Analytical Framework for the Capacity and Delay Evaluation of Next-Generation FiWi Network Routing Algorithms

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***Abstract*—Toward the vision of complete fixed-mobile convergence, a plethora of wireless, integrated optical-wireless, multipath, and energy-aware routing algorithms were proposed for legacy EPON/WLAN-mesh based bimodal fiber-wireless (FiWi) broadband access networks. In this paper, we present the first comprehensive analytical framework for providing deeper insights into the capacity and delay performance of routing algorithms in next-generation FiWi networks based on emerging powerful optical and wireless technologies such as long-reach 10+ Gb/s TDM/WDM PONs and Gigabit-class VHT WLANs.**

I. Introduction

To realize the vision of complete fixed-mobile convergence and deliver peak data rates of 200 Mb/s and higher per user, it is crucial to replace today's legacy wireline and microwave backhaul technologies with converged optical fiber-wireless (FiWi) broadband access networks. FiWi access networks aim at combining the reliability, robustness, and high capacity of optical fiber networks and the flexibility, ubiquity, and cost savings of wireless networks [1].

Although a few FiWi architectural studies exist on the integration of optical access networks with LTE or WiMAX, the vast majority of studies considered FiWi access networks consisting of a conventional IEEE 802.3ah Ethernet Passive Optical Network (EPON) fiber backhaul and an IEEE 802.11b/g WLAN-based wireless mesh front-end [2]. In particular, the design of routing algorithms for such legacy EPON/WLAN-mesh based FiWi networks received a great deal of attention, resulting in a large number of proposed wireless (e.g., DARA [3]), integrated optical-wireless (e.g., availability-aware routing [4]), multipath (e.g., [5]), and energy-aware routing algorithms (e.g., [6]). Most of these previous studies formulated routing in FiWi networks as an optimization problem and obtained results mainly by means of simulation.

In this paper, we present for the first time ever an analytical framework that allows to evaluate the capacity and delay performance of a wide range of different FiWi network routing algorithms, including the aforementioned ones. Importantly, our framework encompasses not only legacy EPON and WLAN networks, but also emerging next-generation optical and wireless technologies such as long-reach and multi-stage wavelength division multiplexing (WDM) PONs as well as very high throughput (VHT) WLANs. The remainder of the paper is structured as follows. Section II describes next-generation FiWi access networks in more detail. The analytical framework is presented in Section III. Section IV provides numerical results and conclusions are drawn in Section V.

This work was supported by the FQRNT MERIT Short-term Research Scholarship Program and NSERC Strategic Project Grant No. 413427-2011.

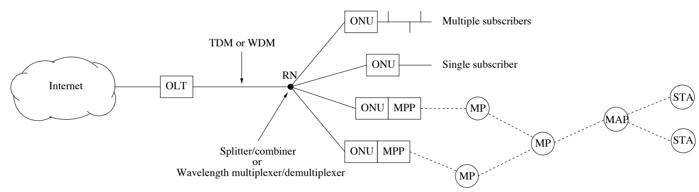

Fig. 1. FiWi network architecture based on single- or multi-stage TDM or WDM PON and multihop WMN (MPP: Mesh Portal Point, MP: Mesh Point, STA: Wireless Station).

II. Next-Generation FiWi Networks

Fig. 1 depicts the generic architecture of an EPON/WLAN-mesh based FiWi access network. The fiber backhaul may be a conventional single-channel time division multiplexing (TDM) IEEE 802.3ah 1Gb/s EPON or high-speed IEEE 802.3av 10 Gb/s EPON with a splitter/combiner at the remote node (RN) to interconnect the central optical line terminal (OLT) with multiple optical network units (ONUs). It may be upgraded to a wavelength-broadcasting multi-channel WDM PON with multiple bidirectional wavelength channels and leaving the splitter/combiner in place. Alternatively, the splitter/combiner may be replaced with a wavelength multiplexer/demultiplexer such that each wavelength channel is routed to a different single or subset of ONUs. The resultant wavelength-routing multi-stage WDM PON offers an extended optical range of up to 100 km, giving rise to so-called long-reach WDM PONs. Note that the described next-generation PON technologies are considered the most promising solutions for near- to mid-term PON evolution, though others do exist [7].

A multihop wireless mesh network (WMN) forms the wireless front-end. The WMN is based on IEEE 802.11n next-generation WLAN, which provides, beside various PHY layer enhancements, the two frame aggregation techniques Aggregate MAC Service Data Unit (A-MSDU) and Aggregate MAC Protocol Data Unit (A-MPDU) as the main MAC enhancement. The WMN may be upgraded with emerging IEEE 802.11ac VHT WLAN technologies that achieve raw data rates of up to 6900 Mb/s and provide an increased maximum A-MSDU/A-MPDU size of 11406/1048575 octets [8].

III. Analytical Framework

A. Network Model

1) Network Architecture: We consider a wavelength-routing multi-stage WDM PON with Λ bidirectional wavelength channels $\lambda,\ \lambda = 1, \ldots, \Lambda$, interconnecting one OLT and O attached ONUs. (TDM PON and WDM PON are treated in [9].) The O ONUs are divided into Λ sectors. We use λ to index the wavelength channel as well as the corresponding sector. ONUs with indices o between $\sum_{v=1}^{\lambda-1} O_v$ and $\sum_{v=1}^{\lambda} O_v$ belong to sector $\lambda,\ \lambda = 1, \ldots, \Lambda$, i.e., form the set of nodes

$$\mathcal{S}_\lambda := \left\{ o | \sum_{v=1}^{\lambda-1} O_v < o \leq \sum_{v=1}^{\lambda} O_v \right\}. \tag{1}$$

The one-way propagation delay between OLT and ONUs of sector λ is $\tau^{(\lambda)}$ (in seconds) and the data rate of the associated wavelength channel λ is denoted by $c^{(\lambda)}$ (in bit/s). Hence, each sector of the wavelength-routing multi-stage WDM PON is allowed to operate at a different data rate serving a subset of ONUs located at a different distance from the OLT (e.g., business vs. residential service areas).

All or a subset of the O ONUs are equipped with an MPP to interface with the WMN. The WMN is composed of different zones z, whereby each zone operates on a distinct frequency such that the frequencies of neighboring zones do not overlap. A subset of MPs are assumed to be equipped with multiple radios to enable them to send and receive data in more than one zone and thereby serve as relay nodes between adjacent zones. We denote each radio operating in a given relay MP in a given zone z by a unique ω. The remaining MPs as well as all MPPs, MAPs, and STAs are assumed to have only a single radio ω operating on the frequency of their corresponding zone. Adopting the notation proposed in [10], we let $\mathcal{R}_z$ denote the set of multi-radio relay MPs and $\mathcal{L}_z$ denote the set of single-radio MPs, MPPs, MAPs, and STAs in zone z, allowing $\mathcal{R}_z$ or $\mathcal{L}_z$ to be empty for any given number of zones and WMN node assignment to each zone. Note that due to this set definition each relay MP is designated by multiple ω; one ω and corresponding set R_z for each zone z in which it can send and receive. The WMN operates at a data rate r (in bit/s).

In the WMN, we assume that the bit error rate (BER) of the wireless channel is $p_b > 0$, while the BER of the PON is negligible and therefore set to zero. However, individual fiber links may fail due to fiber cuts and become unavailable for routing traffic across the PON.

2) Traffic Model and Routing: We denote $\mathcal{N}$ for the set of FiWi network nodes that act as traffic sources and destinations. Specifically, we consider $\mathcal{N}$ to contain the OLT, the O ONUs, and a given number N of STAs. In our model, MPPs, MPs, and MAPs forward in-transit traffic, without generating their own traffic. Hence, the number of traffic sources/destinations is given by $|\mathcal{N}| = 1+O+N$. Furthermore, we define the traffic matrix $\mathbf{S} = (S_{ij}),\ i, j \in \mathcal{N}$, where S_{ij} represents the number of frames per second that are generated at FiWi network node i and destined to FiWi network node j (note that $S_{ij} = 0$ for $i = j$). We allow for any arbitrary distribution F of the frame length L (in bit) and denote $\bar{L}$ and ς_L^2 for the mean and variance of the length of a frame, respectively. The traffic generation is assumed to be ergodic and stationary.

Our capacity and delay analysis flexibly accommodates any routing algorithm. For each pair of FiWi network source node i and destination node j, a particular considered routing algorithm results in a specific traffic rate (in frames/s) Γ_{ij} sent in the fiber domain and traffic rate $\tilde{\Gamma}_{ij}$ sent in the wireless domain such that $S_{ij} = \Gamma_{ij} + \tilde{\Gamma}_{ij}$. A conventional ONU o without an additional MPP cannot send in the wireless domain, i.e., $\tilde{\Gamma}_{oj} = 0$, and sends its entire generated traffic to the OLT, i.e., $S_{oj} = \Gamma_{oj}$. On the other hand, an ONU o equipped with an MPP can send in the wireless domain, i.e., $\tilde{\Gamma}_{oj} \geq 0$. Note that we allow for multipath routing in both the fiber and wireless domains, whereby traffic coming from or going to the OLT may be sent across a single or multiple ONUs and their collocated MPPs.

B. Fiber Backhaul Network

1) Capacity Analysis: For the wavelength-routing multi-stage WDM PON, we define the normalized downstream traffic rate (intensity) in sector $\lambda, \lambda = 1, \ldots, \Lambda$, as

$$\rho^{d,\lambda} := \frac{\bar{L}}{c^{(\lambda)}} \left(\sum_{o \in \mathcal{S}_\lambda} \Gamma_{0o} + \sum_{q=1}^{O} \sum_{o \in \mathcal{S}_\lambda} \Gamma_{qo} \right), \tag{2}$$

where the first term represents the traffic generated by the OLT for sector λ and the second term accounts for the traffic from all ONUs sent to sector λ via the OLT. We define the upstream traffic rate (in frames/s) of ONU o as $R_o^u := \Gamma_{o0} + \sum_{q=1}^{O} \Gamma_{oq}$, where Γ_{o0} denotes traffic destined to the OLT and the second term represents the traffic sent to other ONUs via the OLT. The normalized upstream traffic rate (intensity) of sector λ is

$$\rho^{u,\lambda} := \frac{\bar{L}}{c^{(\lambda)}} \sum_{o \in \mathcal{S}_\lambda} R_o^u. \tag{3}$$

For stability, the normalized downstream and upstream traffic rates have to satisfy in each sector $\lambda,\ \lambda = 1, \ldots, \Lambda$:

$$\rho^{d,\lambda} < 1 \text{ and } \rho^{u,\lambda} < 1. \tag{4}$$

2) Delay Analysis: In the wavelength-routing multi-stage WDM PON, the OLT sends a downstream frame to an ONU in sector λ by transmitting the frame on wavelength λ, which is received by all ONUs in the sector. We model all downstream transmissions in sector λ to emanate from a single queue. For

Poisson frame traffic, the downstream queueing delay is thus modeled by an M/G/1 queue with the P-K formula [11],

$$\Phi(\rho) := \frac{\rho}{2c^{(\lambda)}(1-\rho)}\left(\frac{\varsigma_{\bar{L}}^2}{\bar{L}} + \bar{L}\right) \quad (5)$$

giving the total downstream frame delay

$$D^{d,\lambda} = \Phi\left(\rho^{d,\lambda}\right) + \frac{\bar{L}}{c^{(\lambda)}} + \tau^{(\lambda)}. \quad (6)$$

Weighing the downstream delays $D^{d,\lambda}$ in the sectors λ by the relative downstream traffic intensities $\rho^{d,\lambda}/\sum_{\lambda=1}^{\Lambda}\rho^{d,\lambda}$ in the sectors, gives the average PON downstream delay

$$D^d = \frac{1}{\sum_{\lambda=1}^{\Lambda}\rho^{d,\lambda}}\sum_{\lambda=1}^{\Lambda}\rho^{d,\lambda}\cdot D^{d,\lambda}. \quad (7)$$

For the upstream delay, we model each wavelength channel $\lambda,\ \lambda = 1,\ldots,\Lambda$, as a single upstream wavelength channel of a conventional EPON. Accordingly, from Eq. (39) in [12], we obtain for the mean upstream delay of sector λ

$$D^{u,\lambda} = 2\tau^{(\lambda)}\cdot\frac{2-\rho^{u,\lambda}}{1-\rho^{u,\lambda}} + \Phi\left(\rho^{u,\lambda}\right) + \frac{\bar{L}}{c^{(\lambda)}} \quad (8)$$

and the average PON upstream delay

$$D^u = \frac{1}{\sum_{\lambda=1}^{\Lambda}\rho^{u,\lambda}}\sum_{\lambda=1}^{\Lambda}\rho^{u,\lambda}\cdot D^{u,\lambda}. \quad (9)$$

The accuracy of the delay analysis can be improved by taking into account that traffic coming from an ONU o in sector v and destined to ONU q in sector λ is queued at the intermediate OLT before being sent downstream to ONU q, i.e., the OLT acts like an insertion buffer between ONUs o and q, see [9] for details.

C. Wireless Front-End Network

1) Frame Traffic Modeling: As defined in Section III-A1, we denote the radio operating in a given STA or ONU equipped with an MPP by a unique ω. Moreover, we denote each radio operating in a given relay MP in zone z by a unique ω. For ease of exposition, we refer to "radio ω" henceforth as "node ω."

Similar to [10], we model time as being slotted and denote E_ω for the mean duration of a time slot at node ω. The mean time slot duration E_ω corresponds to the average time period required for a successful frame transmission, a collided frame transmission, or an idle waiting slot at node ω and is evaluated in Section III-C4. We let q_ω denote the probability that there is a frame waiting for transmission at node ω in a time slot.

For a STA or ONU with collocated MPP ω we denote σ_ω for the traffic load that emanates from node ω, i.e., $\sigma_\omega := \sum_{\forall i}\tilde{\Gamma}_{\omega i}$. For a relay MP we obtain for a given wireless mesh routing algorithm the frame arrival rate for each of the MP's radios $\omega \in \mathcal{R}_z$ associated with a different zone z, i.e., $\sigma_\omega := \sum_{\forall i,j}\tilde{\Gamma}_{ij}$, whereby i and j denote any pair of STA or ONU with collocated MPP that send traffic on a path via relay MP ω, as computed by the given routing algorithm for the wireless mesh front-end of the FiWi network.

For exponentially distributed inter-frame arrival times with mean $1/\sigma_\omega$ (which occur for a Poisson process with rate σ_ω), q_ω is related to the offered frame load at node ω during mean time slot duration E_ω via

$$1 - q_\omega = e^{-\sigma_\omega\cdot E_\omega}. \quad (10)$$

2) Frame Aggregate Error Probability: For a WMN using A-MSDU the probability p_e of an erroneously transmitted frame aggregate, referred to henceforth as transmission error for brevity, is given by

$$p_e = 1 - (1-p_b)^A. \quad (11)$$

where A is the size of a transmitted A-MSDU (with distribution $A(l)$, as derived in [9]).

3) Probabilities for Frame Aggregate Collision and Successful Frame Aggregate Transmission: The transmission of any transmitting node $\omega \in \mathcal{R}_z \cup \mathcal{L}_z$ in zone z cannot collide if none of the other nodes $\nu \in \mathcal{R}_z \cup \mathcal{L}_z, \nu \neq \omega$ transmits, i.e., we obtain the collision probability $p_{c,\omega}$ as

$$1 - p_{c,\omega} = \prod_{\substack{\nu\in\mathcal{R}_z\cup\mathcal{L}_z\\ \nu\neq\omega}}(1-\tau_\nu), \quad (12)$$

where τ_ν denotes the transmission probability of WMN node ν. Note that if the considered node is a relay MP, Eq. (12) holds for each associated zone z (and corresponding radio ω). We define the probability of either a collision or transmission error p_ω, in brief collision/transmission error probability, as

$$1 - p_\omega = (1-p_e)\cdot(1-p_{c,\omega}). \quad (13)$$

As derived in [10], for any node $\omega \in \mathcal{R}_z \cup \mathcal{L}_z$

$$\tau_\omega = \frac{1}{\eta}\left(\frac{q_\omega^2\cdot W_0}{(1-q_\omega)(1-p_\omega)[1-(1-q_\omega)^{W_0}]} - \frac{q_\omega^2(1-p_\omega)}{1-q_\omega}\right), \quad (14)$$

where W_0 is node ω's minimum contention window and η denotes a normalization constant that accounts for the maximum backoff window $W_0 2^H$ as derived in [10, Eq. (5)].

The probability that there is at least one transmission taking place in zone z in a given time slot is given by

$$P_{tr,z} = 1 - \prod_{\omega\in\mathcal{R}_z\cup\mathcal{L}_z}(1-\tau_\omega). \quad (15)$$

A successful frame aggregate transmission occurs if exactly one node ω transmits (and all other nodes $\nu \neq \omega$ are silent), given that there is a transmission, i.e.,

$$P_{s,z} = \frac{1}{P_{tr,z}}\left(\sum_{\omega\in\mathcal{R}_z\cup\mathcal{L}_z}\tau_\omega\cdot\prod_{\substack{\nu\in\mathcal{R}_z\cup\mathcal{L}_z\\ \nu\neq\omega}}(1-\tau_\nu)\right). \quad (16)$$

4) Duration of Single Frame Aggregate Transmission Attempt: We denote ϵ for the duration of an empty time slot without any data transmission on the wireless channel in zone z, which occurs with probability $1 - P_{tr,z}$. With probability $P_{tr,z}$ there is a transmission in a given time slot in zone z, which is successful with probability $P_{s,z}$ and unsuccessful (resulting in a collision) with the complementary probability $1 - P_{s,z}$.

We denote $T_{s,z}$ for the mean duration of a successful frame aggregate transmission and $T_{c,z}$ is the mean duration of a frame aggregate transmission with collision in zone z. Note that $T_{s,z}$ and $T_{c,z}$ depend on the frame aggregation technique (A-MSDU or A-MPDU) and on the access mechanism (basic access or RTS/CTS access). Due to space constraints we focus here on A-MSDU with RTS/CTS access and refer to [9] for A-MPDU and basic access. For the RTS/CTS access mechanism, we define $\tau_s = \text{DIFS} + \text{RTS}/r + \text{SIFS} + \delta + \text{CTS}/r + \text{SIFS} + \delta + \text{PHY Header} + \text{SIFS} + \delta + \text{ACK}/r + \delta$. (Note that in IEEE 802.11n the parameters ACK, RTS, and CTS as well as the MAC Header and FCS below are given in bytes, while the other parameters are given in μs.) For a successful frame aggregate transmission and a collision, respectively, we have

$$T_{s,z} = \tau_s + (\text{MAC Header } + E[\text{A-MSDU}] + \text{FCS})/r \quad (17)$$

$$T_{c,z} = \text{RTS}/r + \text{DIFS} + \delta. \quad (18)$$

Thus, we obtain the expected time slot duration E_ω at node ω in zone z (corresponding to [13, Eq. (13)]) as

$$E_\omega = (1 - P_{tr,z})\epsilon + P_{tr,z}\left[P_{s,z}T_{s,z} + (1 - P_{s,z})T_{c,z}\right]. \quad (19)$$

Equations (10), (13), (14), and (19) can be solved numerically for the unknown variables q_ω, p_ω, τ_ω, and E_ω for each given set of values for the known parameters. With the obtained solutions we evaluate the mean delay at node ω as analyzed in the following Sections III-C5 and III-C6.

5) Service Time for Frame Aggregate: We proceed to evaluate the expected service (transmission) time for a frame aggregate, which may require several transmission attempts, at a given node ω.

For the RTS/CTS access mechanism, collisions can occur only for the RTS or CTS frames (which are short and have negligible probability of transmission errors), whereas transmission errors may occur for the frame aggregates. Collisions require only retransmissions of the RTS frame, whereas transmission errors require retransmissions of the entire frame aggregate. More specifically, only one frame transmission ($k = 1$) is required if no transmission error occurs; this event has probability $1 - p_e$. This transmission without transmission error may involve $j,\ j = 0, 1, 2, \dots$ collisions of the RTS/CTS frames. On the other hand, two frame transmissions ($k = 2$) are required if there is once a transmission error; this event has probability $p_e(1 - p_e)$. This $k = 2$ scenario requires twice an RTS/CTS reservation, which each time may experience $j, j = 0, 1, 2, \dots$ collisions, as well as two full frame transmission delays $T_{s,z}$. Generally, $k,\ k = 1, 2, \dots$ frame transmissions are required if $k - 1$ times there is a frame transmission error. Each of the k frame transmission attempts requires an RTS/CTS reservation and a full frame transmission delay $T_{s,z}$. In summary,

$$\Delta_{\text{ser},\omega} = \sum_{k=1}^{\infty} p_e^{k-1}(1 - p_e)k \left[\sum_{j=0}^{\infty} p_{c,\omega}^j (1 - p_{c,\omega}) \left(\sum_{b=1}^{j} \frac{2^{\min(b,H)}W_0 - 1}{2}\epsilon + jT_{c,z}\right) + T_{s,z}\right]. \quad (20)$$

6) Delay at WMN Node: We first evaluate the overall service time Δ_ω from the time instant when a frame aggregate arrives at the head of the queue at node ω to the completion of its successful transmission. Subsequently, with Δ_ω characterizing the overall service time at node ω, we evaluate the queueing delay D_ω^{wi}.

The overall service time Δ_ω is given by the service time $\Delta_{ser,\omega}$ required for transmitting a frame aggregate and the sensing delay $\Delta_{sen,\omega}$ required for the reception of frame aggregates by node ω from other nodes, i.e.,

$$\Delta_\omega = \Delta_{\text{ser},\omega} + \Delta_{\text{sen},\omega}. \quad (21)$$

As a first modeling step for the sensing delay at a node v, we consider the service times Δ_{ser,v_1} at nodes $v_1 \neq \nu$ and scale these linearly with the corresponding traffic intensities $\sigma_{v_1}/(1/\Delta_{ser,v_1})$ to obtain the sensing delay component

$$D_{sen,\nu} = \sum_{\forall_{v_1 \neq \nu \ \text{in} z}} \frac{\sigma_{v_1}}{1/\Delta_{ser,v_1}} \Delta_{ser,v_1}. \quad (22)$$

As a second modeling step, we consider the service times plus sensing delay components scaled by the respective traffic intensities to obtain the sensing delay

$$\Delta_{\text{sen},\omega} = \sum_{\forall_{\nu \neq \omega \text{in} z}} \frac{\sigma_\nu}{1/(\Delta_{\text{ser},\nu} + D_{\text{sen},\nu})}(\Delta_{\text{ser},\nu} + D_{\text{sen},\nu}), \quad (23)$$

employed in the evaluation of the overall service delay (21).

We approximate the queue at node ω by an M/M/1 queue with mean arrival rate σ_ω and mean service time Δ_ω. This queue is stable if

$$\sigma_\omega \cdot \Delta_\omega < 1. \quad (24)$$

The total delay (for queueing plus service) at node ω is then

$$D_\omega^{\text{wi}} = \frac{1}{\frac{1}{\Delta_\omega} - \sigma_\omega}. \quad (25)$$

If node ω is an ONU with a collocated MPP the accuracy of the queueing delay calculation is improved by subtracting a correction term as detailed in [9].

7) Delay on WMN Path: We obtain the wireless front-end delay by averaging the sums of the nodal delays of all possible paths for all source, destination node pairs i, j:

$$D^{\text{wi}} = \sum_{i,j} \frac{\tilde{\Gamma}_{ij}}{\sum_{i,j}\tilde{\Gamma}_{ij}} \left(\sum_{\substack{\forall\omega \text{ on path} \\ \text{from } i \text{ to } j}} D_\omega^{\text{wi}}\right). \quad (26)$$

D. *FiWi Network Stability and Delay*

The entire FiWi access network is stable if and only if all of its optical and wireless subnetworks are stable. For an optical backhaul consisting of a wavelength-routing multi-stage WDM PON the stability conditions in Eq. (4) must be satisfied. The wireless mesh front-end is stable if the stability condition in Eq. (24) is satisfied for each WMN node. The mean end-to-end delay of the entire bimodal FiWi access network is

$$D = D^d + D^u + D^{\mathrm{wi}}. \tag{27}$$

IV. RESULTS

We set the parameters of the FiWi mesh front-end to the default values specified in IEEE 802.11n. First, we verify the accuracy of our analysis by means of simulation[1]. The considered fiber backhaul consists of a TDM PON, wavelength-broadcasting WDM PON or wavelength-routing WDM PON (WR PON) with $\Lambda = 2$, $c = c^{(\lambda)} = 1$ Gb/s, and 4 ONU/MPPs at 20 km from the OLT. The WMN is composed of the aforementioned 4 MPPs plus 4 MPs and 16 STAs uniformly distributed over 11 wireless zones. WMN nodes apply the RTS/CTS access mechanism and the WMN is assumed to operate at $r = 300$ Mb/s with a BER of $p_b = 10^{-6}$. For now, we focus on 802.11n using A-MSDU and fixed-size frames of 1500 bytes. Fig. 2 depicts the throughput-delay performance of a stand-alone WMN front-end, stand-alone TDM PON, and a variety of integrated FiWi network architectures under uniform and nonuniform traffic scenarios and the assumption of minimum hop routing. Under uniform traffic conditions, STAs and ONUs are assumed to send unicast traffic randomly uniformly distributed among themselves; whereas under nonuniform traffic conditions, 2 adjacent ONUs and their associated STAs generate 30% more traffic than the remaining ONUs and STAs. We note that the analysis and verifying simulation results match very well for a wide range of different FiWi network architectures and traffic scenarios.

Next, we exploit the flexibility of our analytical framework and study the impact of different routing algorithms on the throughput-delay performance of next-generation FiWi access networks. For illustration, we consider the following three routing algorithms: (i) *minimum (wireless or optical) hop routing*, (ii) *minimum delay routing* similar to DARA [3], and (iii) our proposed *optimized FiWi routing algorithm (OFRA)*, whose objective function

$$min_p \left(\sum_{\forall n \in p} (\rho_n) + max_{\forall n \in p}(\rho_n) \right) \tag{28}$$

aims at finding the path p with the minimum traffic intensity ρ at intermediate optical and wireless nodes n. To allow for a larger number of possible paths, we double the above FiWi network configuration and focus on a wavelength-routing WDM PON ($\Lambda = 2$) with 8 ONU/MPPs, 8 MPs, and 32

[1]Our simulator is based on OMNeT++ and uses the communication networks package *inetmanet* with extensions for frame aggregation, wireless multihop routing, TDM/WDM PONs, and integrated WMN/PON routing.

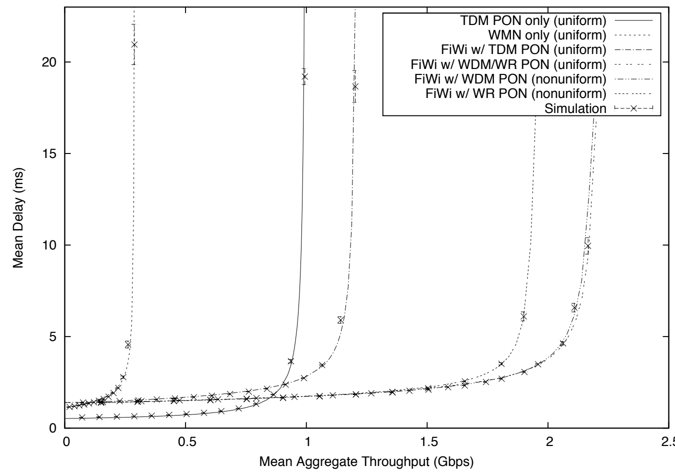

Fig. 2. Mean delay vs. mean aggregate throughput performance of different FiWi network architectures for uniform and nonuniform traffic (simulation results are shown with 95% confidence intervals).

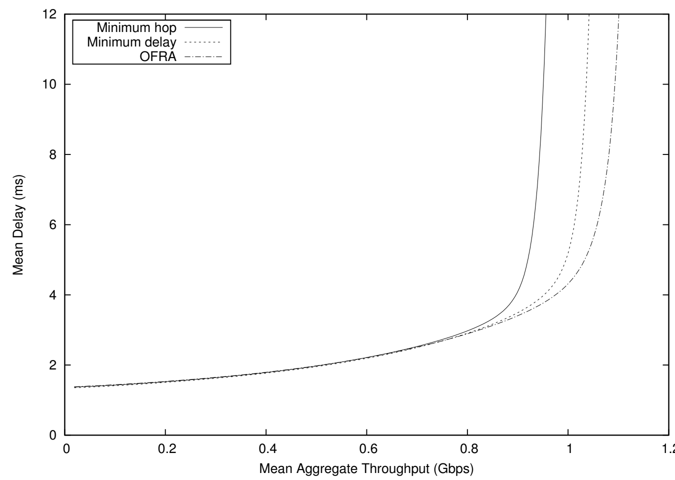

Fig. 3. Mean delay vs. mean aggregate throughput performance of different FiWi routing algorithms for a conventional wavelength-routing WDM PON of 20 km range and $B = 1$.

STAs in 22 wireless zones for the remainder of the paper. Furthermore, we allow the OLT and ONUs to generate $B \geq 1$ times more traffic than a STA, given that an ONU may serve multiple subscribers (see also Fig. 1).

For a wavelength-routing WDM PON with a conventional optical fiber range of 20 km, Fig. 3 shows that OFRA yields the best throughput-delay performance for $B = 1$, i.e., every optical and wireless FiWi node generates the same amount of traffic. Note, however, that the throughput-delay performance largely depends on the given traffic loads and length of the fiber backhaul. To see this, Fig. 4 depicts the impact of an increased optical range of 100 km and an increased amount of fiber backhaul traffic among OLT and ONUs ($B = 100$). We observe that for a 20 km range WDM PON the minimum hop routing algorithm outperforms the minimum delay routing algorithm and is also superior to OFRA in terms of mean delay at small to medium traffic loads. Our measurements at the optical-wireless interfaces showed that at low to medium

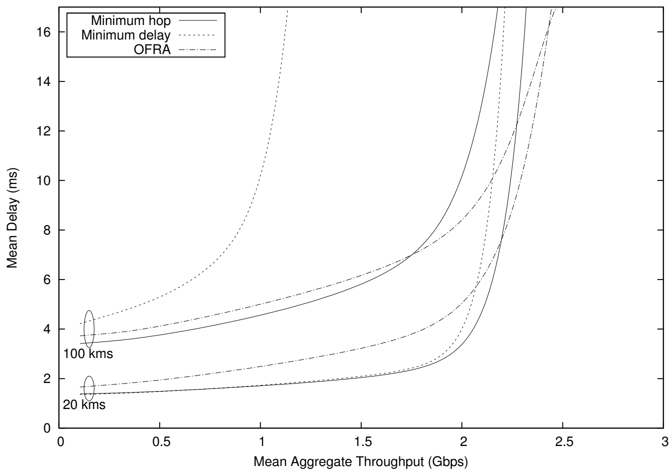

Fig. 4. Mean delay vs. mean aggregate throughput performance of different FiWi routing algorithms for (i) a conventional 20 km range and (ii) a 100 km long-reach wavelength-routing WDM PON and $B = 100$.

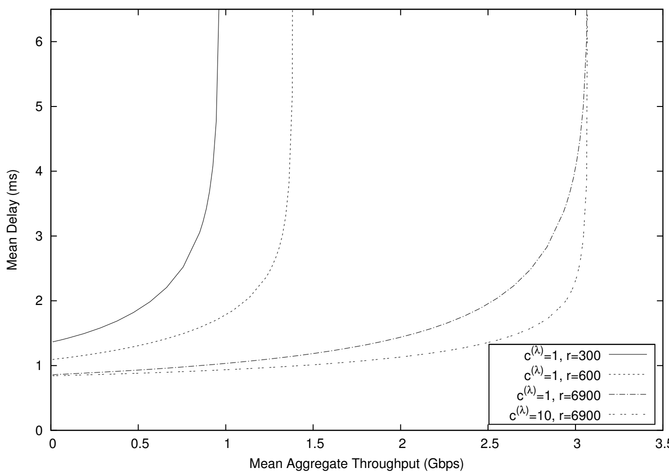

Fig. 5. Mean delay vs. mean aggregate throughput performance of next-generation FiWi access networks based on high-speed wavelength-routing WDM PON and VHT WLAN technologies using minimum hop routing with $B = 1$ ($c^{(\lambda)}$ and r are given in Gb/s and Mb/s, respectively).

traffic loads, OFRA routes significantly less traffic across the WDM PON than the minimum hop and minimum delay routing algorithms for $B = 100$, but instead uses the less loaded wireless mesh front-end. Consequently, for $B = 100$ OFRA routes most traffic across lightly loaded wireless links, even though this implies more wireless hops, resulting in an increased mean delay compared to minimum hop and minimum delay routing. At the downside, the huge bandwidth of the long-reach WDM PON is heavily underutilized while the wireless front-end gets congested, thereby resulting in a deteriorated throughput-delay performance. Fig. 4 also clearly illustrates that minimum delay routing performs poorly in terms of delay and throughput and is ill-suited for long-reach WDM PON based FiWi networks since it steers most traffic across the WMN to avoid the optical propagation delay.

Fig. 5 shows the performance gain achieved by using a wireless front-end based on VHT WLAN instead of state-of-the-art 802.11n WLAN, whose maximum data rate is limited to 600 Mb/s. For a wavelength-routing WDM PON operating at a wavelength channel data rate of 1 Gb/s, we observe from Fig. 5 that VHT WLAN roughly triples the maximum mean aggregate throughput and clearly outperforms 600 Mb/s 802.11n WLAN in terms of both throughput and delay. Furthermore, the figure shows that replacing the 1 Gb/s wavelength-routing WDM PON with its high-speed 10 Gb/s counterpart (both with an optical range of 20 km) does not yield a higher maximum aggregate throughput, but it does help lower the mean delay especially at medium traffic loads before wireless links at the optical-wireless interfaces get increasingly congested at higher traffic loads.

V. Conclusions

We developed the first analytical framework for the capacity and delay evaluation of a wide range of next-generation FiWi network architectures and emerging high-speed optical and wireless technologies. It flexibly accommodates any routing algorithm and allows for arbitrary frame size distributions, optical/wireless propagation delays, and data rates, and also accounts for wireless channel bit errors and fiber failures. Our framework and results quantify the strong dependence of the throughput-delay performance of various routing algorithms on the traffic load and length of fiber backhaul infrastructures and provide important design guidelines for novel FiWi network routing algorithms that leverage on the different unique characteristics of disparate optical and wireless technologies.

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