and video) traffic in FiWi networks. We discovered that hybrid reservation/contention-based MAC benefits significantly from prefetching scheduling of video frames with channel probing. For a wide range of reserved bandwidth levels, prefetching with channel probing robustly achieves playback starvation probabilities that are over an order of magnitude lower than for hybrid reservation/contention-based MAC without prefetching.

A next step could be the standardization of VMP as an extension of the IEEE 802.3 EPON or IEEE 802.11 WiFi standards. Recently, the IEEE has formed a study group to extend EPON reach by implementing the EPON MPCP protocol over coax cables. Similar standardization activities in IEEE 802.3 could address integrated EPON/WiFi networking and enhancing application layer protocols, e.g., for video streaming.

An important direction for future research is to examine the internetworking of the FiWi network MAC protocol considered in this study with metropolitan area networks, such as ring and star-based optical metro networks [59]–[62]. Another important direction for future work is to examine efficient mechanisms for upstream (from the individual wireless stations to the Optical Line Terminal) transport of streaming video.

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