PONizing Wi-Fi for Fiber-to-The-Room Scenario: A Unified PON and Wi-Fi Access Based on PON MAC Protocol

Gangxiang Shen
School of Electronic and Information Engineering,
Jiangsu Engineering Research Center of Novel Optical Fiber Technology and Communication Network,
Suzhou key Laboratory of Advanced Optical Communication Network Technology,
Suzhou, P.R.China

Jun Li*
School of Electronic and Information Engineering,
Jiangsu Engineering Research Center of Novel Optical Fiber Technology and Communication Network,
Suzhou key Laboratory of Advanced Optical Communication Network Technology,
Suzhou, P.R.China
*ljun@suda.edu.cn

Yuxuan Chen
School of Electronic and Information Engineering,
Jiangsu Engineering Research Center of Novel Optical Fiber Technology and Communication Network,
Suzhou key Laboratory of Advanced Optical Communication Network Technology,
Suzhou, P.R.China

Jinhan Cai
School of Electronic and Information Engineering,
Jiangsu Engineering Research Center of Novel Optical Fiber Technology and Communication Network,
Suzhou key Laboratory of Advanced Optical Communication Network Technology,
Suzhou, P.R.China

Tianhai Chang
Huawei Technologies Co., Ltd.,
Shenzhen, P. R. China

***Abstract*—We propose a unified PON and Wi-Fi access scheme tailored for the fiber-to-the-room scenario, in which Wi-Fi access is PONized based on the PON protocol. The proposed scheme can significantly improve network access rate, resource utilization, and handover time, compared with a benchmark based on non-integrated PON and Wi-Fi access.**

Keywords—PON, Wi-Fi, network access rate, resource utilization, handover time

I. INTRODUCTION

The emerging broadband services impose high-bandwidth and low-latency requirements on the next-generation fixed networks (e.g., F5G). For example, more than 3-Gb/s bandwidth and less than 5-millisecond round-trip delay are required by cloud virtual reality (VR) games. To meet these stringent requirements, passive optical networks (PONs) are being extended from home to rooms, forming a new application scenario, i.e., Fiber to The Room (FTTR) [1]. In this scenario, a millimeter-wave (mmWave) based access point (AP) with high bandwidth (e.g., more than 10 Gb/s) is being introduced by cascading it with an FTTR terminal [2] for high and deterministic bandwidth. Here the rapid degradation of mmWave signal in long-distance transmission and significant loss due to wall penetration are no longer the bottlenecks. Rather, the surrounding walls of each room provide isolation to eliminate interference between different APs, thereby improving wireless channel quality. However, although mmWave shows great potentials to provide high data rate, it also brings a big challenge to support seamless roaming when stations (STAs) move across rooms. This is because a mmWave AP can hardly sense the existence of other mmWave APs, which disables the existing Wi-Fi roaming protocol based on signal sensing [2]. As such, the mobile STAs have to compete to access a target AP by using the Wi-Fi random access mechanism, thereby leading to a high delay and degraded user experience. To solve this issue, a centralized controller is needed to coordinate all the mmWave APs deployed in different rooms. However, how to integrate PON with mmWave-enabled Wi-Fi to support the centralized control and management in the FTTR scenario is still a new research topic without much exploration.

In this paper, we propose a unified PON and Wi-Fi access architecture and mechanism tailored for the FTTR scenario. Different from the existing Wi-Fi random access mechanism, the Wi-Fi access is PONized based on the PON protocol and the bandwidth allocation and roaming of mobile STAs are implemented in a centralized way. Simulation results show that the proposed scheme can significantly outperform a benchmark based on non-integrated PON and Wi-Fi access in the aspects of network access rate, resource utilization, and handover time.

II. UNIFIED PON AND WI-FI ACCESS ARCHITECTURE

Figure 1(a) shows a high-level unified PON and Wi-Fi access architecture, in which a mmWave AP is connected with an optical network unit (ONU), and the latter is further connected with an optical line terminal (OLT). Fig. 1(b) shows the data and control planes of the proposed architecture. The data plane consists of a wireless segment (i.e., Wi-Fi) and an optical segment (i.e., PON). In the wireless segment, a physical (PHY) function is deployed at both mmWave APs and STAs, which can use existing Wi-Fi PHY layer protocols. Specifically, orthogonal frequency division multiplexing access (OFDMA) is employed, and wireless spectrum resources are divided into multiple orthogonal sub-channels (i.e., resource units) and can be allocated to different STAs. Here concurrent multi-user (MU) transmissions are employed and therefore resource competition due to the random access can be avoided. In addition, OFDMA is also employed in PONs [3] and the PON PHY function is deployed at the OLT and ONUs. In this case, there is a mapping process between optical subcarriers and wireless subcarriers (see the middle of Fig. 1(b)), which forms wireless-optical subcarriers. The existing Wi-Fi medium access control (MAC) protocol (e.g.,

XXX-X-XXXX-XXXX-X/XX/$XX.00 ©20XX IEEE

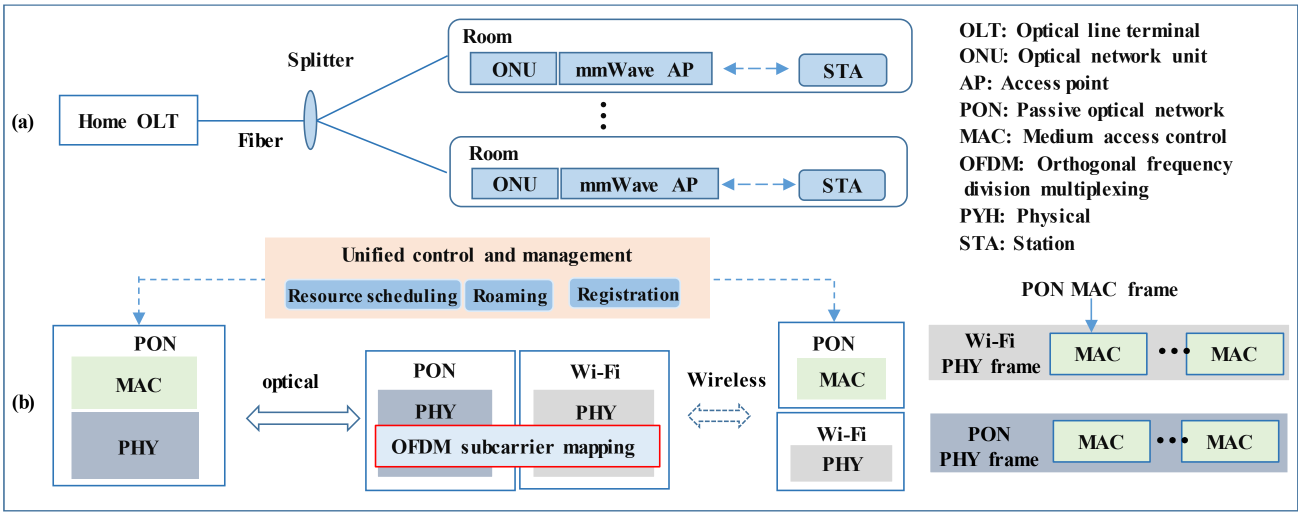

Fig. 1. Illustration of the centralized wireless-optical access network architecture

the random access mechanism) is operated in a distributive way, which poses a big challenge on Wi-Fi to provide a deterministic network performance. On the other hand, in the FTTR scenario, the mobility of STAs is low and therefore there are low probabilities for STAs to randomly access wireless channels of a mmWave AP. This motivates us to propose the adoption of the PON MAC mechanism for the mmWave AP access (i.e., PONizing Wi-Fi) for better control of quality of service. Compared with the traditional Wi-Fi, PONized Wi-Fi can schedule resources in a centralized way, thereby eliminating uncertainty due to the random access. Moreover, PONizing Wi-Fi can unify the heterogenous access networks to form a unified two-level PON-like network, in which a unified PON MAC protocol can be implemented at OLT, ONUs, and STAs, and various management functions including registration, resource scheduling, and roaming can be centralized at the OLT. To establish a deterministic end-to-end physical communication tunnel in the integrated network, and to schedule the wireless-optical subcarriers in a unified way, a centralized MAC function can be implemented to allocate resources in the wireless and optical segments.

III. Operational Principle

Figure 2 shows the operational principle of the proposed unified architecture. First, a newly joining STA needs to register with the OLT before it can transmit data. To avoid impacting the quality of service of existing STAs, a dedicated optical-wireless subcarrier (i.e., registration subcarrier) is reserved for the registration function. Each newly joining STA sends a registration frame to the OLT via the registration subcarrier. If there is a collision (i.e., more than one STA are registering), the STA will try again until it succeeds. Since the number of STAs in a room is usually small and the registration window is large (i.e., the whole subcarrier), the failure probability of the registration is generally low. Once the STA is registered successfully, the OLT will start to allocate wireless-optical subcarriers based on the buffer states and services' priorities of all the registered STAs. Again, because the number of STAs in a room is small, a newly joining STA has a very high chance of getting the required subcarrier resource. When there are not sufficient available wireless-optical subcarriers, the OLT can dynamically reallocate resources to the STAs according to their priorities and send Grant messages to inform the involved STAs.

As STAs may roam, they need to handover from the current AP to a target AP. The central controller is also responsible for the roaming function, which monitors channel conditions between the STA and its associated AP and triggers the handover. Once the handover is made, the OLT will stop sending downstream data and send a Hanover message to the STA, which contains the information on the allocated subcarriers at the target AP. Here, different from a

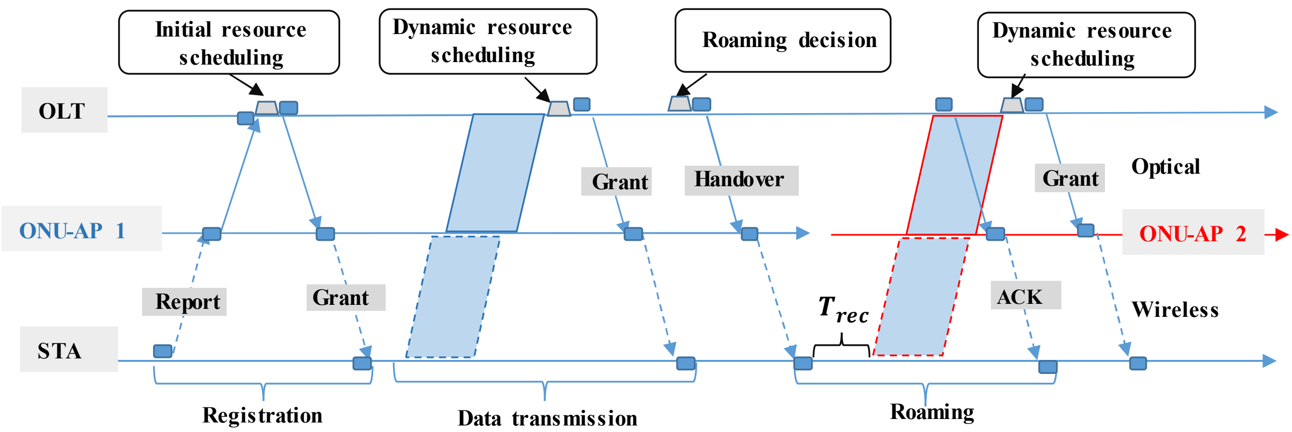

Fig. 2 Illustration of operation principle of the centralized control and management

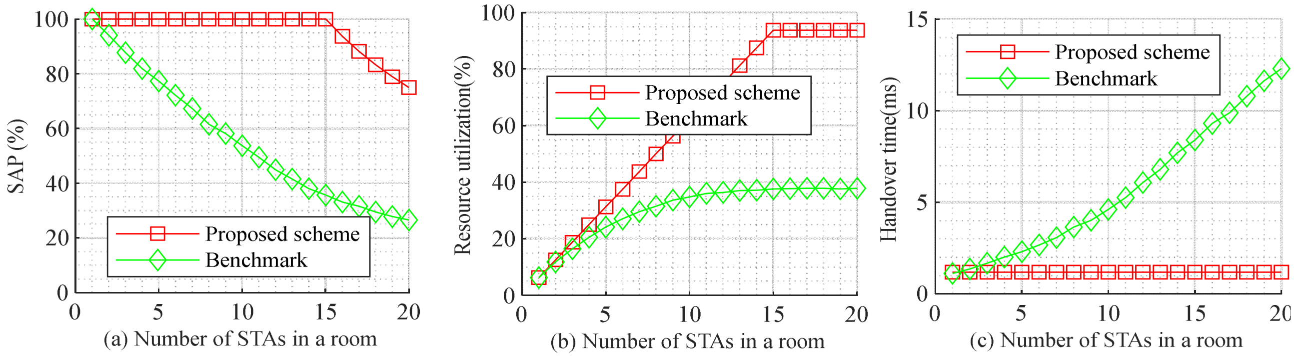

Fig. 3: (a) Successful access probability (SAP); (b) Resource utilization; (C) Handover time.

newly joining STA, the STA involved in the handover will be given a higher priority of resource allocation so as to keep the continuity of its service. After receiving the Handover message, the STA will stop sending upstream data and shift its connection from the source AP to the target AP, which takes a time of $Trec$. The latter will send an ACK to the STA once receiving the header of the data frame to inform that the new connection is established successfully. Otherwise, the STA needs to connect the target AP through a new registration procedure. Since there are few STAs in rooms, in most cases, a STA can handover seamlessly without experiencing a new registration.

IV. Performance Evaluation

The performance of the proposed scheme and a benchmark based on non-integrated PON and Wi-Fi access is evaluated by simulations. In the benchmark, wireless segment (i.e., Wi-Fi) and wireline segment (i.e., PON) are managed independently. In addition, uplink OFDMA random access (UORA) mechanism introduced as a new feature in Wi-Fi 6 [4] is used for Wi-Fi. Without a central controller, when STAs roam, they need to suspend their connections from the current AP and compete to access the target AP following the UORA mechanism.

In the simulations, the number of rooms is eight, and each room is equipped with one ONU-AP that provides 16 resource units (RUs). In the FTTR scenario, since STAs often support bandwidth-intensive services, their buffers are assumed to be always full. Each STA is assumed to allocated with one RU that consists of multiple optical-wireless subcarriers, which is set according to services' bandwidth requirement. T_{rec} is set to 1 ms. The length of a Wi-Fi PHY frame is 3.84 *ms*, and the other parameters used in the UORA mechanism are the same as those in [4]. There are a random number (fewer than a half of STAs in a room) of roaming STAs.

Figure 3(a) shows that the probability of a STA that successfully accesses the network (i.e., SAP) in both the proposed scheme and the benchmark. We note that the proposed scheme can achieve about 100% SAP when N is less than 16 thanks to the dedicated registration channel. Its SAP decreases when N is larger than 16 due to the limited number of available RUs. Compared with the proposed scheme, the SAP of the benchmark significantly decreases with an increasing N. This is because the STAs compete to obtain RUs based on the UORA mechanism and collisions occur when more than one STA competes to access the same RU. In addition, because a RU incurred with a collision cannot be used, a low resource utilization (i.e., less than 40%) is suffered by the benchmark, as shown in Fig. 3(b). In contrast, because the proposed scheme schedules resources in a centralized way, it improves the resource utilization significantly, up to 90% when N is larger than 15.

We also compare the handover times of the proposed scheme and the benchmark. We note that the benchmark has a sharply increased handover time with an increasing N, which can be more than 10 *ms*. This is because the STAs involved in handover need to compete with other STAs to access the network. For a large N, the STAs need to compete for several rounds to successfully access the network, thereby leading to a high handover time. In contrast, the central controller of the proposed scheme allocates RUs for the STAs involved in handover at a higher priority, which therefore enables the STAs to successfully connect their target APs quickly and reduce the handover time, which is significantly short, at around 1 *ms*.

V. Conclusion

For the FTTR scenario, we proposed a unified PON and Wi-Fi access architecture and mechanism by PONizing the Wi-Fi access. In the new architecture, a PON-based registration is implemented for each STA, and centralized scheduling and roaming management are employed to allocate bandwidth (i.e., OFDM subcarriers) and roaming for each STA, respectively. Simulation studies show that the proposed architecture can provide a significantly improved quality of service with a much higher network access rate (i.e., SAP) and resource utilization and a much lower handover latency, compared with the non-integrated PON and Wi-Fi access.

Acknowledgment

The work is supported by National Nature Science Founding of China (62101372), Open Fund of IPOC (BUPT, IPOC2022A07), and State Key Laboratory of Advanced Optical Communication Systems and Networks (2023GZKF11).

References

[1] ITU-T Technical Paper, "Use cases & requirements of fiber-to-the-room (FTTR)," *GSTP-FTTR ITU-SG15*, Apr. 2021J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[2] C. He et al. "Millimeter-wave wireless communications for home network in fiber-to-the-room scenario," Frontiers of Information Technology& Electronic Engineering, 2021, 22(4):441-456.

[3] W. You, "Randomized dynamic bandwidth allocation algorithm for upstream access in OFDMA-PON," IEEE/OSA Journal of Optical Communications and networking, vol. 7, no. 6, pp. 597-601, Jun. 2015.

[4] L. Lanante, H. O. T. Uwai, Y. Nagao, M. Kurosaki and C. Ghosh, "Performance analysis of the 802.11ax UL OFDMA random access protocol in dense networks," in Proc. IEEE International Conference on Communications (ICC), pp. 1-6, May 20.