Centralized Wi-Fi Access Networks over OFDM-PON with Joint System Load-based Resource Scheduling

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***Abstract*—We propose centralized Wi-Fi access networks over orthogonal frequency division multiplexing (OFDM) passive optical network, in which optical and wireless resources are jointly scheduled based on system load to improve resource utilization.**

Keywords—PON, Wi-Fi, random access, resource utilization, latency

I. INTRODUCTION

IEEE 802.11 ax-based wireless local area network (i.e., Wi-Fi 6) employs the orthogonal frequency division multiple access (OFDMA) mode to provide gigabit access for users [1]. To guarantee quality of service (QoS), multiple access point (Multi-AP) cooperation (e.g., coordinated OFDMA) is also considered in the next generation Wi-Fi network (i.e., Wi-Fi 7) [2]. To efficiently support this Multi-AP cooperation, one promising way is to centralize the medium access control (MAC) layer and higher layers in a central entity, forming a centralized Wi-Fi access network (i.e., C-WAN) [3]. C-WAN is similar to the traditional cloud radio access network (C-RAN) in cellular networks [4], in which the fronthaul has stringent requirements of high bandwidth and low latency. However, in C-WAN, the latency requirement is less than 16 microseconds [5], much lower than that of C-RAN. It is difficult for time division multiplexing passive optical network (TDM-PON) to meet such a stringent requirement. Meanwhile, although wavelength division multiplexing (WDM) PON can achieve a low latency, allocating each access point (AP) with a dedicated wavelength using a pair of transceivers would be very costly.

In this paper, we propose to realize C-WAN based on OFDM-PON to avoid dedicated transceivers as in WDM-PON. For efficient resource utilization, we specifically develop a joint system-load based resource scheduling scheme to allocate optical and wireless subcarriers adaptively based on the actual system load, which depends on the Wi-Fi random access mechanism and the number of wireless stations (STAs). Simulation results show that the proposed scheme can significantly improve resource utilization without sacrificing the performance of access latency. To the best our knowledge, little research has been conducted on how to centralize Wi-Fi access network over OFDM-PON, and in particular, how to efficiently map optical subcarriers to wireless subcarriers is still an open research problem. Thus, this is the first work focusing on this research perspective.

II. CENTRALIZED WI-FI ACCESS NETWORK OVER OFDM-PON

Figure 1(a) shows an overall architecture of C-WAN over OFDM-PON. In the PON segment, an AP is connected to an optical network unit (ONU), which is further connected to an optical line terminal (OLT). In APs, the physical-layer (PHY) function is implemented with the MAC-layer function deployed in a centralized Wi-Fi server (or a centralized Wi-Fi AP, co-located with the OLT), as shown in Fig. 1(b). The STAs are implemented with full functions of the Wi-Fi protocols, where MAC frames are encapsulated into PHY frames. Once STAs successfully access wireless channels, their PHY frames are transmitted directly via dedicated subcarriers to their corresponding AP (the middle AP, co-located with an ONU), which are further forwarded to the centralized Wi-Fi AP via the OFDM-PON uplink. Here, the AP co-located with ONU is simplified to relay PHY frames only. The centralized AP will de-encapsulate these Wi-Fi PHY frames into MAC frames and respond ACK frames to the STAs via the relay of the middle AP. Here, the time interval between sending Wi-Fi PHY frames by a STA and receiving ACK frames by the STA is defined as short inter-frame space (SIFS), and is set to be 16 μs according to the Wi-

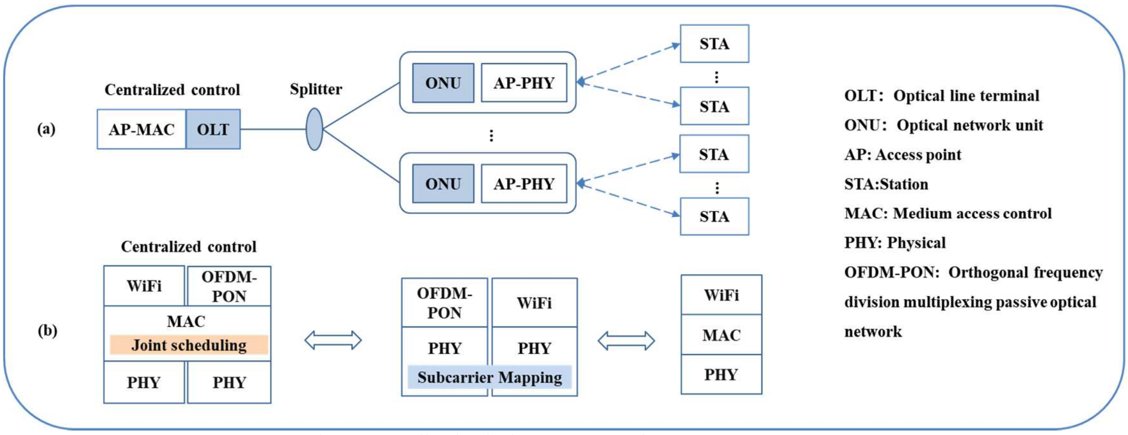

Fig.1. Centralized Wi-Fi access networks over OFDM-PON.

Fi standards [6]. To meet such a low latency requirement, a straightforward way is to deploy PHY-layer function only at ONUs and the OLT in the OFDM-PON, where the Wi-Fi PHY frames are only encapsulated into OFDM-PON frames without via the OFDM-PON MAC function so that the processing time of encapsulation can be reduced.

The throughput of Wi-Fi depends on the Wi-Fi access mechanism and stations' actual traffic demands that vary with time. If simply employing a fixed subcarrier allocation strategy to carry APs' traffic in the OFDM-PON, its network resources can be wasted. Therefore, to tackle this issue, a joint MAC-layer function should be implemented at the centralized AP to jointly schedule Wi-Fi and OFDM-PON resources according to the actual traffic demands. We next introduce such a joint system load-based resource scheduling scheme.

III. Joint System Load-based Resource Scheduling

In the Wi-Fi network, the spectrum resources are divided into multiple orthogonal sub-channels (i.e., resource units, RUs), which can be allocated to different STAs, thereby enabling concurrent multi-user (MU) transmissions. The Wi-Fi MAC-layer function coordinates the downlink and uplink MU transmissions. For the uplink, an OFDMA-based random access (UORA) mechanism is employed, in which STAs access RUs randomly based on competition. According to [7], the probability that a STA can successfully access the Wi-Fi network is represented as

$$\tau = \begin{cases} 1, W_{max} - 1 < R; \\ \frac{2R}{A}, W - 1 > R; \\ \frac{2R}{B}, W - 1 < R < W_{max} - 1 \end{cases} \tag{1}$$

where R is the number of RUs that can be provisioned by each AP and W is the size of OFDMA contention window (OCW). W_{max} is the maximum value of W. Terms A and B are calculated by Eqs. (2) and (3), respectively [7].

$$A = W\frac{1-p-p(2p)^m}{1-2p} + R - 2 + \frac{2R}{W}\cdot\frac{1-p+\frac{p}{2}(\frac{p}{2})^m}{1-\frac{p}{2}} \tag{2}$$

$$B = A - W\frac{1-p-(2p)^{c+1}+p(2p)^{c+1}}{1-2p} + (R+2)(1-p^{c+1}) - \frac{2R}{W}\cdot\frac{1-p-\left(\frac{p}{2}\right)^{c+1}+p\left(\frac{p}{2}\right)^{c+1}}{1-\frac{p}{2}} \tag{3}$$

where p is the collision probability, $c = \lfloor log_2(R) \rfloor$ is the last OFDMA back-off (OBO) stage when the contention window is smaller than R, and m is the maximum value of the back-off stage. If all the RUs are uniformly selected during the random access, p can be calculated as

$$p = 1 - (1 - \tau/R)^{n-1} \tag{4}$$

where n is the number of STAs associated with each AP. Then, the average number of RUs utilized can be calculated as

$$r = n \cdot \tau \cdot (1 - \tau/R)^{n-1} \tag{5}$$

It can be seen from (5) that r mainly depends on the parameters of (n, R, m, W). To meet the stringent latency requirement, the minimum number of RUs actually used at the AP must be no smaller than r, represented by

$$g = \lceil \alpha \cdot R \rceil \geq r \tag{6}$$

where α is the system load at the AP ($\alpha \in [0,1]$), calculated as $\alpha = r/R$. Then, the minimum number (k) of optical subcarriers (i.e., transmission units, TUs) allocated to the each AP in the OFDM PON must provide capacity just greater than that of g RUs, represented by

$$\lceil \beta \cdot k \rceil \geq g \tag{7}$$

where β is the ratio of the capacities between each optical subcarrier and each wireless subcarrier. Note that if there are not sufficient TUs to carry the traffic from each AP, some of STAs associated with the AP can be denied for delivering their traffic over the OFDM-PON, even though they may have accessed the Wi-Fi network successfully.

Based on the above equations, we further propose a system load-based resource scheduling algorithm, i.e., **Algorithm 1**, in which TUs and RUs are scheduled jointly and periodically. Specifically, at the beginning of each period, the number of utilized RUs at each AP can be calculated using Eqs. (1)-(6) based on a certain set of parameters (n, R, m, W). Then, the

Algorithm 1: System Load-Based Algorithm

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Input: n_i, m_i, R_i, W_i; i ∈ {1,2,..L}
For i = 1: L     //L is the number of ONU-APs
  Calculate r_i and g_i according to Eqs. (1)-(6);
  Calculate k_i according to Eq. (7);
End for
U ← Σ_{i=1}^{L} k_i;
If U ≤ T
  G_i ← k_i;
Else if
  G_i ← ⌊(T/U) × k_i⌋;
End if
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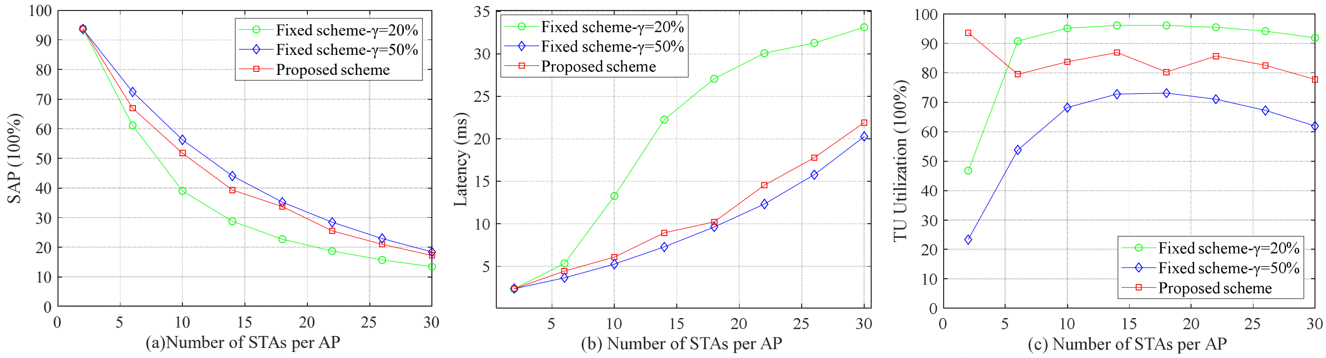

Fig. 2. (a) SAP versus the number of STAs per AP; (b) Latency versus the number of STAs per AP; (c) TU utilization versus the number of STAs per AP.

number of TUs required by each ONU-AP in the current period can be calculated by Eq. (7), which can further be used to find the total number of TUs required by all the ONU-APs in the OFDM-PON. If this total number is smaller than the total number of TUs that can be provided by the OFDM-PON, then these ONU-APs are allocated with sufficient TUs according to their requirements. Otherwise, they will be allocated with the OFDM-PON's system capacity proportional to their bandwidth requirements.

IV. Performance Evalution

To verify the effectiveness of the proposed scheme, simulations are conducted using MATLAB. The total number of OFDM-PON TUs is 64, and the total number of RUs provisioned by each AP is 16. Assume that the capacity of each TU is equal to that of a RU, i.e., $\beta = 1.0$. The maximum OCW is set to be 127, and the minimum OCW is set to be 0. The maximum value of the back-off stage is set to be 7. The transmission opportunity (TXOP) is set to be 3.84 ms. TXOP defines the time duration, in which a station can send frames. The PHY preamble length is set to be 40 μs and the Trigger frame length is set to be 100 μs. The multi-user block-Ack length is set to be 68 μs and the SIFS time is set to be 16 μs. We consider two TU allocation schemes in the OFDM-PON, i.e., the fixed scheme and system load-based schemes. The fixed scheme means that each ONU-AP is statically allocated with a fixed number of TUs, while the system load-based scheme allocates TUs based on the actual system load.

We first evaluate the successful access probability (SAP) of the different schemes. Fig. 2(a) compares the SAP for the fixed and system load-based resource allocation schemes. We note that the SAP decreases with an increasing number of STAs per AP. This is because a large number of STAs contending to access the wireless channel would lead to more collisions. Also, comparing the different schemes, we note that the system load-based scheme has a SAP similar to that of the fixed scheme with γ=50% RUs utilized at each ONU-AP, and a higher SAP than that of the fixed scheme with γ=20% RUs utilized at each ONU-AP. This is because, according to [7], the maximum RU utilization in the Wi-Fi network is about 37% for a large number of STAs. Therefore, when γ is assumed to be 50%, the number of TUs allocated is sufficient for carrying STAs' traffic, no matter how many STAs try to access the Wi-Fi network. In contrast, when γ is assumed to be 20%, TUs allocated are insufficient to carry the traffic, which causes the STAs that successfully join the wireless network to fail to access the OFDM-PON capacity. The proposed system load-based scheme finds the actual system load α and adjusts the number of TUs adaptively according to the actual traffic demands from different STAs, which therefore leads to a SAP very close to that of the fixed case with γ=50%.

We also compare the access latency of the different schemes in Fig. 2(b). Similar to the results in Fig. 2(a), as the number of STAs per AP increases, the access latency becomes longer. In addition, when γ=20%, its access latency is longer than the other two cases, and there is little difference between the system load-based scheme and the fixed scheme with γ=50%. The reason is similar to that of the SAP performance.

Finally, we compare the TU utilization of all the three cases as shown in Fig. 2(c). It is noted with an increasing number of STAs, the utilization of TUs increases at the beginning, saturates later, and finally drops slightly under the fixed scheme. This is because the number of TUs allocated to each ONU-AP is fixed. When the number of STAs increases, more resources are used and therefore the utilization increases. Then, due to the limited network resources, the number of STAs connecting to each AP reaches saturation gradually, and when the number of STAs further increases, the access competition in the Wi-Fi network becomes more severe, which leads to a higher collision probability, thereby less actual STAs' traffic demand and a slightly lower TU utilization. It is also noted that the utilization of the fixed scheme with γ=20% is higher than that of the fixed scheme with γ=50%. This is because insufficient TUs are allocated in the fixed scheme with γ=20%, which leads to a higher utilization. In contrast, the TU utilization of the system load-based scheme is quite stable with little difference under different numbers of STAs. This is because the proposed scheme adjusts the number of allocated TUs according to the actual traffic demand of different STAs, thereby enabling to balance the performance of access delay and TU utilization. In addition, the system load-based scheme has a TU utilization higher than that of the fixed scheme with γ=50% and lower than that of the fixed scheme with γ=20%, when the number of STAs is larger than 5. This is because the numbers of TUs allocated under different number of STAs just fall in between the fixed scheme with γ=50% and γ=20%, thereby leading to the TU utilization falling between the two cases.

V. Conclusion

To support multi-AP cooperation, we proposed a centralized Wi-Fi access network over OFDM-PON, based on which a joint system load-based scheduling scheme was further developed. Simulation results show that, compared with the fixed resource scheduling scheme, the proposed system load-based scheme can significantly improve the utilization of optical subcarrier resources and support more APs without affecting the performance of access latency.

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REFERENCES

[1] E. Khorov, A. Kiryanov, A. Lyakhov, and G. Bianchi, "A tutorial on IEEE 802.11ax high efficiency WLANs," IEEE Communications Surveys & Tutorials, vol. 21, no. 1, pp. 197-216, Firstquarter 2019.

[2] A. Garcia-Rodriguez, D. López-Pérez, L. Galati-Giordano, and G. Geraci, "IEEE 802.11be: Wi-Fi 7 strikes back," IEEE Communications Magazine, vol. 59, no. 4, pp. 102-108, Apr. 2021.

[3] X. Wu, Y. Zeng, X. Si, X. Wang, and X. Liu, " Fiber-to-the room (FTTR): standards and deployments," in Proc. 2023 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 2023, pp. 1-3.

[4] C. Pan, M. Elkashlan, J. Wang, J. Yuan and L. Hanzo, "User-centric C-RAN architecture for ultra-dense 5G networks: challenges and methodologies," IEEE Communications Magazine, vol. 56, no. 6, pp. 14-20, June 2018.

[5] S. Naribole, W. B. Lee, and A. Ranganath, "Impact of MU EDCA channel access on IEEE 802.11ax WLANs," in Proc. 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), Honolulu, HI, USA, 2019, pp. 1-5.

[6] IEEE standard for information technology--telecommunications and information exchange between systems local and metropolitan area networks--specific requirements Part 11: wireless LAN medium access control (MAC) and physical layer (PHY) specifications amendment 1: enhancements for high-efficiency WLAN, in IEEE Std 802.11ax-2021 (Amendment to IEEE Std 802.11-2020) , vol., no., pp.1-767, 19 May 2021.

[7] 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. 2017 IEEE International Conference on Communications (ICC), Paris, 2017, pp. 1-6.