Frame aggregation in fibre-wireless (FiWi) broadband access networks

N. Ghazisaidi, M. Scheutzow and M. Maier

MAC enhancements of emerging high-throughput WLANs are considered and a novel FiWi network architecture is introduced that integrates next-generation WLAN-based WMN and EPON in a pay-as-you-grow manner while providing backward compatibility with a legacy infrastructure and protecting previous investments. To investigate the performance of FiWi networks, the capacity of WMNs is evaluated through probabilistic analysis and verifying simulations. Advanced aggregation techniques are proposed and examined to improve FiWi network throughput-delay performance for voice, video, and data traffic under realistic wireless channel conditions.

Introduction: Bimodal FiWi access networks aim at providing wired and wireless services over the same infrastructure simultaneously, thus potentially leading to major cost savings [1]. Recently, various FiWi network architectures have been investigated by integrating different optical and wireless technologies [2]. The University of California (UC) Davis FiWi testbed integrates two Ethernet passive optical networks (EPONs) and an IEEE 802.11g wireless local area network (WLAN)-based single-channel wireless mesh network (WMN) with a maximum transmission rate of 54 Mbit/s [3]. Experimental results show that the quality of video transmissions sharply deteriorates for an increasing number of wireless hops. Therefore, a more involved analytical investigation of integrated FiWi network performance, especially in the wireless segment, is needed.

Capacity analysis of wireless mesh frontend: Fig. 1 shows the proposed FiWi network architecture consisting of a tree-based IEEE 802.3ah EPON and IEEE 802.11n next-generation WLAN-based single-channel IEEE 802.11s WMN. In this Figure, the optical-wireless interface consists of the following three components: (i) an optical network unit (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) a mesh portal point (MPP) – this unit includes the wireless equipment, and (iii) a central processing unit (CPU) – this component synchronises the two aforementioned units and controls both optical and wireless network segments by monitoring their operation. The WMN provides multihop communications to forward traffic en route to and from MPPs by using intermediate mesh points (MPs).

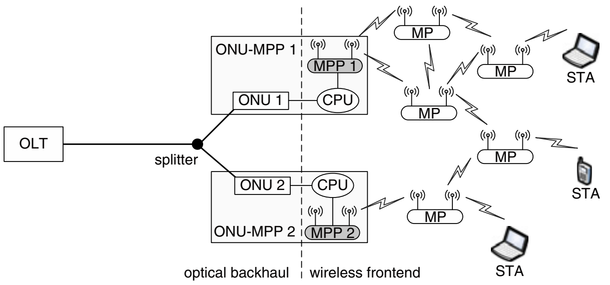

Fig. 1 *FiWi network architecture: integrated EPON and next-generation WLAN-based WMN*

In the WMN, we let N nodes [i.e. MPPs, MPs, or STAs] be uniformly distributed. In an error-free single-channel WMN, a pair of nodes are connected (shown by wireless edges) if and only if the distance between them is less than their maximum radio transmission range to satisfy the constraints of the DCF or EDCA modes [4]. For instance, the maximum distance between two connected nodes is less than 2.7 km in IEEE 802.11n with a *slot size* = 9 µs and *short interframe space* (SIFS) = 16 µs. In our network model, the simultaneous data transmission on two different edges $e = \{i, j\}$ and $\tilde{e} = \{k, l\}$ is possible if and only if e and $\tilde{e}$ are sufficiently far apart from each other, i.e. none of the nodes i and j is adjacent to any of the nodes k and l. We note that edges are undirected (i.e. we write $\{i, j\}$ rather than (i, j)). For simplicity, we consider shortest path routing in terms of number of hops. Let λ_{ij} be the *traffic rate* from WMN node i to j scaled such that $\lambda_{ij} = 1$ corresponds to the maximal capacity of the edges. For each edge $e = \{i, j\}$, we determine the total traffic in both directions $t_{\{i,j\}}$ by summing up all λ_{kl} for nodes k and l which use edge e. Let ξ denote the set of all edges. We call $\zeta \subseteq \xi$ *admissible*, if any two different edges in ζ are far apart. Note that a set of edges is admissible if and only if all edges of the set can be used simultaneously for data transmission. We say that $\zeta \subseteq \xi$ is *maximally admissible*, if ζ is admissible and $\zeta \subseteq \tilde{\zeta} \subseteq \xi$, where the admissibility of $\tilde{\zeta}$ implies $\tilde{\zeta} = \zeta$. In a stable system, there exists a maximally admissible set ζ such that only edges of that set are used for each data transmission. We note that ζ may not be unique. If α_ζ denotes the long-time probability in which ζ is used, then the stability condition is $\Sigma_\zeta \alpha_\zeta \le 1$. The network stability means that each edge $e \in \xi$ can cope with the traffic t_e that has to go through e. Therefore, a necessary condition for network stability is that for each maximally admissible ζ, there exists $\alpha_\zeta \ge 0$ such that

$$\begin{cases} \Sigma_\zeta \alpha_\zeta = 1 \\ \Sigma_{e \in \zeta} \alpha_\zeta \ge t_e \end{cases} \tag{1}$$

Linear programming can be used to solve the stability limits of (1) and thus obtain the capacity of WMN.

Advanced aggregation techniques: The main MAC enhancement of 802.11n is frame aggregation which comes in two flavours [4]: (i) aggregate MAC service data units (A-MSDU) are used to join multiple MSDU subframes into one MAC protocol data unit (MPDU), and (ii) aggregate MAC protocol data units (A-MPDU) are used to join multiple MPDU subframes into one PHY service data unit (PSDU). It was shown in [4] that joint two-level aggregation is able to achieve higher throughput efficiency. According to the pros and cons of single- and two-level aggregation schemes, we propose and investigate various advanced aggregation techniques for our FiWi network.

We apply A-MSDU in the optical segment since A-MSDU is able to achieve a higher throughput than A-MPDU for error-free channels [5]. A-MPDU is considered for the wireless network segment. For optical downstream traffic destined to STAs, two-level aggregation techniques are used to improve throughput-delay performance, where the OLT and ONU-MPP perform A-MSDU and the second level A-MPDU, respectively.

Results: In our simulations, we consider uniform unicast traffic between OLT, ONU-MPPs, and STAs. We assume that 48 STAs are connected to the OLT through 80 MPs and 32 ONU-MPPs (see Fig. 1 where three STAs are connected to a pair of ONU-MPPs), whereby the distance between ONU-MPPs and the OLT is set to 20 km. The STAs are located at a range of 2 km of the associated MPs, while the distance between a connected pair of MPs and MPPs is set to 2 km. The optical line rate is set to 1 Gbit/s.

First, we consider Poisson data traffic with different packet sizes equal to 40, 552, and 1500 bytes according to a distribution of 50, 30, and 20%, respectively, transmitted with an additional 20-byte TCP header and 20-byte IP header. Also we use the voice codec standard ITU-T G.711 with a CBR source rate of 64 Kbit/s, where each packet contains 12, 8, and 20 bytes of RTP, UDP, and IP headers, respectively. We deploy the MPEG-4 video codec to encode 600-byte packets at a data rate of 768 Kbit/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 generated traffic, while Poisson traffic uses 20% of the network capacity. In EPON, we use the limited-service interleaved polling with adaptive cycle time (IPACT) with a maximum grant size of $G_{max} = 15$ kbytes as the DBA algorithm [6]. In WLAN, the BER of the wireless channel is set to 10^{-5}. Fig. 2 shows the beneficial impact of our proposed advanced aggregation techniques on the performance of FiWi network for various WMN data rates under data traffic. In Fig. 2, the analysis results show the upper-bound of network throughput (i.e. capacity) verified by simulation. The simulations yield smaller throughput results than the analysis owing to the realistic wireless channel conditions and applying request to send/clear to send (RTS/CTS) packets in WMN as well as REPORT/GATE packets in EPON. Furthermore, (1) shows the stability limits of WMN for a flow of packets, while the limited-service granting approach is used in our simulations. As a result, we observe that the simulation results of the proposed aggregation techniques (with smaller overhead) are closer to the analysis results than without aggregation, including larger overhead. Fig. 3 shows the impact of our proposed aggregation techniques on the performance of the FiWi network for various WMN data rates under triple-play traffic. In this Figure, mean throughput and mean delay are averaged over all three traffic types.

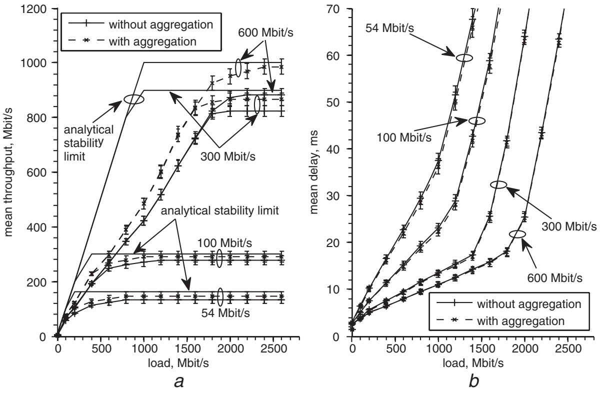

Fig. 2 *Impact of advanced aggregation techniques on network performance under data traffic*

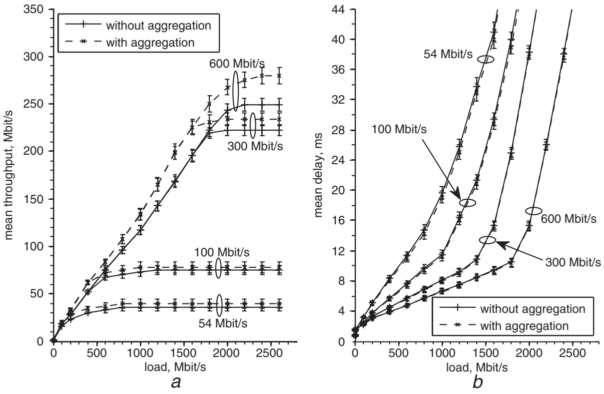

Fig. 3 *Impact of advanced aggregation techniques on network performance under triple-play traffic*

Conclusions: We evaluated the capacity of WMNs through probabilistic analysis and verifying simulations and investigated the performance of a FiWi network consisting of an EPON and WLAN-based WMN. The obtained results show that the proposed aggregation techniques improve the throughput-delay performance of the FiWi network under data and triple-play traffic types.

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N. Ghazisaidi and M. Maier (*Optical Zeitgeist Laboratory, Institut National de la Recherche Scientifique (INRS), Montréal, QC, H5A 1K6, Canada*)

M. Scheutzow (*Department of Mathematics, Technical University Berlin, Berlin 10623, Germany*)

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