Grouping by Cycle Length (GCL) for long-range FiWi networks

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Abstract
The integration of wireless access networks with optical access networks in the so-called fiber-wireless (FiWi) networks has recently emerged as a promising strategy for providing flexible network services at relatively high transmission rates. FiWi network research to date has mainly focused on optical access networks with the normal reach (around 20 km) of passive optical networks (PONs). We make two main contributions to the study of FiWi networking with a long-range PON with a propagation distance on the order of 100 km in this paper. First, through extensive simulations, we investigate the packet delays when relatively low-rate traffic that has traversed a wireless network is mixed with conventional high-rate PON-only traffic. We consider a range of different FiWi network architectures with different dynamic bandwidth allocation (DBA) mechanisms. Second, we closely examine the grouping of the optical network units (ONUs) in the double-phase polling (DPP) DBA mechanism in long-range FiWi networks. We introduce a novel grouping by cycle length (GCL) strategy that achieves favorable packet delay performance.

1. Introduction
Fiber-Wireless (FiWi) access networks combine wireless access networks with optical access networks. Wireless access networks can flexibly support distributed wireless users, while optical access networks provide high transmission bit rates through the optical fiber [2–5]. FiWi networks have begun to attract extensive research interest as they represent a promising approach for solving the problem of high-speed Internet access “over the last mile”. In particular, FiWi networks with a Passive Optical Network (PON) as the optical network have been intensely studied in the past few years as a PON can provide high transmission bit rates to support demanding applications, e.g., multimedia applications, at relatively low maintenance cost [6–10]. A normal-range PON covers a distance of about 20 km between the central Optical Line Terminal (OLT) and the distributed Optical Network Units (ONUs), where users connect to the PON. FiWi network research based on PONs has mainly focused on normal-range PONs to date, as reviewed in detail in Section 2.

In contrast, in this paper, we investigate FiWi networks based on long-reach (LR) PONs covering on the order of 100 km. LR PONs can amortize costs over a larger user population in the larger covered area, but pose unique challenges due to the long propagation delays [11–14]. Our first main contribution is an extensive simulation study of the mixing of two traffic types in the LR FiWi network: wireless traffic that is generated at wireless stations and traverses the wireless network before transmission over the PON; this wireless traffic is true FiWi traffic as it traverses both the wireless and fiber network parts. Due to the transmission over the relatively lower-rate wireless
network (compared to the fiber network), the wireless (FiWi) traffic has typically a relatively lower bit rate than conventional traffic that is transmitted only over the PON. This conventional PON-only traffic is our second considered traffic type. In our extensive simulations we examine the packet delays of wireless (FiWi) traffic and PON traffic for a wide range of FiWi network architectures and dynamic bandwidth allocation (DBA) mechanisms.

Our simulations revealed that the double-phase polling (DPP) DBA mechanism [15] achieves low packet delays for both traffic types. DPP relies on an assignment of the ONUs to two groups that take turns transmitting on the shared upstream wavelength channel and strive to mask each others’ idle times due to the long round-trip propagation delay of the PON polling control messages. The effects of this group assignment have to the best of our knowledge not yet been examined in detail. We compare several elementary grouping strategies and introduce a novel grouping by cycle length (GCL) strategy. The GCL strategy strives to balance the lengths of the polling cycles of the two ONU groups so that they can effectively mask each others’ idle times. We find that the GCL strategy, which is based on the OLT-to-ONU distances and the ONU load levels, significantly outperforms elementary grouping strategies that consider only OLT-to-ONU distances or ONU load levels.

The remainder of the paper is organized as follows: in Section 2, we discuss the related work. In Section 3, we present our evaluation model of the FiWi network, including the architecture and DBA mechanisms. In Section 4, we introduce the elementary ONU grouping strategies based on either OLT-to-ONU propagation distances or ONU traffic levels as well as the GCL strategy. In Section 5, we give the details of the set-up of the simulation evaluations. We present evaluation results for the mixing of wireless and PON traffic in Section 6 and results for the ONU grouping strategies in Section 7. Section 8 concludes the article and outlines directions for future research.

2. Related work

2.1. FiWi networks

The general challenges and benefits of FiWi networking have been discussed in [16–19]. Architectures for FiWi networks have been examined in [4,5]. FiWi networks appear particularly promising for the backhaul of wireless network traffic [20–22], and integrated control structures for low-delay transmission of mobile wireless traffic over PONs have been examined in [23,24]. A wide range of specific issues have been examined for FiWi networks, such as the ONU placement [25–29], energy efficient operation [30,31], quality of service provisioning [32,33], as well as survivability [34,35].

The vast majority of the FiWi studies to date has considered normal-range FiWi networks with one-way PON propagation distances on the order of 20 km. To the best of our knowledge, only few studies have examined FiWi networks with long-range PONs covering on the order of 100 km. Specifically, the few prior studies on LR FiWi networks have mainly focused on energy-efficiency and fault tolerance [36–39]. Complementary to these prior studies, we focus on the packet delay performance of dynamic bandwidth allocation (DBA) mechanisms in LR FiWi networks in this paper.

2.2. Dynamic Bandwidth Allocation (DBA) mechanisms

DBA mechanisms have been extensively studied for both normal-range and long-range PONs [40–45]. One branch of the DBA research has focused on PONs with multiple wavelength channels in each direction [46–55] or larger network structures encompassing several PONs [56]. In contrast, we focus on a FiWi network with a single PON with a single wavelength channel in the upstream (ONUs to OLT) direction.

A wide variety of DBA enhancements have been developed in recent years to cope with the idle times due to the propagation delay of the polling control messages. The DBA enhancements typically stagger multiple polling processes over a basic polling cycle, so that the payload upstream transmissions of some polling process(es) mask the idle times of the other polling process(es) [57–60]. Also, recent enhancements have sought to efficiently and fairly utilize the transmission resources within a given polling process [61–63] and to optimize the timing of the polling processes [64–67].

In the present study, we focus on the Double-Phase Polling (DPP) DBA mechanism [15,68] as an example of an enhanced DBA mechanism with staggered multiple polling processes. DPP is simple and robust: the ONUs in a given PON are assigned to two distinct (non-overlapping) groups, and each group is then served with the elementary offline polling scheduling framework [68,69]. DPP has also been found to give favorable performance [68,58,64,70]. DPP has served as the basis for a number of recent DBA refinements, namely a predictive bandwidth DBA scheme with multiple QoS classes [71,72] as well as a recent FiWi study with a long-term evolution LTE wireless component [73]. An approach similar to DPP has recently been proposed in [74] to use offline polling for low load and online polling for high load. Complementary to [74], our GCL approach exploits the load level to adapt the ONU grouping in DPP. To the best of our knowledge, the grouping of ONUs has not been previously examined in detail, neither in the general PON context, nor in the FiWi network context.

3. Long-reach FiWi network model

This section gives an overview of the general features of the Fiber-Wireless (FiWi) network model considered in this study. We first present the general architectural structure of FiWi networks in Section 3.1. Then, we give an overview of the examined Dynamic Bandwidth Allocation (DBA) mechanisms in the optical part of the FiWi network in Section 3.2. The novel grouping strategies for ONUs in the double-phase polling (DPP) DBA mechanisms are introduced in Section 4.
3.1. Architecture

As illustrated in Fig. 1, we consider a FiWi network architecture with $O$, $O > 1$, distributed Optical Network Units (ONUs). The ONUs are connected with a single shared upstream wavelength channel to the central Optical Line Terminal (OLT). We denote $\tau_o$, $o = 1, \ldots, O$, for the one-way propagation delay [in seconds] from ONU $o$ to the OLT, which we assume to be equal to the OLT-to-ONU $o$ one-way propagation delay. Some of the ONUs are connected with wires to wireless gateway routers. The wireless gateway routers communicate wirelessly with distributed wireless stations. The other ONUs (without attached wireless gateway routers) support only conventional high-speed wired Internet access to homes and businesses.

3.2. Dynamic Bandwidth Allocation (DBA) mechanisms

The ONU upstream transmissions on the shared upstream wavelength channel are coordinated by the standard (IEEE 802.3ah) polling-based Multi-Point Control Protocol (MPCP). In the MPCP protocol, REPORT messages that are included in the ONU upstream transmissions inform the OLT about the ONU queue occupancies. Based on the REPORT messages, the OLT dynamically allocates bandwidth in the form of upstream transmission windows (grants) to the ONUs. The OLT informs each ONU through a GRANT message about its allocated upstream transmission window; we denote $G_o$ for the grant duration [in seconds] allocated to ONU $o$ in a given polling cycle. We denote $t_G$ for the transmission time [in seconds] of a GRANT message on the downstream wavelength channel. Successive upstream transmissions from different ONUs are separated by a guard time $t_g$ [in seconds] on the upstream wavelength channel.

As summarized in Table 1, the design space of DBA mechanisms for the PON part [68] of the FiWi network consists of the dimensions:

- **Grant scheduling framework**: Decides when and for which ONUs the grants are sized and scheduled by the OLT.
- **Grant sizing**: Determines the amount of bandwidth (duration of upstream transmission window) allocated to an ONU.
- **Grant scheduling policy**: Determines the ordering (sequence) of the ONU upstream transmission windows on the upstream wavelength channel.

The offline scheduling framework awaits REPORTs from all $O$ ONUs before sizing and scheduling grants to all $O$ ONUs [69]. In contrast, the online scheduling framework sizes and schedules a grant for an ONU $o$, $o = 1, \ldots, O$, immediately after receiving a REPORT from ONU $o$. The double-phase polling (DPP) scheduling framework partitions the set of $O$ ONUs into

### Table 1

<table>
<thead>
<tr>
<th>Grant scheduling framework</th>
<th>Grant sizing</th>
<th>Grant scheduling policy</th>
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<tbody>
<tr>
<td>Offline</td>
<td>Gated</td>
<td>SPD</td>
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<tr>
<td>Online</td>
<td>Limited</td>
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<tr>
<td>Double-Phase Polling (DPP)</td>
<td>Excess, share</td>
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*Limited Excess, share*
two groups; each group follows then the offline scheduling framework.

The so-called "gated" grant sizing allocates the full grant size requested by the ONU. In contrast, "limited" grant sizing allocates the requested grant size up to a prescribed maximum [69]. Excess bandwidth grant sizing refines the limited grant sizing by allocating the "slack" between the maximum grant size and an ONU's actual request to those ONUs requesting more than the maximum. For DPP, the excess bandwidth can be shared among successive groups [68].

We consider throughout the shortest propagation delay (SPD) [75] grant scheduling policy. For brevity, we use the terminology (on., gat.) for Online, Gated; (on., lim.) for Online, Limited; (on., exc.) for Online, Excess; (off., lim.) for Offline, Limited; (off., exc.) for Offline, Excess; (dpp., lim.) for DPP, Limited; and (dpp., exc.) for DPP, Excess with sharing.

4. ONU grouping strategies

4.1. Motivation

A key principle of efficient polling-based medium access in PONs with long propagation delays is the masking of idle times arising from control message propagation. In particular, the delay between the ONU transmission of a REPORT message and the arrival of the corresponding grant message leads to idle times on the upstream channel, unless transmissions by other ONUs mask the idle time. Therefore, the principal strategy of double-phase polling (DPP) is that the upstream transmission of one ONU group mask the idle times between transmissions of the other ONU group. We consider four elementary grouping strategies based on ONU traffic load and propagation distance as well as a grouping strategy based on the polling cycle durations of the ONU groups.

4.2. ONU traffic load estimation

The propagation delays \( \tau_{o}, \ o = 1,\ldots, O \), are constants available from the registration of the ONUs with the OLT. (Inaccuracies in the propagation delays can be compensated with the approaches in [76].) The ONU traffic loads are typically variable quantities. By combining historic traffic patterns with traffic measurements and estimations following the strategies in [77–80], the ONU traffic loads can be periodically updated with strategies similar to [81,82]. We denote \( \hat{R}_{o}, \ o = 1,\ldots, O \), for the ONU traffic load long-run estimates expressed in terms of the requested bandwidth per ONU REPORT. These long-run ONU traffic loads vary typically slowly, e.g., with a diurnal pattern.

In DPP, the polling cycles of the two ONU groups are interleaved. Thus, in order to update the ONU grouping, e.g., according to new ONU load estimates, the operation of the PON needs to be briefly interrupted. After the new ONU groups have been formed, the interleaved DPP polling cycles are launched anew. The long-run ONU traffic load estimates vary typically on the time scale of hours while the interruption due to regrouping is on the time scale of a polling cycle (usually a few milliseconds in duration). Thus, the service disruption due to the regrouping should typically be minimal.

We denote \( \hat{G}_{o}, \ o = 1,\ldots, O \), for the corresponding estimates of the durations of the ONU upstream transmission windows that are obtained according to the employed grant sizing policy from the traffic load estimates \( \hat{R}_{o}, \ o = 1,\ldots, O \).

4.3. Distance Grouping (DG)

Distance Grouping (DG) orders the \( O \) ONUs in increasing one-way propagation distance from the OLT. In particular, with \( (o), \ o = 1,\ldots, O \), denoting the ordered position, e.g., (1) denotes the first ONU in the ordering, the ordered ONUs satisfy \( \tau_{(1)} \leq \tau_{(2)} \leq \cdots \leq \tau_{(O)} \). We initially assume that the number of ONUs \( O \) is an even number; which is common since the splitting ratio of optical splitters is typically a power of two. DG assigns the first \( \frac{O}{2} \) of the ONUs, i.e., the ONUs (1), (2),\ldots,(\( O/2 \)) with relatively short propagation delays, to group 1, while the second \( \frac{O}{2} \), i.e., the ONUs (\( O/2+1 \)),\ldots,(\( O \)) with the relatively long propagation delays, is assigned to group 2. If the number of ONUs \( O \) is an odd number, then one (arbitrarily selected) group is assigned one less ONU than the other group; the impact of this uneven assignment is minimal for typical ONU numbers.

4.4. Distance Balancing (DB)

Distance Balancing (DB) is also based on the ordering of the ONUs in increasing propagation delays. DB assigns the ONUs to the two groups in a round-robin fashion, i.e., ONU (1) to group 1, ONU (2) to group 2, ONU (3) to group 1, and so on.

4.5. Load Grouping (LG)

Load Grouping is analogous to DG, but is based on the estimated ONU loads \( \hat{R}_{o} \). The ONUs are sorted in increasing load, i.e., the ordered ONUs satisfy \( \hat{R}_{(1)} \leq \hat{R}_{(2)} \leq \cdots \leq \hat{R}_{(O)} \). Then, LG assigns the relatively lightly loaded half, ONUs (1), (2),\ldots,(\( O/2 \)), to group 1, and the relatively heavier loaded half, ONUs (\( O/2+1 \)),\ldots,(\( O \)), to group 2.

4.6. Load Balancing (LB)

Load Balancing (LB) is analogous to DB and assigns ONUs, which are ordered in terms of increasing load, in a round-robin fashion to the two groups.

4.7. Grouping by Cycle Length (GCL)

GCL strives to balance the durations of the offline polling cycles of the two ONU groups. As a basis for GCL, we first analyze the duration of the offline polling cycle of a given ONU group. Suppose that there are \( \gamma, \gamma > 1 \), ONUs in the group that have been sorted in increasing order of the one-way propagation delay, i.e., \( \tau_{(1)} \leq \tau_{(2)} \leq \cdots \leq \tau_{(\gamma)} \).

We initially consider only the first ONU, i.e., ONU (1). The cycle duration is commonly defined as the time period
from the instant when the OLT begins to transmit the GATE message to the instant when the end of the corresponding upstream transmission arrives at the OLT. The components of the cycle duration $\Gamma_1$ for one ONU are: the transmission time $t_G$ of the GATE message, the round-trip propagation delay $2\tau_G$ for the GATE message to propagate from the OLT to the ONU and for the upstream transmission to propagate from ONU to OLT, as well as the upstream transmission time (transmission window duration) $G_{(1)}$ (which includes the REPORT message). Thus,

$$\Gamma_1 = t_G + 2\tau_G + G_{(1)}. \quad (1)$$

We proceed to consider the first two ONUs, i.e., ONUs (1) and (2). There are two cases: first, the propagation delay $\tau_2$ is sufficiently short and the transmission window $G_{(1)}$ sufficiently long such that the upstream transmission of ONU (2) can immediately (with a guard distance) follow after the upstream transmission of ONU (1); resulting in the overall cycle duration $t_G + 2\tau_G + G_{(1)} + t_G + G_{(2)}$. Second, the propagation delay $\tau_2$ is sufficiently long and the transmission window $G_{(1)}$ is sufficiently short such that the upstream transmission of ONU (1) is finished before the upstream transmission of ONU (2) can start; thus, ONU (2) governs the overall cycle duration with $2t_G + 2\tau_2 + G_{(2)}$ (the second $t_G$ accounts for the GATE message transmission to ONU (1), which precedes the ONU (2) GATE message according to the SPD scheduling). Thus, the overall cycle duration for first two ONUs is analogous to [75, Eqn. (3)]:

$$\Gamma_{(1,2)} = \max\{t_G + 2\tau_G + G_{(1)} + t_G + G_{(2)}, 2t_G + 2\tau_2 + G_{(2)}\} \quad (2)$$

$$\Gamma_{(1,2)} = \max\{\Gamma_1 + t_2 + G_{(2)}, 2t_G + 2\tau_2 + G_{(2)}\} \quad (3)$$

$$\Gamma_{(1,2)} = \max\{\Gamma_1 + t_2, 2t_G + 2\tau_2 + G_{(2)}\}. \quad (4)$$

Analogous to the reasoning leading to Eq. (4), we complete the induction step to the first three ONUs:

$$\Gamma_{(1,2,3)} = \max\{\Gamma_{(1,2)} + t_3, 3t_G + 2\tau_3 + G_{(3)}\}. \quad (5)$$

We obtain in general for $\gamma$ ONUs:

$$\Gamma_{(1,2,\ldots,\gamma)} = \max\{\Gamma_{(1,2,\ldots,\gamma-1)} + t_\gamma, \gamma t_G + 2\tau_\gamma + G_{(\gamma)}\}. \quad (6)$$

Based on the cycle duration in Eq. (6), GCL assigns the ONUs as follows to the two groups: ONU (1) is assigned to group 1 and ONU (2) is assigned to group 2. We compare the resulting cycle durations evaluated with Eq. (1). Then, we add ONU (3) to the group with the shorter cycle duration and update the cycle duration with Eq. (6). Then, we repeat comparing the cycle durations and adding the next ONU to the group with the shorter cycle duration until all O ONUs have been placed in a group.

5. Setup of simulation evaluation

We conducted our simulation evaluations with the OMNet++ (http://www.omnetpp.org) simulator framework. Within OMNet++, we employed the INETMANET-2.2 modules (https://github.com/inetmanet/inetmanet) and integrated a self-built optical network simulator with the INETMANET modules.

5.1. FiWi network architecture

(1) Overall FiWi architecture: We consider two FiWi architectures: a dedicated ONU architecture illustrated in Fig. 2 and a mixed ONU architecture illustrated in Fig. 3.

(2) Optical network: The one-way distances from the OLT to the ONUs are uniformly randomly distributed: for the normal-reach PON in the range from 5 km to 20 km

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Fig. 2. Dedicated ONU FiWi network architecture set-up: four ONUs (ONUs 1–4) are dedicated to wireless (FiWi) traffic while four ONUs (ONUs 5–8) are dedicated to wired (PON) traffic. The figure also illustrates CluLoR routing: the wireless network is organized into zones, each operating on a different frequency. Wireless stations route traffic through a cluster head towards the gateway for transmission over the PON.
and for the long-reach (LR) PON in the ranges from 90 km to 100 km or 80 km to 120 km. Each ONU, including the ONUs in the mixed architecture serving FiWi and PON traffic, has one queue serving the traffic in first-come-first-served order.

(3) Wireless network: The wireless network supported by the FiWi network has a total of 64 wireless stations (regular wireless source and destination nodes) and four gateway routers (one for each ONU supporting the FiWi network). The 64 wireless stations are uniformly distributed in an area of $1000 \times 1600$ m. More specifically, the wireless stations are arranged into 16 zones, each containing four wireless stations, whereby any two wireless stations are 100 m apart. Each zone operates on a different radio frequency channel compared to its neighboring zones. We employ the 11 radio channels of the IEEE802.11g standard and reuse some of the radio channels in distant zones in order to minimize interference. Each gateway router operates on four radio channels to serve four zones. A 1 Gbps cable connects a given gateway router to the corresponding ONU. In addition, there are 22 relay routers, each operating on two radio channels to serve two adjacent zones. The two wireless stations closest to the gateway router in a zone are designated to serve as cluster heads in the wireless routing protocol, see Section 5.3(2).

We employ a path loss wireless channel model with an alpha value of 2 and a signal-to-noise ratio of 4 dB. Received packets that are below 4 dB are considered as noise. The radio sensitivity is set to $-85$ dBm and the transmission power of the wireless stations is 20 mW, which permits the most distant wireless station in a zone to reach the gateway router. The transmission range is around 250 m. The physical transmission rate for all wireless stations is 54 Mbps. Each wireless station has a buffer size of 1000 packets for each radio channel interface. The queues in the wireless stations follow the drop tail queueing policy.

5.2. Network traffic scenarios

(1) Packet level traffic characteristics: We consider UDP packet traffic with packet sizes based on quad mode distribution: 60% 64 byte packets, 25% 1518 byte packets, 11% 580 byte packets, and 4% 300 byte packets. These packet sizes include the payload as well as 8 bytes of UDP header, 20 bytes of IP header, and 18 bytes of MAC (Ethernet) header. The maximum transmission unit (MTU) for the wireless domain is set to 1500 bytes to avoid packet fragmentation.

Packets are generated following independent Poisson processes. All wireless stations have the same wireless packet traffic generation rate, while all wired PON traffic generators have the same PON traffic generation rate.

(2) Flow level traffic characteristics (Source-destination traffic matrix): PON traffic is generated by the PON traffic generators attached (wired) to the ONUs and is always destined upstream to the server (sink) node, which is directly attached (wired) to the OLT.

We consider three traffic matrices (scenarios) for FiWi traffic:

(a) All-server scenario: The FiWi traffic generated at all wireless stations, including cluster heads, is destined to the server attached to the OLT.

(b) CH-server; STN-P2P scenario: The FiWi traffic generated at the wireless nodes that are cluster heads is destined to the server. The FiWi traffic generated at the other (non-cluster head) wireless stations is peer-to-peer (P2P) traffic that is uniformly randomly destined to any other wireless node (including the cluster heads); whereby for each generated FiWi packet, a new random destination is drawn. We consider this two traffic matrices (scenarios) for FiWi traffic.

(c) All-P2P scenario: The FiWi traffic generated at all wireless stations (including the cluster heads) is P2P traffic destined to any other uniformly randomly drawn wireless station.
Traffic ratios: In the dedicated ONU architecture, we set the FiWi traffic:PON traffic ratio to 1:30, that is the aggregate wired (PON) packet traffic generation rate is 30 times higher than the aggregate FiWi (wireless) packet traffic generation rate in the overall FiWi network.

In the mixed ONU architecture, we prescribe FiWi traffic:PON Traffic at mixed ONUs:PON Traffic at PON-only ONUs ratios of 1:10:40 or 1:20:30. With the 1:10:40 ratio, the packet generation rate of the PON traffic generator at a given mixed ONU (that serves FiWi and PON traffic) is ten times higher than the aggregate packet generation rate of the 16 wireless stations associated with the ONU. Moreover, a traffic generator at an ONU that serves only PON traffic has a four times higher packet generation rate than the PON traffic generator at a mixed ONU.

5.3. Network protocols

(1) Optical network: In the optical network, we examine the dynamic bandwidth allocation (DBA) mechanisms outlined in Section 3.2.

(2) Wireless network: We consider clustered localized routing (CluLoR) [83] for the wireless (FiWi) traffic with two cluster heads in each zone. CluLoR routes traffic from wireless stations in a zone through the two cluster heads in the zone to the gateway router. FiWi traffic destined to the server is then forwarded to the corresponding ONU for PON upstream transmission. FiWi traffic destined to a non-adjacent zone is also forwarded from the corresponding ONU to the OLT, and then transmitted downstream on the PON to the ONU associated with the zone of the destination wireless station (and then onwards via a cluster head to the destination). FiWi traffic destined to an adjacent wireless zone is forwarded by the relay router between the two adjacent zones. The wireless network follows the IEEE802.11g MAC protocol with a retransmit limit of seven.

5.4. Delay metrics

Throughout, we evaluate the mean end-to-end packet delays, i.e., the mean time periods from the instant of packet generation to complete delivery to the destination. Specifically, we evaluate the mean PON packet delay, i.e., the mean end-to-end delay for PON packet traffic from the instant of packet generation at a PON packet generator to the instant of complete packet delivery to the server (sink). We also evaluate the mean FiWi packet traffic delay, i.e., the mean end-to-end delay for FiWi traffic from the instant of packet generation at a wireless station to complete packet delivery to the server or destination wireless station. The delay samples are collected with a batch means method from the simulation runs until the 95% confidence intervals of all delay metrics are less than 5% of the corresponding sample means. These confidence intervals are too small to be visible in the plots.

6. Results for mixing of wireless (FiWi) and PON traffic

In this section we investigate the effects of mixing traffic from the wireless stations, i.e., FiWi traffic, with conventional PON traffic. In particular, we initially focus on the dedicated ONU network architecture, see Fig. 2, in order to bring out the fundamental effects due to mixing...
FiWi and PON-only traffic from distinct ONUs. We investigate the impact of the DBA mechanisms and the PON propagation distance on the delays experienced by wireless (FiWi) traffic and PON-only traffic.

6.1. Impact of DBA mechanism

We focus initially on the All-Server traffic scenario, see Section 6.2(2), to observe the effects of all the FiWi traffic and the PON-only traffic competing on the upstream wavelength channel. We consider the CH-Server; STN-P2P traffic scenario, which includes P2P traffic components in the FiWi traffic, in Section 6.1(6).

(1) Online, Gated: We observe from Fig. 4 that the (on., gat.) DBA achieves the lowest mean delays for the PON packet traffic across the entire range of traffic loads. On the other hand, (on., gat.) DBA gives the highest delays for wireless (FiWi) packet traffic at high traffic load levels, e.g., for traffic loads above 0.5 Gbps in Fig. 4(a). The granted grant sizing allocates to each ONU an upstream transmission window corresponding to its full request. This is beneficial for the conventional high-rate PON-only packet traffic which dominates the network for the considered FiWi: PON traffic ratio of 1:30. Even as the traffic load grows very high, the (on., gat.) DBA allocates the PON-only ONUs their full requests, leading to very long cycles. The long cycles result in relatively long mean wait times for the lower-rate FiWi traffic that arrives over the wireless network and gateway router to the FiWi ONUs; i.e., the FiWi ONUs have to wait relatively long for their turn on the upstream wavelength channel and then only occupy it for a relatively short time.

The (on., gat.) DBA mechanism does not depend on a prescribed cycle length and hence has been repeated in Fig. 4(a)–(c) as a reference for the other DBA mechanisms.

(2) Offline, Limited: We observe from Fig. 4 that the (off., lim.) DBA mechanism works in favor of FiWi traffic, compared to the (on., gat.) DBA. Limiting the cycle length ensures that the relatively lightly loaded FiWi ONUs can transmit more frequently and do not have to wait until the PON traffic ONUs transmit their entire frames. However, limiting the allocations to the heavily loaded PON traffic ONUs results in growing queues, and eventually buffer overflow, for increasing traffic load. The load point where buffer overflows for PON traffic occur indicates the stability limit of the network. Average packet delays grow very high near and beyond the stability limit.

We observe a “knee point” of the FiWi traffic delay near the load level corresponding to the stability limit for the PON traffic. Once the PON traffic queues fill up and the PON traffic completely utilizes its limited share of the cycle length, no further increases in the carried upstream load are possible for PON traffic. Instead, further increases in the carried upstream traffic load are due to FiWi traffic only, which follows the fixed 1:30 FiWi:PON traffic ratio. That is, only 1/30th of a given increase in the total traffic load contributes to the actual increase of the carried upstream traffic load. This “switch” from all generated traffic contributing to the carried upstream traffic load to only 1/30th of the generated traffic load contributing to the carried upstream traffic load results in the substantially lower slope of delay increases with increasing generated traffic load, i.e., the observed “knee point”.

(3) Online, Limited: The (on., lim.) DBA follows the same performance trend as of the (off., lim) DBA, while performing slightly better than the (off., lim.) DBA. The offline scheduling framework [68,69] waits for the REPORTs from all ONUs before commencing the sizing and scheduling of the grants. The delay difference is small because only eight ONUs are considered. As the number of ONUs increases, the delay difference would also increase.

(4) Offline, Excess: For the (off., exc.) DBA, we observe from Fig. 4 that for low loads, the PON traffic delay is the same as for the (off., lim.) DBA. This is because, all ONUs have typically requests below the limit at low loads and do not require the excess feature. However, as the traffic load increases, the delay for the (off., exc.) DBA is lower than for the (off., lim.) DBA. Also, the (off., exc.) DBA reaches higher stability limits than the (on., lim.) DBA due to the re-allocation of unused portions of the grant limit to ONUs with presently large requests. Comparing Fig. 4(a) and (c), we observe that the relative increase of the stability limit is especially pronounced for short cycle length limits. Specifically, the increase is approximately 40% for Z = 1 ms in Fig. 4(a) compared to about 15% for Z = 4 ms in Fig. 4(c).

Longer cycle length limits are less restrictive, thus re-allocations of excess “slack” are relatively less effective for long cycle length limits.

For FiWi traffic, we observe that the (off., exc.) delay is higher than the (off., lim.) delay. This is due to the increase in the average cycle length as the re-allocation of unused portion of the grant limits leads to longer mean cycle lengths. The re-allocation benefits mainly the heavily loaded PON ONUs. On the other hand, the FiWi ONUs need to wait on average longer for the next grant, while typically not enlarging their grants with the re-allocation.

(5) Impact of cycle length: We observe from Fig. 4 that increasing the cycle length limit Z benefits PON traffic through increasing stability limits and lowered mean packet delays. Longer cycle length limits allow the heavily loaded PON ONUs to transmit more traffic in each cycle, thus fewer cycles and cycle overhead (e.g., guard times) are incurred to transmit a given PON traffic amount.

On the other hand, FiWi traffic benefits from short cycle length limits. Shorter cycles allow the FiWi ONUs to transmit their relatively small upstream grants more frequently, incurring shorter FiWi packet traffic delays. We also observe that the “knee points” in the FiWi delay curves move to lower traffic load levels for decreasing cycle lengths. This is because the PON traffic queues fill up at lower traffic loads, preventing the PON ONUs from transmitting more traffic (beyond their respective stability limits) already at relatively low traffic loads.

(6) DBA impact for CH-Server; STN-P2P traffic: We observe from Fig. 5 for the CH-Server; STN-P2P traffic scenario similar trends as for the All-Server traffic scenario with Z = 2 ms in Fig. 4(b). However, we observe that the FiWi packet delays tend to be higher in Fig. 5 compared to Fig. 4(b). The CH-Server; STN-P2P traffic scenario has wireless packet traffic entering the zones to reach the P2P traffic destinations. Thus, more interference and collisions are introduced in the zones, causing the wireless nodes to
resend the traffic more frequently than in the All-Server traffic scenario. The retransmissions cause wireless (FiWi) packets to queue up longer and experience longer delays as they traverse the wireless network.

6.2. Impact of long-reach propagation

In this section we focus on the impact of the long propagation delays of long reach PONs with 90–100 km between the OLT and the ONUs. For ease of comparison with the normal-range PON, we consider initially in Section 6.2(1) the same dedicated ONU architecture as in Section 6.1. In order to comprehensively examine the impact of the long-range propagation, we consider then in Section Section 6.1(2) the mixed ONU FiWi network architecture.

(1) Dedicated ONU FiWi network architecture: We consider initially the same scenario as in Section 6.1, however, we doubled the considered cycle length limits from 1, 2, and 4 ms in Fig. 4 to 2, 4, and 8 ms in Figs. 6 and 7. Long cycle length limits are important for good utilization of the long-range PON so as to ensure that the long propagation delays and resulting idle times are kept small relative to the durations of the upstream transmission windows (grants). In particular, we observe from Fig. 7(a) that with a $Z = 2$ ms cycle length, the (off., lim.) DBA reaches the stability limits around 0.173 Gbps, compared to approximately 0.46 Gbps for the normal-range PON in Fig. 4(b).

Generally, we observe from Figs. 6 and 7 that the cycle length limit $Z$ affects the stability limits and the knee points of the different DBA mechanisms in a similar manner as for the normal reach PON in Fig. 4. Specifically, the stability limits for the PON traffic and the knee points of the FiWi traffic curves are pushed to higher loads as the cycle length increases. However, for the PON traffic, the trend for the performance impact of the DBA mechanism for the long-range PON is different from the normal-range PON: for the normal-range PON in Fig. 4 the stability limit increase achieved by the sophisticated (off., exc.) DBA compared to the simple (off., lim.) DBA is approximately 63% for $Z = 1$ ms and 18% for $Z = 4$ ms; in contrast the corresponding increases for the long-range PON are 57% for $Z = 2$ ms and 33% for $Z = 8$ ms. Thus, in comparison to the normal-range PON, the impact of the DBA mechanism remains relatively stronger for increasing cycle length in the long-range PON.

For FiWi traffic, we observe from Fig. 6 that lower cycle length limits benefit the FiWi traffic in the long-range FiWi network. In particular, reducing the cycle length from 8 to 2 ms reduces the mean FiWi (on., lim.) packet delay by approximately 29% in Fig. 6, which is equivalent to the corresponding delay reduction in the normal-range FiWi network.

(2) Mixed ONU FiWi network architecture: In this section we expand the investigation of the impact of the long-range propagation delay in FiWi networks by considering the mixed ONU network architecture, see Section 5.1(1). In the considered mixed ONU architecture, four ONUs serve wireless (FiWi) and PON traffic, while the other four ONUs serve only PON traffic. In the mixed ONU architecture, the ONUs serving FiWi and PON traffic have already a large upstream traffic component from the PON traffic; thus, we consider the All-P2P traffic scenario for the wireless FiWi traffic, specifically with the 1:20:30 traffic ratio, see Section 5.2.

(a) Online and offline DBA mechanisms: We observe from Figs. 8 and 9 for the mixed ONU architecture generally similar behaviors for the PON traffic and FiWi traffic as for the dedicated ONU architecture in Section 6.2. However, we observe that the stability limits and delays are generally slightly higher for the mixed architecture compared to the dedicated architecture. The PON traffic at the mixed ONUs leads to longer upstream transmission grants of the mixed ONUs serving both FiWi and PON traffic. These longer grants increase the utilization of the upstream wavelength channel relative to the idle times (and overheads), resulting in increased stability limits.

On the other hand, FiWi traffic suffers from substantially higher delays in the mixed architecture, see Fig. 8, compared to the dedicated architecture, see Fig. 6. The wide load range with very slowly increasing FiWi packet delays from the “knee point” onwards towards high loads in Fig. 6 is replaced by a narrow load range between the knee point and the load point indicating the stability limit for the FiWi traffic (where the FiWi packet delays shoot up sharply) in Fig. 8. In the mixed ONU architecture, wireless (FiWi) traffic is mixed with high-rate conventional PON traffic. Thus, for increasing traffic load, the queues in the mixed ONUs grow very large, causing high FiWi packet delays. In order to preserve the wide load range of slowly increasing FiWi packet delays for traffic loads above the knee point, QoS mechanisms would be needed to protect the FiWi traffic from the PON-only traffic.

(b) Double-Phase Polling (DPP): Following the indication of the strong effect of sophisticated DBA mechanisms for long-range PONs in Section 6.2(1), we included the sophisticated DPP DBA mechanism (with DG ONU grouping, see Section 4.3) in the evaluation of the long-range mixed ONU architecture. The results in Figs. 8 and 9 demonstrate the superiority of the DPP DBAs over the online and offline scheduling framework DBAs. With DPP,
the upstream transmissions of one ONU group can mask the idle times of the other ONU group. Reduced idle times increase the utilization of the upstream transmission wavelength for payload transmissions.

We observe from Figs. 8 and 9 that DPP achieves lower PON and FiWi packet delays than the other DBA mechanisms, except for (on., gat.), which however has the drawback that a single ONU can monopolize the upstream
bandwidth usage for extensive time periods [69]. We also observe that DPP with sharing of the excess bandwidth (dpp, exc.) gives significant performance improvements over simple limited grant sizing (dpp, lim.). Given the favorable performance of DPP with excess sharing (dpp., exc.), we proceed to examine the ONU grouping strategies for this DBA mechanism in the next section.

7. Results for ONU grouping in DPP with excess sharing

In this section we examine the different ONU grouping techniques introduced in Section 4 in the context of the double-phase polling (DPP) DBA mechanism with excess bandwidth sharing. As in the preceding Section 6.2(2), we continue to consider the mixed ONU FiWi network architecture with long-range propagation and with the All-P2P traffic scenario. The ONUs within a group continue to be scheduled based on SPD. We focus on the $Z = 4$ ms cycle length in this section and initially consider the 1:10:40 traffic ratio, followed by the 1:20:30 traffic ratio.

7.1. Traffic ratio 1:10:40: pronounced mixed ONU to PON-only ONU load difference: For PON packet traffic, we observe from Fig. 10(b) that load balancing (LB) gives lower mean packet delays than load grouping (LG). LG assigns the lightly loaded ONUs to one group and the highly loaded ONUs to the other group. The lightly loaded ONU group has typically shorter upstream transmission windows than the highly loaded ONUs. Consequently, the lightly loaded ONU group has shorter mean cycle lengths than the highly loaded ONU group. With shorter cycles there is a smaller probability that the upstream transmissions of the lightly loaded ONU group mask the idle time between the upstream transmissions of the highly loaded ONU group in successive cycles. In contrast, with LB grouping, there is a higher chance that the upstream transmissions of each group are sufficiently long to mask the idle times between the successive upstream transmission cycles of the other group. Improved masking of idle times increases the utilization of the upstream wavelength channel and lowers the packet delays.

![Fig. 8](image)

**Fig. 8.** Mean FiWi packet delay for different DBAs for mixed ONU FiWi architecture. Fixed parameters: 90–100 km long-range FiWi network, All P2P traffic, 1:20:30 traffic ratio.

![Fig. 9](image)

**Fig. 9.** Mean PON packet delay for different DBAs for mixed ONU FiWi architecture. Fixed parameters: 90–100 km long-range FiWi network, All P2P traffic, 1:20:30 traffic ratio.
We further observe from Fig. 10(b) that for low to moderate loads up to around 0.4 Gbps, distance balancing (DB) gives lower mean PON packet delays than distance grouping (DG). This result is due to the analogous masking effect as for the LB vs. LG result, i.e., the two ONU groups can mask each others’ idle times better if the propagation delays are balanced. However, for loads above 0.4 Gbps, DB gives higher PON packet delays than DG. In order to further investigate the DB and DG behaviors, we plot the FiWi and PON packet delays for DB and DG with the simple (dpp., lim.) DBA mechanism in Fig. 11. We observe from Fig. 11 the expected reduction of the mean packet delays achieved with DB in comparison to DG. In contrast, with the complex (dpp., exc.) DBA mechanism, the sharing of the excess bandwidth among the groups, which do not have balanced loads in the DB and DG strategies may counter the effects of the distance balancing and lead to unexpected results. This indicates that it is crucial to consider both ONU traffic load and propagation distance, i.e., the two main variables that govern the durations of the upstream transmission windows and the round-trip idle times, and thus the cycle lengths (see Eq. (1)).

Grouping by Cycle Length (GCL), as derived in Section 4.7, considers both the ONU traffic loads and the propagation delays to balance the cycle durations of the two DPP groups. We observe from Fig. 10(b) that GCL indeed achieves the lowest delays and highest stability limit among the considered grouping strategies.

For FiWi packet traffic, we observe from Fig. 10(a) that LG achieves significantly lower mean packet delays than GCL (while the other grouping strategies give very similar delays). LG assigns the lightly loaded ONUs, i.e., the four ONUs with FiWi traffic, to one group. Since these four ONUs are all lightly loaded, they typically do not need to share any excess bandwidth among themselves; rather they typically provide excess bandwidth to be shared among the four highly loaded ONUs in their next cycle. Since the four FiWi ONUs are grouped together, the (typically short) FiWi ONU upstream transmissions (within a given cycle) follow each other on the upstream wavelength channel. In contrast, with GCL, lightly loaded ONUs with FiWi traffic are typically grouped with heavily loaded PON-only ONUs. Thus, there is typically some excess bandwidth sharing within a given GCL group. Consequently, the (typically short) upstream transmissions of the FiWi ONUs (within a given cycle) are interspersed with (typically long) upstream transmissions of heavily loaded PON-only ONUs. This interspersing of (long) PON-only ONU transmissions among the (short) FiWi ONU transmissions within the upstream transmission of a given group in a given cycle tends to increase the FiWi packet delays.

7.2. Traffic ratio 1:20:30: mild mixed ONU to PON-only ONU load difference: We note that with the 1:10:40 traffic ratio considered in Section 7(3), the load differences between the mixed ONUs serving FiWi and PON traffic and the ONUs serving only PON traffic are relatively pronounced. We next reduce this load difference by considering the 1:20:30 traffic ratio in Fig. 12.

We observe from Fig. 12 that for the 1:20:30 traffic ratio the FiWi and PON packet delays exhibit generally similar
trends as for the 1:10:40 traffic ratio in Fig. 11. GCL gives still the lowest PON packet traffic delays while LG still gives the lowest FiWi packet delays. However, we observe that for FiWi packets, the delay difference between LG and GCL is reduced in Fig. 12(a) compared to Fig. 11(a). For the mild load difference between the lightly loaded mixed (FiWi and PON traffic) ONUs and the heavily loaded PON-only ONUs, the delay effect of interspersing long PON-only ONU upstream transmissions among the short FiWi ONU upstream transmissions within a given group and cycle is reduced.

We also observe from the comparisons of Figs. 12(a) and 11(a) that FiWi traffic has lower stability limits for the 1:20:30 traffic ratio compared to the 1:10:40 traffic ratio. With the 1:20:30 traffic ratio, the mixed ONUs are relatively higher loaded (21/51 proportion of the total traffic) compared to the 1:10:40 ratio (11/51 of total traffic). Thus, with the 1:20:30 ratio, the mixed ONUs saturate for a lower total traffic load, thus reducing the maximum throughput levels that FiWi traffic can achieve.

Overall, the results for the ONU grouping strategies indicate that GCL has favorable performance characteristics. GCL achieved the lowest PON packet traffic delays among the considered five grouping strategies. LG achieved lower FiWi packet delays than GCL; however, for FiWi networks with only mild load differences between the ONUs serving FiWi traffic and the ONUs serving only PON traffic, the delay reduction with LG is relatively small. Thus, GCL appears overall to be a promising ONU grouping strategy for FiWi networks.

8. Conclusion

We have examined fiber-wireless (FiWi) networks with long-range propagation on the order of 100 km in the fiber-based passive optical network (PON) part of the overall FiWi network. We have conducted extensive simulations to investigate the mixing of low-rate wireless (FiWi) traffic that first traverses the wireless network and then the PON with high-rate PON traffic that traverses only the PON. For a FiWi network architecture with dedicated ONUs for wireless (FiWi) traffic and dedicated ONUs for PON-only traffic, we found that strategies that lower the PON traffic delay, generally increase the FiWi traffic delay. That is, enhancements to the dynamic bandwidth allocation (DBA) mechanisms and extended cycle lengths reduce the PON packet traffic delay, but increase the FiWi packet traffic delay in the dedicated ONU FiWi network. In contrast, for a mixed ONU FiWi network architecture where some ONUs serve both low-rate wireless (FiWi) and high-rate PON traffic, the enhanced DBA mechanisms and extended cycle lengths benefit both FiWi and PON packet traffic. We also found that the double-phase polling (DPP) DBA mechanism gives the best performance among a wide range of compared DBA mechanisms.

We closely examined the ONU grouping in DPP and introduced a novel grouping by cycle length (GCL) strategy. The GCL strategy considers both the OLT-to-ONU propagation distances and the ONU load levels and strives to balance the polling cycle durations of the two ONU groups in DPP. We found that DPP achieves the lowest PON packet traffic delays among a range of considered grouping strategies and gives relatively low delays for FiWi traffic. For FiWi networks with a pronounced disparity between the traffic load levels of the ONUs serving FiWi traffic and the ONUs serving only PON traffic, ONU grouping by load levels can achieve somewhat lower FiWi delay than GCL.

There are many directions for important future research on long-range FiWi networks. One direction is to examine quality of service differentiation for different classes of wireless and PON-only traffic in long-range FiWi networks. Another important direction is to examine the interactions with specific wireless networking protocols and standards, such as long-term evolution (LTE) in the wireless part of the long-range FiWi network. Also, the internetworking of the PON part of the long-range FiWi network with metropolitan area networks [84–88] leading to the backbone of the Internet is an interesting direction for future research. Yet another emerging important research direction is the incorporation of energy efficiency
mechanisms, such as [89–91], into low-delay long-range FiWi networking.

References


