Smart FiWi Networks: Challenges and Solutions for QoS and Green Communications

Smart FiWi Networks: Challenges and Solutions for QoS and Green Communications

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***Abstract*—Combined Wireless Local Area Networks (WLANs) and Passive Optical Networks (PONs), shortly referred to as Fiber Wireless (FiWi) networks, can be considered as attractive Cyber Physical Systems (CPSs) whereby the WLANs collect data as part of autonomous and/or mobile systems, and PONs send the collected information to other autonomous systems through "high speed core networks". For FiWi based CPS communication, however, a bottleneck is likely to exist in the combined PON-WLAN link because these technologies operate with inherently different medium access layer specifications (e.g., "green" or energy-efficient power saving techniques and quality of service control policies for WLAN and PON are essentially different). In this article, we propose a smart integration of WLAN with PON technology by carefully "synchronizing" or coordinating their different quality of service specifications and energy saving modes in such a way that they may be seamlessly combined to facilitate efficient CPSs.**

***Keywords*-CPSS, WLAN, PON.**

I. Introduction

The vision of ubiquitous communication has gained a great momentum recently with the integration of optical fiber-based broadband technologies with various wireless mobile communication networks. Indeed, the heterogeneous next-generation networks are gradually converging toward a high-speed optical fiber backbone network using the Internet Protocol (IP). One notable example of these next-generation heterogeneous communication technology is the Fiber Wireless (FiWi) [1], [2] access networks. The FiWi networks aim at integrating Passive Optical Networks (PONs) [3] with Wireless Local Area Networks (WLANs) [4], and they have attracted a great deal of attention from researchers in academia as well as industria in order to satisfy the ever increasing Internet access demands of the users. The prime advantage of such integrated networks is their wide coverage and high capacity communication capability because of the wireless and optical network features, respectively.

A promising application of FiWi networks can be in terms of Cyber Physical Systems (CPSs). For example, the 802.11 based WLANs can be used to collect data as part of autonomous and/or mobile systems. On the other hand, PON can be exploited to send a large volume of the collected data, at high speed, to other autonomous systems through "high speed core networks". For FiWi based CPS communication, however, a bottleneck is likely to exist in the combined PON-WLAN link since they operate with inherently different medium access layer specifications. For instance, the energy-efficient (i.e., "green") power saving techniques and quality of service control policies for WLAN and PON are essentially different. As a result, for an effective integration of these two different technologies to complement each other in an optimal fashion, a smart mechanism to seamlessly connect them is a quite critical issue. In this article, we propose a smart integration of WLAN with PON technology by carefully "synchronizing" or coordinating their different energy-efficient and quality of service specifications in such a manner that they may be seamlessly combined.

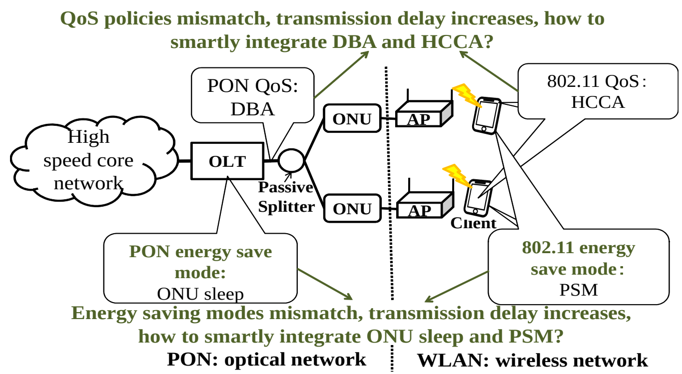
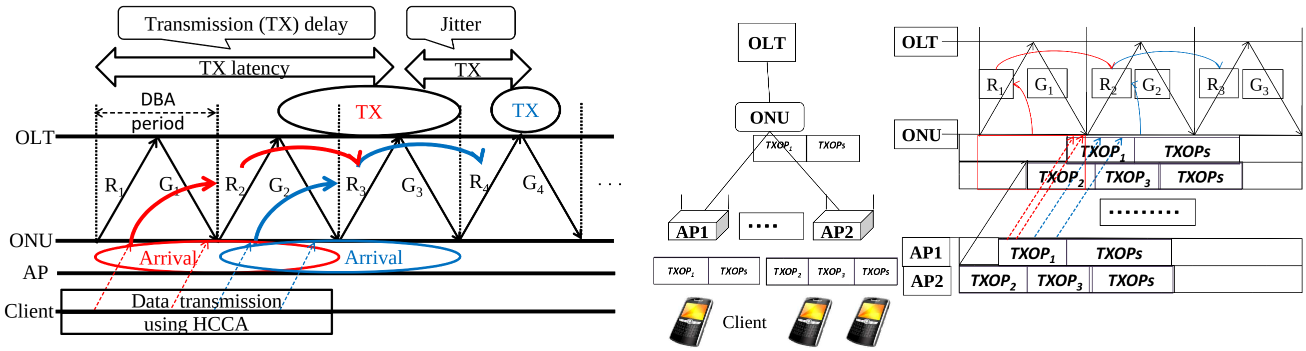


Fig. 1. Considered FiWi architecture.

The remainder of our article is structured as follows. Section II presents a brief overview of our considered FiWi network. Section III describes the shortcoming of combining existing QoS policies and energy saving modes of the PON and WLAN components of a FiWi network. Our proposed way of smartly integrating the PON and WLAN QoS policies and energy saving strategies are also provided in this section. Section IV demonstrates the performance of our proposed approaches. Finally, concluding remarks and future directions are presented in Section V.

II. Overview of FiWi Networks and Their Shortcoming

A FiWi [1], [2] network is an integrated network which provides the advantages of both a PON [3] and WLAN as shown in Fig. 1. The highspeed cost-efficient backhaul is derived from a PON, and is combined with the flexible access provided by a WLAN. In PON, multiple users share the same optical line and signals are spread by a splitter without any electric processing. The data sent downstream from Optical Line Terminal (OLT) toward Optical Network Units (ONUs)



(a) Shortcoming of combining QoS policies of PON and WLAN. (b) Smartly synchronizing QoS policies of PON and WLAN.

Fig. 2. FiWi QoS control issue and solution.

are split at a passive splitter and simultaneously broadcasted to each of the ONUs. Note that each ONU receives all of downstream traffic destinated to not only itself but also every other ONU. Data received by non-destination ONUs is discarded. In upstream transmissions from ONUs to the OLT, a polling technique is used as a multiple access technology to allow the ONUs to share the same optical line. ONUs are assigned time slots and they are allowed to transmit data only during the assigned time slots. On the other hand, the IEEE 802.11 based WLAN part of the FiWi network provides wireless connection to fixed or mobile users. WLAN based self-organized, self-configured mesh networks are also another variant that can be exploited in FiWi networks. In the FiWi access network, each ONU acts as a gateway for the WLAN's Access Points (APs). The ONUs, which connect the PON to the WLAN, play a significant role in controlling the traffic in FiWi networks.

III. Integration Issues of Optical and Wireless Technologies in FiWi Networks and Our Solution

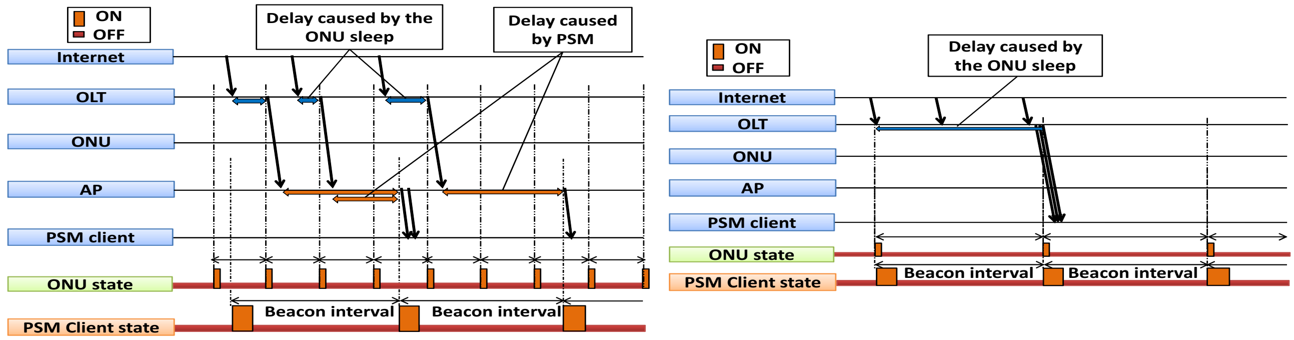
Because of the combined wireless and optical network features, FiWi access networks present a promising solution for offering wide coverage and high capacity communication. However, since each network operates independently in the FiWi access networks, a novel mechanism to connect them seamlessly is crucial due to possible mismatch in the operation of the inherently different technologies used by WLAN and PON. For example, as shown in Fig. 1, QoS controlling in FiWi may lead to problems as *H*ybrid Coordination Function *C*ontrolled *C*hannel *A*ccess (HCCA) [5] used by WLAN may not be synchronizable with the Dynamic Bandwidth Assignment (DBA) [3] scheme adopted by PON. On the other hand, for saving energy, WLAN uses Power Saving Mode (PSM) [6] while a totally different technique called "ONU sleep" [7] is exploited by PON. In the remainder of this section, we present the shortcomings of combining wireless and optical network components of FiWi (i.e., simultaneous use of HCCA and DBA for QoS control, and that of PSM and ONU sleep for energy saving) without any smart adjustment or integration, followed by our proposed approaches to deal with these shortcomings.

A. FiWi QoS control issue and how to deal with it

1. *Shortcoming of FiWi QoS control technique:* As shown in Fig. 2(a), the issue arising from combined operation of HCCA of WLAN and DBA of PON is demonstrated. With HCCA, QoS-enabled clients can request specific transmission parameters (data rate, jitter, etc.) which should allow advanced CPSS applications like medical monitoring, critical infrastructure monitoring, and so forth. Using HCCA, the wireless client transmits data to the WLAN access point (AP) in uneven time intervals. The AP is responsible for transmitting the client data to the ONU.

On the other hand, on the PON side, the OLT determines the delay of all the ONUs, and then transmits grants to the individual ONUs. The grant gives permission to each ONU to use a defined time interval (referred to as "DBA period") to perform upstream tranmission to the OLT. The grant is dynamically updated every few milliseconds, and the OLT assigns bandwidth to the ONUs as per their current traffic requirement. Each ONU sends a REPORT message to the OLT. The REPORT message contains the amount of bandwidth required by the ONU. The amount of data waiting to be transferred at the ONU's queue is used as a measure to specify its bandwidth reuirement. When the OLT receives the REPORT message, it accordingly assigns the uplink bandwidth to the ONU. The OLT also sends a GATE message to the ONU. The GATE message informs the ONU when it may be able to transmit without risk of collisions.

In a combined WLAN-PON topology, an ONU receives the data transmission from the AP in uneven intervals as shown in Fig. 2(a). The example shown in the figure comprises four DBA periods. In the i^{th}DBA period, the REPORT and GATE messages between the OLT and the ONU are denoted by R_i and G_i, respectively. The first and the second packets from the client arrives at the ONU through the AP in 1st DBA period. However, the bandwidth required for transmitting these two packets to the OLT is assigned in the second DBA period. Finally, the first two packets from the client are transmitted by the ONU in the third DBA period. This leads to transmission delay as shown in Fig. 2(a). Similarly, the ONU experiences delay in transmitting the third and fourth client-packets. Moreover, in case of QoS-sensitive CPSs communication, the additional time-interval, for which the ONU has to wait, results in jitter.



(a) Shortcoming of combining energy saving modes of PON and WLAN. (b) Smartly synchronizing energy saving modes of PON and WLAN.

Fig. 3. FiWi energy saving issue and solution.

2. *Envisioned QoS Control in FiWi Network:* The delay and jitter in transmitting the client packets to the OLT as described in Section III-A-1 indicates that there are some significant gaps in the DBA and HCCA based QoS control policies. Therefore, a technique to coordinate these two is imperative to improve the system performance and guarnetee the users' QoS satisfaction. Toward this end, our proposed solution is depicted in Fig. 2(b). Each client is assigned some transmission opportunities or TXOPs. The client is able to send multiple packets in a row in the given TXOP. The TXOP is determined by the HCCA technique depending on the client's QoS need. Fig. 2(b) shows an example comprising two APs, namely AP1 and AP2, which deal with clients 1 and 2 respectively. The TXOP assigned to client j is denoted by $TXOP_j$. When the ONU receives $TXOP_1$ in the first DBA period from AP1, it immediately knows at most how many packets may arrive from the WLAN AP. Accordingly, it requests for the required bandwidth in the second DBA period. By this way, the transmission of the packets from client 1 starts taking place much sooner (in the second DBA period) in contrast with that in the existing approach described in Section III-A-1. Thus, our proposal involves calculating the maximum number of client-frames to arrive at a single DBA period based on the TXOP information.

B. FiWi power saving issue and how to deal with it

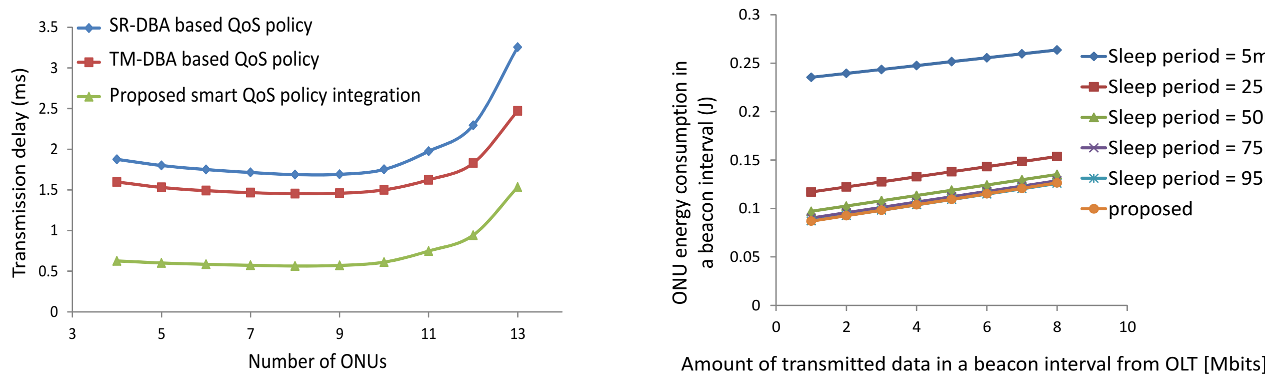
1. *Shortcoming of FiWi power saving technique:* Recently, energy-efficient communication technologies are substantially stressed upon in many fields [9]. Also, for CPSs communication using FiWi networks, the power saving issue needs to be carefully considered. In FiWi networks, there exist two main power saving techniques, namely PSM for the WLAN end and ONU sleep on the PON side. Practically, these two power saving technologies operate independently in the FiWi environment. Because both PSM and ONU sleep attempt to save energy by turning off the transmitting device(s), the end-to-end latency across the FiWi network significantly increases, and the throughput of the network decreases. This indicates the need to integrate the power saving modes used in the PON and WiFi networks by taking into consideration the relationship between energy efficiency and end-to-end delay.

At first, each client in the AP coverage area notifies the AP whether it uses PSM or not. Therefore, the AP detects the current mode of all the clients. If the AP receives data frames addressed to a client in PSM, the AP does not relay them immediately and fills its buffer with these data frames. To exchange specific information, a beacon frame is sent every fixed interval. This is referred to as the beacon interval (usually 100ms [8]). The AP informs the client regarding the APs buffer contents through the Traffic Indication Map (TIM) included in the beacon frame. The client changes from the sleep state to the active state during every beacon interval for checking the beacon information. When a client finds that the AP is storing its data frames, it requests them from the AP by sending a specific frame called "power save poll" until it receives all stored data. Then, the client goes back to the sleep state until the next beacon interval, otherwise the client reenters into the sleep state at once. Thus, the client remains in the sleep state during the idle period. As a consequence, the PSM can considerably reduce energy consumption. Meanwhile, since all data frames addressed to the client in PSM are buffered at the AP until the next beacon, PSM leads to additional delay and the observed latency becomes quite long for a connection.

On the PON side, OLT manages the ONU sleep period. The OLT sends a sleep request message containing the sleep period to the ONU. Then, the ONU sends an acknowledgment to the OLT and switches to the sleep state. If the OLT receives data frames addressed to an ONU in the sleep state, the OLT stores the data frames until the end of the current ONU sleep state. After waiting, the ONU wakes up and the OLT dispatches a sleep request message to the ONU, which indicates a sleep period of 0 ms, followed by the data frames addressed to the ONU.

Fig. 3(a) depicts the delays caused by both the PSM and ONU sleep. It is noticable that the lack of coordination between these two techniques leads to longer waiting time for packet transmission and delivery. Furthermore, ONU sleep leads to additional delay since down stream traffic is temporarily stored at the OLT. Hence, there is a tradeoff relationship between energy saving and throughput.

2. *Envisioned Smart FiWi Network for Efficient Energy:* From Section III-B-1, it is clear that the conventional ONU sleep method does not consider the AP beacon interval for determining the ONU active-sleep cycle. Therefore, the data frame cannot always reach the AP during the current beacon



(a) Performance of the FiWi QoS control policies.

(b) Performance of the FiWi energy management approaches.

Fig. 4. Performance evaluation of our proposals.

interval. To address this issue, we envision a smart AP-ONU synchronization strategy as shown in Fig. 3(b). As shown in the figure, the ONU enters the sleep state just after the AP sends a beacon. The ONU wakes up and relays data traffic to the AP before the AP dispatches the next beacon. Thus, in our approach, the ONU sleep and energy consumption states cooperate with the AP beacon interval.

Moreover, in the existing approach, ONU sleep period is fixed and determined without considering PSM operation. So, the ONU wastes energy. By considering dynamic sleep period every beacon, ONU needs to wake up only once between the beacon intervals. Thus, energy may be conserved by the ONU.

IV. Performance Evaluation

First, we compare our proposed smart QoS policy integration with two existing methods, namely Status Reporting-DBA (SR-DBA) combined with HCCA and Traffic Monitoring-DBA (TM-DBA) with HCCA. The result is shown in Fig. 4(a), which plots the transmission delays experienced by the three methods for varying number of ONUs, from 4 to 13. As demonstrated by the results, the transmission delays increase gradually as the number of ONUs increases for all the considered methods. Nevertheless, our proposal outperforms the existing methods by a significant margin. In fact, when the number of ONUs is 13 (i.e., the highest number of ONUs considered in this case), the proposed method leads to transmission delay of only approximately 1.5ms, which is lower than even the transmission delays experienced by the existing methods for the minimum number of ONUs (i.e., 3).

Next, we evaluate the performance of the FiWi energy save modes including our proposal. The ONU energy consumption in a beacon interval is plotted in Fig. 4(b) for various traffic rates in case of the existing approaches with various sleep periods as well as our proposal. The result clearly shows that the energy consumption in the ONU using our proposed method is much lower than the short sleep period. In contrast with the sleep period of 5 ms, our proposed method reduces the energy consumption by more than a half. It is evident from the result depicted in Fig. 4(b) that the energy reduction is attributed largely to sleep periods. In our proposal, sleep periods are smartly kept similar to the beacon interval so that the energy consumption at the ONU is reduced significantly.

V. Conclusion

In this article, we introduced FiWi access networks as a promising technology to facilitate CPSs communication. We alsodiscussed how the lack of coordination or synchronization in QoS control policies and energy saving modes of the WLAN and PON technologies in FiWi networks can lead to substantial performance degradation, which can hamper the reliability and performance of the CPSs. We demonstrated how simple yet smart adjustments to combine these different standards in FiWi networks can improve the transmission delay and energy consumption. In future, with the emergence of next generation high-throughput WLAN standards such as IEEE 802.11ac, the gap between WLAN and PON specifications may increase even further. In such case, similar smart adjustments may be required to exploit the potential of FiWi access networks to facilitate efficient CPSs. Also, future investigation, on how to coordinate OLTs located on different ends of the high speed core network to further improve delay and throughput performance, may open up interesting research topics.

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Biographies

Zubair Md. Fadlullah [M’11] (zubair@it.ecei.tohoku.ac.jp) received B.Sc. degree with Honors in computer sciences from the Islamic University of Technology (IUT), Bangladesh, in 2003, and M.S. and Ph.D. degrees from the Graduate School of Information Sciences (GSIS), Tohoku University, Japan, in 2008 and 2011, respectively. Currently, he is serving as an Assistant Professor at GSIS. His research interests are in the areas of smart grid, network security, intrusion detection, game theory, and quality of security service provisioning mechanisms. He was a recipient of the prestigious Deans and Presidents awards from Tohoku University in March 2011 for his outstanding research contributions.

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Nei Kato [M’03,SM’05,F’13] (kato@it.ecei.tohoku.ac.jp) has been a full professor at GSIS, Tohoku University, since 2003. He has been engaged in research on satellite communications, computer networking, wireless mobile communications, smart grid, image processing, and pattern recognition. He has published more than 300 papers in peer-reviewed journals and conference proceedings. He is a distinguised lecturer of IEEE ComSoc, and a Fellow of IEICE. He currently serves as the Vice Chair of the IEEE Ad Hoc & Sensor Networks Technical Committee. His awards include Minoru Ishida Foundation Research Encouragement Prize (2003), Distinguished Contributions to Satellite Communications Award from the IEEE Communications Society, Satellite and Space Communications Technical Committee (2005), the FUNAI Information Science Award (2007), the TELCOM System Technology Award from Foundation for Electrical Communications Diffusion (2008), the IEICE Network System Research Award (2009), the IEICE Satellite Communications Research Award (2011), the KDDI Foundation Excellent Research Award (2012), IEICE Communications Society Distinguished Service Award (2012), IEEE GLOBECOM Best Paper Award (twice), IEEE WCNC Best Paper Award, and IEICE Communications Society Best Paper Award (2012).

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Naoto Yoshimoto received B.E., M.E., and Ph.D. degrees in electronics and information engineering from Hokkaido University, Japan, in 1986, 1988, and 2003, respectively. He joined NTT Corporation in 1988, and mainly engaged in the research and development of optical transmission systems and devices for broadband access systems. He is currently engaged in the planning of next-generation optical-wireless converged access networks and architectures. He is a vice president at NTT access network service systems laboratories. Dr. Yoshimoto is a member of the IEEE, and he has served the chair of technical sub-committee ”Access Network” in OFC2012 and OECC2013. He is also the visiting professor of Hokkaido University since 2010.