Improving the Performance of FiWi Networks

Through Collaboration Between ONU and APs

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Improving the Performance of FiWi Networks Through Collaboration Between ONU and APs

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***Abstract*—Fiber-Wireless (FiWi) Networks which are made up of fiber networks such as Passive Optical Networks (PONs) and wireless networks such as Wireless Local Area Networks (WLANs), can leverage the advantages of both types of networks, namely, the mobility support of users and high bandwidth. However, the increased number of users causes long queuing delay in the Optical Network Unit (ONU) of FiWi networks. Conventional methods that allocate bandwidth to minimize queuing delay only work in the PON, and WLANs do not consider state of the ONU. Thus, we propose a cooperative method between the PON and WLANs, which takes into consideration the data rate allocated to the ONU and controls the amount of messages by the WLANs, to decrease the queuing delay at the ONU. We mathematically analyze the queuing delay of the conventional method and our proposed method. Then, we show that our proposed method can decrease the queuing delay and improve the performance of FiWi networks.**

I. Introduction

In recent years, wireless networks have underwent great advances in terms of data rate, mobility support, and so on. For example, the IEEE 802.11ac standard specifies a data rate ranging from 290Mbps to 6.9Gbps, which is over 10 times faster than the conventional standard of IEEE 802.11n. This facilitates high-speed Internet and mobility support for users. However, as the number of users who use wireless networks increase, the more the throughput that the wireless networks have to sustain. Hence, improving the throughput of wireless networks is of prime importance. Fiber-Wireless (FiWi) networks are an attractive solution that can provide high throughput [1]–[3]. FiWi networks are the convergence of both wireless networks and optical networks. They can deliver the advantages of both wireless and optical networks, i.e., the mobility support of wireless networks and the high bandwidth of optical networks. Concerning the optical network part, Passive Optical Networks (PONs) are popular due to their low set up cost, high bandwidth, and low delay [4], [5]. Concerning the wireless network part, many kinds of wireless networks can be connected to the optical network part. These include Wireless Area Networks (WLANs) [6], Wireless Mesh Networks (WMNs) [7], Worldwide Interoperability for Microwave Access (WiMAX) and third generation (3G) networks [8]. Here, WMNs in the FiWi networks consist of many Access Points (APs) connected together with one AP acting as a gateway to the Optical Network Unit (ONU). The STAtions (STAs) are connected to the network through these APs. In this paper, we focus on FiWi networks composed

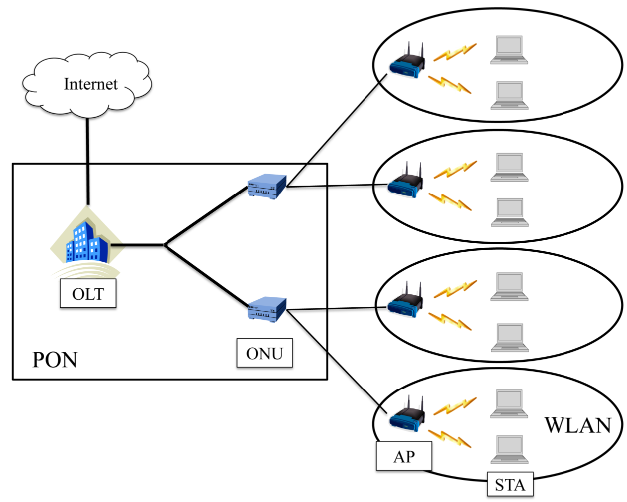

Fig. 1. A FiWi network composed of a PON and several WLANs

of PONs and WLANs, as shown in Fig. 1, since WLANs have seen wide deployment in homes, offices, and so forth. In this structure, the PON, which has plentiful bandwidth, accommodates the upstream traffic generated by the users in the WLANs. However, due to the development of the wireless devices and the increase in the number of users who have various terminal devices such as laptop, smartphone, and tablet PC, traffic in the FiWi network is increasing. Especially, the appearance of applications such as Social Network Service (SNS) results in the increase of upstream traffic from WLANs that the PON has to transfer, which leads to the increased delay in the PON. Conventional mechanisms that minimize the queuing delay already exist in PONs. For example, many types of Dynamic Bandwidth Allocation (DBA) mechanisms [9]–[11], are proposed so far. However, these mechanisms only work in PONs, so a PON cannot control the upstream traffic that is generated in the WLANs. Therefore, new methods are required that work in the entire FiWi network to decrease the queuing delay in the PON.

In this paper, we focus on a method that works on both the PON and the WLANs. The PON needs to know the state of the WLANs, which is the number of STAs and the sum of the traffic in each WLAN, and WLANs also need to know the state of the PON to solve the queuing delay issue in the PON.

Based on this requirement, we propose a method that shares information about upstream traffic between the PON and the WLANs.

The remainder of this paper is organized as follows. Section II provides an overview of the structure of both PONs and WLANs, and discusses the queuing delay problem at the ONU in FiWi networks with mathematical analysis. Section III presents the proposed method that solves the queuing delay problem in the PON along with its mathematical analysis. Section IV provides performance evaluation of the mathematical models presented in Section III. Section V concludes the paper.

II. Structure of FiWi Networks

In this section, we introduce in detail the structure of both PONs and WLANs, including their medium access control. Moreover, we show how packet loss occurs in the ONU part of PON.

A. Structure of a PON

The structure of a PON is shown in the left side of the Fig. 1. A PON consists of an Optical Line Terminal (OLT), splitter, and some Optical Network Units (ONUs). An OLT is the terminal device connected to the Internet in the Internet Service Provider's (ISP's) side, and the ONU is the terminal device for the users. ONUs are connected to one OLT by using a splitter that splits the optical signal from the OLT to ONUs, or pass the optical signal from several ONUs to the OLT. The splitter does these processes passively without doing any type of controlling. Thus, the deployment cost of a PON can be kept low. However, the OLT has to schedule the transmission right and interval of each ONU to avoid collisions at the splitter. The Multi-Point Control Protocol (MPCP) specifies the communication mechanism between an OLT and the ONUs. According to MPCP, each ONU sends to the OLT a REPORT frame, which contains the queue size of the ONU. Therefore, the OLT can know the queue size of all ONUs, and then sends to each ONU a GATE frame, which contains the transmission right and interval. The mechanism that decides the transmission right and interval is out of the MPCP standard and this is decided by the DBA. There are a lot of DBA algorithms, such as calculation of the transmission right and interval is left to the vendor. After the ONU receives the GATE frame from the OLT, the ONU sends the data at the informed time for the informed interval according to the GATE message. Also, the ONU sends the REPORT frame with the data for the next sending opportunity. Exchanging these REPORT and GATE frames between an OLT and ONUs, allows the PON to avoid collisions, and each ONU to send its data frames according to the demands of all ONUs.

B. Structure of a WLAN

The structure of a WLAN is shown in the right side of Fig. 1. A WLAN consists of an AP and a number of STAs. For the medium access control between the AP and the STAs, the IEEE 802.11 standard defines the Distributed Coordination Function (DCF) [12]–[14], and the Point Coordination Function (PCF) [15], [16].

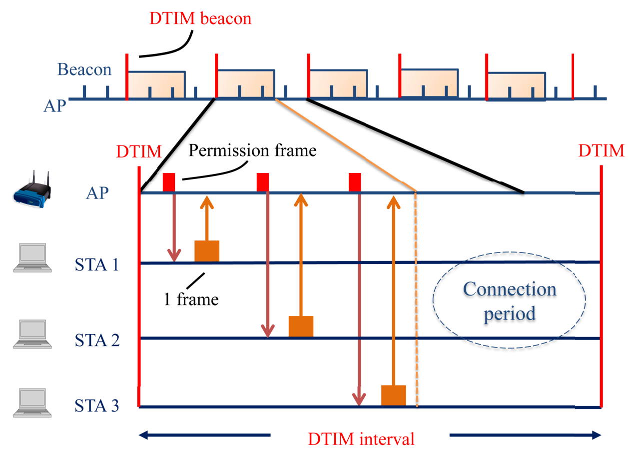

Fig. 2. The procedure of the PCF mechanism.

In DCF, STAs access the AP according to their desired time and each STA competes to get the transmission right. Therefore, the DCF is contention-based access control, so collisions among STAs might occur in this process. To avoid collisions, the medium access control mechanism of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) is adopted in the DCF. CSMA/CA defines two collision avoidance mechanisms, namely, the carrier sense and the contention window mechanisms. When a STA wishes to initiate a transmission, the STA senses if others STAs are transmitting or not, and starts transmission if no other STA is transmitting. This sensing is the carrier sense mechanism, however, collisions still occur in DCF when several STAs are doing carrier sensing and start to transmit in the same time. The contention window mechanism avoids this situation. The contention window mechanism waits a random amount of time to avoid collision when an STA wishes to transmit and a collision occurs. These mechanisms are very effective to decrease the probability of collisions. However, if the number of STAs connected to an AP increases, the probability of collision will also increase.

In PCF, the STAs access to the channel is coordinated by the AP, and STAs access the channel without contention in scheduled times. The AP transmits a frame called a beacon to all STAs. The beacon contains information that includes the supported data rate, beacon interval and channel number. Also, the AP adds the Delivery Traffic Indication Message (DTIM) flag, which informs the STAs to start transmitting at one beacon every several beacons. PCF's mechanism is illustrated in Fig. 2. The period between the last STA on the polling list sends its frame and the next DTIM beacon is defined as the connection period. STAs which are not on the polling list can use the connection period to request to start communication. The time between DTIM beacons is called DTIM interval and it is divided into a communication period and a connection period. In the communication period, the AP sends a permission message to the STAs and each STA transmits a frame. The connection period is the remaining time after the communication period is finished, and it is used for the STAs that wish to connect to the AP and are not in the polling list. When the STAs receive a DTIM beacon, they know the start time of the contention-free period and wait for the AP's signal. The contention-free period is the period of time where STAs do not compete with each other to get the transmission right where their transmission rights are controlled by the AP. Then, the AP sends the permission frames called Contention Free-Poll (CF-Poll) to one of the STAs on the polling list, which contains the STAs connected to the AP. The STA that receives the CF-Poll is allowed to send one frame to the AP. However, if the STA does not have data to send, STA sends a Null Function frame. After the AP receives this frame, the AP sends back an ACK frame and sends another CF-Poll to the next STA on the polling list. The AP sends the CF-Poll to all the STAs in the polling list in order, so that collision between STAs does not occur. After each STA on the polling list sends its message, the STAs wait until the next DTIM beacon is sent by the AP. In this paper, we focus on PCF because we want to schedule the time of sending frame and control the data rate between the AP and its connected STAs. So we assume that the access control between the AP and the STA is conducted according to PCF.

C. Queuing delay problem at the ONU

In this paper, the FiWi network consists of a PON and WLANs which we mentioned above and is shown in Fig. 1. Each ONU is connected to several APs, i.e., several WLANs are connected to each ONU. In this topology, traffic generated by each STA arrives first to the APs and then arrives to the ONU. The ONU is the junction point of many WLANs. Thus, a lot of traffic arrives at the ONU, and each ONU sends the traffic to the OLT. In this stage, the DBA mechanism allocates bandwidth between the ONUs. When many ONUs transfer heavy traffic, the bandwidth allocated to each ONU becomes smaller. Therefore, the maximum supported traffic between the OLT and the ONU can become smaller than the sum of the traffic from the WLANs in a short period of time, which results in increased queuing delay in the ONUs. Even if the supported traffic between the OLT and ONU is not so small, the queuing delay can occur in the ONU if the traffic that arrives to the ONU instantaneously exceeds its allocated bandwidth. We assume that the packets arrive at the ONU following the Poisson distribution model, and we assume an M/M/1 queuing model at the ONU. M/M/1 model is the queuing theory in which the Poisson arrival to one system and the service time cost at the system follow the exponential distribution. According to the M/M/1 queuing model, queuing delay at the ONU can be given as follows:

$$W_{\mathrm{ONU}} = \frac{\rho_{\mathrm{ONU}}}{(1-\rho_{\mathrm{ONU}})} \cdot \frac{1}{\mu_{\mathrm{ONU}}}, \tag{1}$$

where ρ_{ONU} denotes the utilization rate at the ONU and $1/\mu_{\mathrm{ONU}}$ denotes the service time at the ONU. ρ_{ONU} can be calculated as:

$$\rho_{\mathrm{ONU}} = \frac{R_{\mathrm{ONU}}}{R_{\mathrm{ONU-OLT}}}, \tag{2}$$

where R_{ONU} denotes the average data rate of arriving data at the ONU and $R_{\mathrm{ONU-OLT}}$ denotes the average bandwidth allocated to the ONU from the OLT. The increase of ρ_{ONU} means that the capacity of the link between the ONU and the OLT is filled up and hence queuing delay at the ONU increases. Also, the decrease of the bandwidth allocated to the ONU from the OLT leads to the increase of the queuing delay according to Eq. (1).

III. Collaborative Traffic Control Technique between ONU and APs

In this section, we propose a traffic control technique that is based on an idea of sharing the ONU's bandwidth information between the ONU and its connected APs. Furthermore, we analyze the queuing delay in the proposed method.

A. Technique

The queuing delay occurs at the ONU in conventional FiWi networks because each AP sends its data without considering the bandwidth allocated to the ONU from the OLT. Therefore, in our proposal, when the bandwidth allocated to the ONU is smaller than the arriving traffic at the ONU from APs, each AP needs to control the data rate between itself and its STAs so that the sum of traffic that arrives to the ONU is within the amount of traffic that the ONU can handle. In our proposed method, each ONU informs its connected APs about the bandwidth allocated to the ONU from the OLT in order to control the traffic at each WLAN. APs control their traffic sent out to the ONU so that the total traffic rate arriving at the ONU becomes less than or equal to the bandwidth allocated to the ONU from the OLT. Here, if a data traffic at an AP is much larger than at other APs, the AP should be controlled to get a higher bandwidth than the others. Thus, we have to assign the ONU's bandwidth according to the traffic demands of APs. When the traffic demand that ith AP receives from STAs within its service area is r_i, an ONU assigns its bandwidth to ith AP according to the following equation:

$$R_i = R_{\mathrm{ONU}} \times \frac{r_i}{\sum_{k=1}^{N_{\mathrm{AP}}} r_k}, \tag{3}$$

where N_{AP} and R_i denote the number of APs and the bandwidth assigned to ith AP. By controlling traffic sent to the ONU from APs by following the above equation, the ONU does not suffer buffering delay.

In a WLAN, an AP can control traffic from STAs by adjusting DTIM interval, T_{DTIM}. Since the AP has no idea about the number of STAs that have data traffic to send in the DTIM interval, our proposed scheme expects the amount of traffic arriving at the AP by multiplying the number of STAs, N_{STA}, with the maximum frame size. In other words, the following formula has to be always satisfied.

$$R_i \geq \frac{F_{\mathrm{MPDU}} \times N_{\mathrm{STA}}}{T_{\mathrm{DTIM}}}. \tag{4}$$

Here, T_{DTIM} is in multiples of the beacon interval which is a constant value, the proposed scheme sets the DTIM interval to the maximum possible value, $T_{\mathrm{DTIM}}^{\max}$, which is a multiple of the beacon interval and satisfies Eq. (4). As a result, the data rate assigned for each STA connected to the AP becomes equal to

$$B = \frac{F_{\mathrm{MPDU}} \times N_{\mathrm{STA}}}{T_{\mathrm{DTIM}}^{\max}}. \tag{5}$$

Since all APs connected to the ONU control data traffic from STAs by adjusting their DTIM intervals, in the proposed scheme, queuing delay at the ONU can be maintained at almost zero. However, data generated by the application in each STA can be instantaneously buffered at the queue embedded on the STA, which is evaluated by mathematical analysis in the next subsection.

B. Queuing delay at the STA

The queuing delay at the ONU can be handled since we can control data traffic at each AP to let the sum of the traffic which arrive at the ONU smaller than the bandwidth allocated to the ONU from the OLT. However, there is a possibility that the queuing delay at the STA gets longer when the number of APs increases and the DTIM interval becomes longer. The packets which could not be sent are queued at the STA, so the queuing delay at the STA increases as the DTIM interval gets longer. We assume that the number of transmissions generated at the STA in a period of time follows Poisson distribution, and the average data size generated at one transmission follows the exponential distribution. In this assumption, we consider the M/M/1 queuing model at the STA. According to the formula of M/M/1 queuing model, queuing delay at the STA, W_{STA}, can be given as:

$$W_{\mathrm{STA}} = \frac{\rho_{\mathrm{STA}}}{(1-\rho_{\mathrm{STA}})} \cdot \frac{1}{\mu_{\mathrm{STA}}}, \tag{6}$$

where ρ_{STA} is the average utilization rate of process at the STA and $1/\mu_{\mathrm{STA}}$ is the time to service the average data. ρ_{STA} can be calculated as:

$$\rho_{\mathrm{STA}} = \frac{R_{\mathrm{STA}}}{B}, \tag{7}$$

where R_{STA} and B denote the average traffic load at the STA and the data rate assigned to the STA, respectively. $1/\mu_{\mathrm{STA}}$ is the process time at the STA and can be expressed as:

$$\frac{1}{\mu_{\mathrm{STA}}} = \frac{D}{B}, \tag{8}$$

where D is the average data size generated at one transmission. The process time is influenced by the B and it is defined by Eq. (8). Accordingly, the queuing delay increases when the controlled data rate between the AP and STAs decrease.

IV. Numerical Analysis

In this section, we evaluate the performance of the proposed method by analyzing the queuing delay using the analyses in Sections II and III. Although the data rate arriving at the ONU can be higher than the bandwidth allocated to the ONU from the OLT in a specific period of time, we assume that the average data rate arriving at the ONU is smaller than the average bandwidth allocated to the ONU from the OLT. In the remainder of this section, the analysis environment is described, followed by the analysis result.

A. Parameter set up

We assume that the considered network consists of 1 OLT, 32 ONUs, and 5 APs connected to each ONU. We set the same number of STAs connected to each AP. Each STA generates the transmission with the same average data rate. In this analysis, we assume that the average data sizes arriving at the ONU and generating at STAs are the same and are set to 1Mb. We have conducted two analyses to evaluate the queuing delay at ONUs and STAs as shown in Eqs. (1) and (6). The parameters, which are the same in both analyses, are listed at Table I.

TABLE I. Parameters

Average bandwidth allocated to one ONU	50 Mbps
Beacon interval length	5 msec
Maximum data size	1 Mb
Number of APs	5

In the first evaluation, we assume that the number of STAs connected to one AP is fixed by 10, and we change the average data rate generated at each STA from 0Mbps to 0.8Mbps. The average bandwidth allocated to the ONU from the OLT is set to 50Mbps. Here, we evaluate the queuing delay at an ONU for conventional method and at a STA for the proposed method while increasing the data rate of each STA.

In the second evaluation, we assume that the average data rate generated at each STA is fixed by 0.5Mbps, and the number of STAs connected to each AP varies from 1 to 10. Here, we evaluate the relationship between the queuing delay and the total number of STAs sending data to the ONU in both the conventional method and the proposed method.

B. Analytical results

Firstly, we study the result of the relationship between the data rate at each STA and the queuing delay. From Fig. 3, we can confirm that the queuing delay at a STA in the proposed method is shorter than that of ONU in the conventional method with any data rate at each STA. In both cases, the queuing delay increases when the data rate generated at each STA increases. Since the ONU is the traffic convergence point, even if the data rate at each STA is not high, the arriving data rate at the ONU can be higher following the number of the STAs, which results in a longer queuing delay at the ONU than that of the STA in the proposed scheme. On the other hand, the proposed scheme controls the data rate between the STAs and the AP, which is connected to the ONU, such that the sum of the data rate originating from APs does not go over the bandwidth allocated to the ONU. As a result, we can achieve a smaller queuing delay at the STA compared with that of the ONU in the conventional method.

Secondly, we study the result of the relationship between the number of STAs connected to an AP and the queuing delay. From Fig. 4, we can confirm that the queuing delay at a STA in the proposed method is shorter than that of the ONU in the conventional method with every number of STAs. Since we assume that the number of STAs connected to each AP is fixed, the increase of the number of STAs connected to one AP means that the whole number of STAs is increased with respect to the same number of APs. Therefore, we can say that the increase of the whole number of STAs sending the data to ONU increases the queuing delay at the ONU. In our proposed method, the data traffic is slightly delayed at the queue of STA when the traffic load instantaneously exceeds the data rate

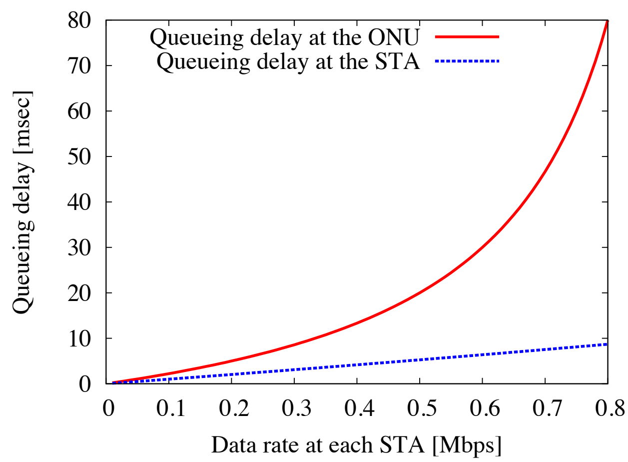

Fig. 3. Relationship between the data rate at each STA and the queuing delay.

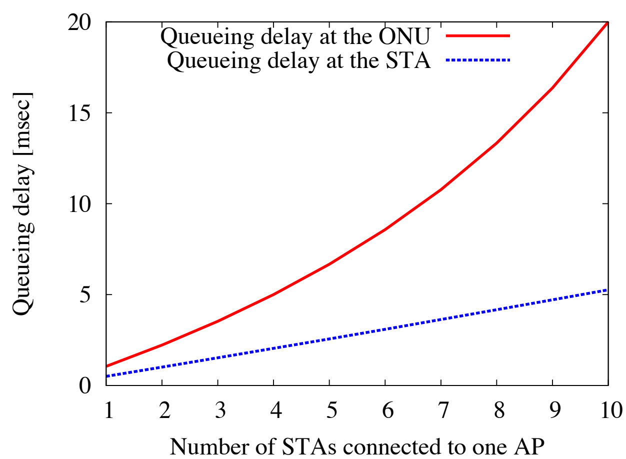

Fig. 4. Relationship between the number of STAs and the queuing delay.

between the STA and the AP. However the queuing delay at the ONU can be dramatically reduced and maintained at almost zero. Therefore, the queuing delay at a STA in the proposed method is shorter than that at the ONU in conventional method.

In conclusion, our proposed method can control the data rate at the WLAN considering the bandwidth between the ONU and the OLT, and thus, can decrease the queuing delay in the FiWi networks. Hence, our proposed method is promising since it can improve the performance of FiWi networks.

V. Conclusion

In this paper, we focused on FiWi networks, which are vulnerable to severe queuing delay at the ONU when heavy traffic arrives at the ONU in a short period of time since the conventional methods do not consider the bandwidth allocated to each ONU. Our proposed method can decrease the queuing delay by controlling the data rate between APs and STAs so that the sum of the traffic arriving at the ONU is within the bandwidth allocated to the ONU. We analyzed the queuing delay at the ONU of the conventional method and at the STA of our proposed method. The analytical results showed that our proposed method decreases the queuing delay while the conventional method suffers from increased queuing delay at the ONU as the number of users that are connected to the FiWi network increases. Thus, we conclude that our proposal is an effective scheme to achieve efficient communication when many users use the FiWi network.

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