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A Hybrid Fiber-Femtocell Indoor Network to Support Low-Latency and High-Bandwidth Indoor Communication Applications

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***Abstract*—Indoor networks carry most mobile user activities and industrial communication practices. Beyond 5G (B5G), ultra-responsive and high-capacity indoor networks will be increasingly demanded by sectors such as manufacturing, healthcare, edutainment and many others. The need of indoor networks of low latency and high capacity drives passive optical networks, a traditional wide-area access technology, to synergize with wireless networks inside premises. The feasible network architecture and management strategies are in open exploration. In this study, we investigate a hybrid fiber-femtocell indoor network architecture and propose a flexible temporal and spatial bandwidth sharing (FTSS) scheme in supporting the low latency and high capacity required by B5G applications. In specific, we exploit short-range inter-connections among room optical network units integrated with femtocells (ONU-FBSs) to achieve efficient indoor network traffic delivery. The FTSS facilitates direct local traffic exchange among ONU-FBSs and collaborative uplink traffic delivery by the ONU-FBSs not needing central coordination. In this way, the latency and capacity performance of the network are improved. With modeling analysis and simulations, we evaluate the performance of the hybrid network with FTSS to carry indoor traffic in comparison with existing solutions.**

***Index Terms*—B5G indoor communications, ultra-reliable and low-latency communications, fiber-to-the-room, fiber-femtocell integration**

I. Introduction

INDOOR networks are critical in beyond 5G (B5G) network evolution since most user activities and industrial practices happen indoors [1]. Social sectors, such as industrial manufacturing, healthcare and edutainment, envision paradigm shifts brought by diverse B5G applications that need to be supported by ultra-low-latency and high-capacity networks inside buildings and premises. Take the next-generation manufacturing as an example. The emerging factory networks need stringent low latency in milliseconds to succeed real-time human-to-machine interactions, extended reality applications [2]. Capacity needs upgrading in order to sustain complex applications and device connections, e.g., massive Internet of Things (IoT), robots and sensor devices and applications [3]. Not limited to such industrial scenarios, improving indoor network latency and capacity is widely necessitated to empower future user applications and daily experiences, such as in smart campuses and homes [3].

Recently, the integration of passive optical networks (PONs) and femtocell networks has emerged as a promising solution for indoor networks that require superior latency, capacity, and reliability performance. Femtocell is a key wireless technology for high data rate indoor mobile coverage, while its backhaul, i.e., communications among room femto base stations (FBSs), remains an issue due to high-frequency signal blockage caused by obstacles [4]. With PONs and fiber-wireless (FiWi) integration, commonly adopted for wide-area access networks, are being considered indoors, the indoor wireless backhaul can be ideally consolidated [5]–[10].

A. State of the art

State-of-the-art indoor FiWi integration, including the fiber-femtocell networks as in [11] and [12], mainly adopts a point-to-multi-point (P2MP) configuration. As illustrated by Fig. 1, multiple optical network units (ONUs) link with a gateway optical line terminal (OLT) at the premise edge in a $1 \times N$ optical splitter. Further, by co-locating computing and content resources at the edge, indoor application quality of service can be improved [13]. As recognized by existing studies [6], [14], the P2MP architecture is cost-effective but may meet bottlenecks in capacity and latency as entire network traffic needs to traverse the OLT. Local traffic exchange among wireless front ends consumes both uplink and downlink bandwidth. In addition, in the uplink, the OLT adopts dynamic bandwidth allocation (DBA) to allocate bandwidth to ONU in a report-then-grant procedure [15], which incurs waiting time to the uplink packets. In light of these issues, viable indoor FiWi architectural solutions are worth exploring.

Though majority of indoor FiWi architectures are in P2MP form, ring and hybrid networks with inter-ONU links have received attention in wide-area FiWi access networks [17]–[20]. Different architectures impact how bandwidth resources are utilized and hence yield different network latency and

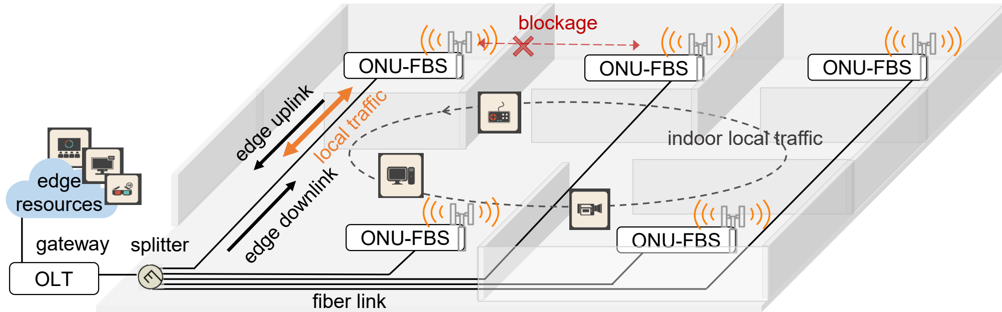


Fig. 1. An illustration of a typical indoor fiber-femtocell network solution. ONUs are integrated with FBSs and connected to the gateway OLT in P2MP configuration.

capacity performance. For example, when ONUs are interconnected, the studies [21]- [23] designed decentralized DBA schemes to coordinate ONUs' transmissions. In decentralized DBA, exchanging control messages among ONUs and/or synchronization are required, which may increase the delay of packets at ONUs. Alternately, ONUs can spatially reuse the common link, e.g., in [18], [19]. In [20], the authors comprehensively investigated a hybrid FiWi network to handle LTE and WiFi offloaded traffic with inter-ONU links. Note that in contrast to typical access networks that have long reaches and support numerous ONUs, indoor networks are featured by short spans, e.g., less than 200 m links, and a small number of ONUs, e.g., fewer than 10 [3], [5]–[7]. Architectures to exploit the unique indoor network features are yet to be fully considered.

B. Contributions

In this paper, we investigate a hybrid indoor fiber-femtocell architecture that leverages the short inter-connections among ONUs to integrate with distributed FBSs (ONU-FBSs) towards achieving high-capacity and low-latency indoor network performance. A flexible temporal and spatial bandwidth sharing (FTSS) scheme is proposed to coordinate uplink, downlink and indoor local traffic. The FTSS facilitates direct ONU-FBS mutual traffic exchange and collaborative uplink traffic delivery to the OLT via flexibly using the inter-connections, thereby improving the network latency and capacity performance. We summarize the main contributions of this paper:

- The first architectural and performance study of an indoor hybrid fiber-femtocell network for emerging low-latency and bandwidth-intensive application scenarios.
- Proposal of FTSS scheme that takes advantage of indoor short-range ONU-FBSs links to achieve indoor local traffic exchange and ONU-FBS collaborative uplink delivery.
- Latency and capacity modeling and simulation evaluations. Results show that the FTSS adjusts the traffic loads splitting on different links to reduce latency. Performance improvement is compared with existing solutions.

In the rest of this paper, Section II presents the proposed hybrid network and FTSS scheme. Analytical latency and capacity performance modeling are in Section III. Section IV includes simulation results. Finally, we conclude in Section V.

II. Hybrid Fiber-Femtocell Indoor Network

A. Hybrid architecture

We consider a hybrid fiber-femtocell architecture as illustrated in Fig. 2. The ONU-FBSs are mutually connected in a ring. Meanwhile, the OLT connects with N numbers of ONU-FBSs in P2MP via a splitter. In this case, one transceiver is needed by the OLT and an ONU-FBS for uplink and downlink communication using two different wavelengths, i.e., μ_{up} and μ_{down} in Fig. 2. Another transceiver is adopted by ONU-FBSs to send and receive packets clockwise using wavelength μ_{local} in the ring. As shown in Fig. 2, to coordinate traffic in the hybrid network, an ONU-FBS has a local buffer to store packets from the wireless network and an optical transit buffer to transit packets coming from the ring similar as in [19] and [18]. To prevent packet collision, we consider the transit buffer to be able to hold at least two maximum-length packets. This allows the ONU-FBS to identify the idle interval between two consecutive transit packets. A locally buffered packet can be sent in the idle interval without colliding with a transit packet. In this way, transit packets have a fixed delay, which is the time to pass the transit buffer, instead of being stopped and queued by the ONU-FBS for collision avoidance.

In the hybrid architecture, we propose the FTSS scheme for utilizing bandwidth resource. Indoor local traffic among ONU-FBSs is exchanged in the ring in μ_{local}, avoiding consuming uplink and downlink bandwidth. Downlink traffic occupies μ_{down}. To reduce uplink latency caused by uplink bandwidth contention, the FTSS scheme enables ONU-FBSs to utilize μ_{up} and μ_{local} for uplink flexibly. The underlying principle is to facilitate ONU-FBSs collaboratively deliver uplink packets to the OLT exploiting the ring. We detail the operations next.

B. Flexible temporal and spatial bandwidth sharing

In the FTSS scheme, ONU-FBSs spatially reuse bandwidth in the ring to exchange local traffic and assist each other in uplink traffic delivery. The key operations involve:

- **Time division multiplexing (TDM) in μ_{up}**: In the uplink direction, TDM by assigning fixed uplink time slots (TSs) to ONU-FBSs is adopted. The time duration of a TS for an ONU-FBS is denoted by T_s. Uplink packets destined

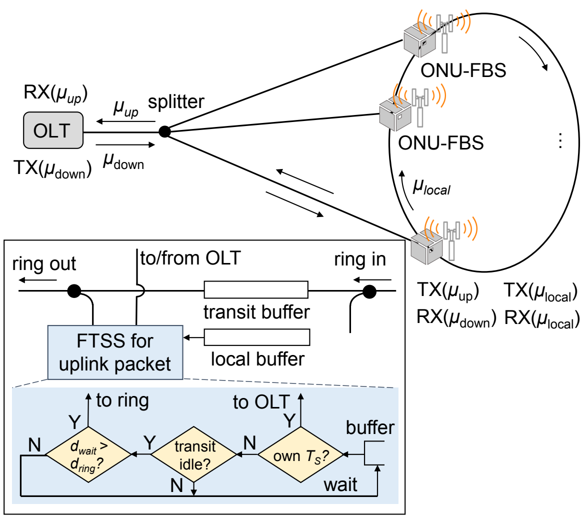


Fig. 2. An illustration of the hybrid fiber-femtocell architecture and FTSS operations for uplink packets link decision. (TX: transmitter; RX: receiver)

to the OLT can be transmitted in a TS and ONU-FBSs assist each other in sending uplink packets.

- **Spatial bandwidth reuse (SBR) in** μ_{local}: An ONU-FBS can send packets in first-in-first-out (FIFO) rule into the ring given there is idle space identified in the transit buffer as mentioned above. When transit packets pass through, an ONU-FBS receives and removes the packets destined to it from the ring. Indoor local packets are exchanged only in the ring, while ONU-FBSs can decide whether to send an uplink packet into the ring, as detailed next.
- **Collaborative uplink delivery**: For a head-of-line (HoL) uplink packet at the local buffer, an ONU-FBS decides if to keep the packet waiting for its own TS or to send the packet in the ring, depending on which delay would be smaller. When the ONU-FBS with available TS identifies that an uplink packet is transiting through, it forwards the transit packet to the OLT first. Then, it transmits its HoL uplink packet for collision avoidance.

With the above operations, packets put on the ring traverse the ring in sequence until they reach their destinations. As such, the traveling time of a packet on the ring can be precisely known. Fig. 2 illustrates the decision flow for uplink packets. We detail the decision criterion by characterizing the latency in different path choices next. The latency in this letter refers to the time interval upon a packet is first stored at the source ONU-FBS until it is received by its destination, which includes the packet queuing time, transmission time and link propagation time.

C. FTSS decision criterion

To keep a HoL uplink packet waiting for a TS will adds delay to the all packets buffered behind. In this case, we estimate the average latency of buffered packets, denoted by d_{wait}. Alternatively, when the HoL packet travels to an ONU-FBS with available TS using the ring, the latency is denoted by d_{ring}. The FTSS compares the d_{wait} and d_{ring} for a decision.

We estimate d_{wait} by assuming uplink packets are delivered to the OLT in TDM only. In this case, the best-case TDM latency of buffered packets is counted, neglecting the transit uplink packets. The reason lies in that an ONU-FBS cannot know when uplink packets from other ONU-FBSs will transit to utilize its TS. Specifically, given an HoL uplink packet of an ONU-FBS and the current time t_0, let us suppose the next available TS for the ONU-FBS starts at time t_{start} and there are α uplink packets buffered behind. In TDM, a packet may have to wait multiple cycles before its turn to transmit. Hence, consider that the i-th buffered packet will be sent in the β_i-th TS after t_0, and there are N ONU-FBSs in total. The latency of the i-th packet, termed d_i, can be computed[1]:

$$d_i = t_{start} - t_0 + (\beta_i - 1)(T_s + T_{guard})N + t_{\beta_i} + T_{prop}, \quad (1)$$

where T_{guard} is the guard time between two adjacent ONU-FBSs' transmission and T_{prop} is the propagation time from an ONU-FBS to a neighbor ONU-FBS or the OLT. The t_{β_i} in (1) represents the time since the start of the β_i-th TS until the i-th packet is transmitted. Using (1), d_{wait} of waiting for TSs to send packets can be estimated by:

$$d_{wait} = \frac{1}{\alpha} \sum_{i=1}^{\alpha} d_i. \quad (2)$$

Next, we characterize the latency if an ONU-FBS chooses to transit a HoL uplink packet in the ring. Denote the transmission completion time of the HoL packet as t_{hol} and the time for a packet to transit through an ONU-FBS as $T_{transit}$. Then, the $t_{hol} + k(T_{transit} + T_{prop})$ is the time that the packet transits through the k-th ONU-FBS after the source one. If this time is within the start and end time of the k-th ONU-FBS's TS and the residual TS time is enough for the packet, uplink packet delivery by the k-th ONU-FBS is possible. As the packet goes through ONU-FBSs in order, the smallest k indicates where the packet will be delivered to the OLT. With the k-th ONU-FBS for uplink delivery, the d_{ring} can be estimated by:

$$d_{ring} = t_{hol} + kT_{transit} + (k+1)T_{prop}. \quad (3)$$

In the FTSS scheme, an ONU-FBS compares the best-case TDM latency estimate d_{wait} in (2) and d_{ring} in (3) to decide where to send the uplink packets. As exemplified in Fig. 2, if $d_{ring} < d_{wait}$, a HoL uplink packet of an ONU-FBS will be sent in the ring since the latency of delivering this packet by another ONU-FBS with TS available is smaller. Otherwise, the ONU-FBS waits for its own TS to send the packet to the OLT. In the next section, we analytically justify the performance.

D. Network parameters

We consider a set $\mathcal{N} = \{1, 2..., N\}$ of ONU-FBSs in a ring in sequence and a gateway OLT at the premise edge. Three types of network traffic, i.e., indoor local, uplink and downlink

[1] In FTSS, the capital notations, T, N, are for network parameters and small t, d, α, β are for realizations, e.g., buffer status upon making decisions.

traffic, have arrival rates λ_l, λ_u and λ_d, respectively. For a tractable analysis, Poisson arrivals and balanced ONU-FBS traffic are assumed. That is, indoor local and uplink arrival rates at an ONU-FBS are λ_l/N and λ_u/N, respectively. A local packet of an ONU-FBS n destinates to an ONU-FBS $m \in \mathcal{N}, m \neq n$, in an equal probability. Performance considering other possible indoor traffic models will be included in future extensions of this paper. The first and second moments of a packet's transmission time are $\overline{S}$ and $\overline{S^2}$. The loads of the three types of traffic are $\rho_l = \lambda_l\overline{S}$, $\rho_u = \lambda_u\overline{S}$ and $\rho_d = \lambda_d\overline{S}$, respectively.

E. Latency and capacity performance

As the downlink from OLT to ONU-FBSs is in a broadcast fashion, we derive the average downlink latency as follows.

Proposition 1. *In the proposed hybrid fiber-femtocell network, the average latency of downlink traffic from the gateway OLT to ONU-FBSs, denoted by D_d, is expressed as:*

$$D_d = \frac{\lambda_d\overline{S^2}}{2(1-\rho_d)} + \overline{S} + T_{prop}. \tag{4}$$

Proof. It is straightforward to model the downlink queuing time by a M/G/1 queue with arrival rate λ_d [24]. The latency in (4) sums the queuing, transmission and propagation time. ■

From (4), the hybrid network can accept a downlink traffic load $\rho_d = \lambda_d\overline{S} < 1$. This is intuitive since $\rho_d \geq 1$ incurs accumulated packet queue and thus a large latency D_d. Next, we analyze the latency of indoor local and uplink traffic by assuming T_s is large enough such that ONU-FBSs whose TSs are unavailable prefer transiting uplink packets in the ring. Note that to accurately and tractably model the latency with different T_s is challenging. We consider this assumption to draw theoretical insights as in indoor networks, a TDM cycle $(T_s + T_{guard})N$ is typically greater than the ring transit time with short links, e.g., in a few tens or hundreds of meters.

Given ONU-FBSs choose to send uplink packets in the ring due to inaccessible TS, Lemma 1 derives the aggregated uplink and indoor local packet arrival rate to an transit buffer in ring.

Lemma 1. *Given available uplink time slot at the m-th ONU-FBS, the aggregated uplink and indoor local packet arrival rate to the transit buffer at the n-th ONU-FBS, $\forall n \neq m \in \mathcal{N}$, denoted by $\eta_m(n)$, is expressed as:*

$$\eta_m(n) = \frac{\mathbb{1}_{\{n<m\}} \times N + (n-m-1)}{N}\lambda_u + \frac{(N-2)}{2N}\lambda_l, \tag{5}$$

in which $\mathbb{1}_{\{\bullet\}}$ is an indicator function.

Proof. An ONU-FBS generates uplink packets in a rate λ_u/N, and indoor local packets in a total rate $\lambda_0(N-1)$ with $\lambda_0 = \lambda_l/\{N(N-1)\}$ to each ONU-FBS in the rest. Given a source ONU-FBS, the local traffic rate is deducted by λ_0 after the traffic passes through an ONU-FBS. Consider the n-th ONU-FBS to transit local traffic of the rest $(N-1)$ ONU-FBSs. It outputs the traffic generated by the (n-1)-th ONU-FBS in rate $\lambda_0(N-2)$, and traffic of the (n-2)-th in rate $\lambda_0(N-3)$, and so forth. By Kleinrock approximation, the aggregated arrival rate output at the n-th ONU-FBS is derived as $\frac{(N-1)}{2N}\lambda_l$. Further, counting the uplink rates from ONU-FBSs derives (5). ■

The right two terms in (5) present the transit uplink and local arrival rates aggregated from $(N-1)$ ONU-FBSs at an ONU-FBS n, respectively. The local packet rate is irrelevant to n under the balanced traffic assumption, while the aggregated uplink packet rate depends on the ONU-FBS's position, i.e., index n. Moreover, with $\frac{(N-1)}{2N}\rho_l$ load of local traffic transiting through an ONU-FBS, each ONU-FBS sees local traffic load $\rho_l/2$ after adding ρ_l/N-load local traffic of its own. This implies the ring can accommodate $\rho_l > 1$, attributed to the spatial bandwidth sharing by ONU-FBSs. We detail the capacity discussion in the following modeling.

The $\eta_m(n)$ in (5) indicates the aggregated arrival rate to a transit buffer. A locally-buffered packet at an ONU-FBS has to wait for the pass of transit packets and the transmission of packets buffered ahead of it. In Propositions 2 and 3, we characterize the average latency of uplink and local traffic.

Proposition 2. *Given large uplink time slot duration in the FTSS scheme, the average latency of uplink traffic from ONU-FBSs to the OLT, denoted by D_u, can be approximated as:*

$$\begin{aligned} D_u =& \frac{1}{N}\sum_{n=1}^{N-1}\frac{(n\lambda_u/N + \lambda_l/2)\overline{S^2}}{2\{1-(n\rho_u/N+\rho_l/2)\}} + \frac{\lambda_u\overline{S^2}}{2N(1-\rho_u)} \\ &+ \overline{S} + \frac{(N-1)}{2}T_{transit} + \frac{(N+1)}{2}T_{prop}. \end{aligned} \tag{6}$$

Proof. Given arrivals to the transit buffer with rate $\eta_m(n)$ in Lemma 1 and arrivals to a local buffer at rate $(\lambda_u+\lambda_l)/N$, the queuing latency of packets in the local buffer at the n-th ONU-FBS can be characterized by a M/G/1 queue with aggregated rate $\eta_m(n) + \frac{(\lambda_u+\lambda_l)}{N}$. We term the average queuing latency, as $Q_m(n)$, which can be approximated by:

$$Q_m(n) = \frac{(\eta_m(n) + (\lambda_u+\lambda_l)/N)\overline{S^2}}{2\{1-(\eta_m(n)+(\lambda_u+\lambda_l)/N)\overline{S}\}}. \tag{7}$$

Averaging the $Q_m(n)$ over all n, m yields the average uplink queuing latency. Here, the reference ONU-FBS m is trivial since in TDM, each ONU-FBS has an equal chance to have its TS available. This allows us to replace m by N, i.e., the N-th ONU-FBS to deliver uplink packets to the OLT. The average queuing delay is derived as the sum of the first and second terms on the right-hand side of (6). Once a packet is sent in the ring, it experiences fixed $T_{transit}$ and T_{prop} to pass an ONU-FBS. The uplink packets from the n-th ONU-FBS go through $(N-n)$ ONU-FBSs to reach the OLT. ■

The term $\frac{(n\lambda_u/N+\lambda_l/2)\overline{S^2}}{2\{1-(n\rho_u/N+\rho_l/2)\}}$ in (6) estimates the queuing delay of the n-th ONU-FBS when the local and uplink traffic split the ring capacity. The denominator conveys the aggregated load on the ring shall meet $(N-1)\rho_u/N + \rho_l/2 < 1$ to prevent buffer and queuing delay from exploding. In addition, regarding the uplink, the network can carry $\rho_u < T_s/(T_s + T_{guard})$ subject to the TDM mechanism. The hybrid network capacity, i.e., the acceptable ρ_u and ρ_l, is addressed with the above two inequalities. In Proposition 3, we further provide the average latency of indoor local traffic.

Proposition 3. *Given large uplink time slot duration in the FTSS scheme, the average latency of indoor local traffic among ONU-FBSs, denoted by D_l, can be approximated as:*

$$D_l = \frac{1}{N}\sum_{n=1}^{N-1}\frac{(n\lambda_u/N+\lambda_l/2)\overline{S^2}}{2\{1-(n\rho_u/N+\rho_l/2)\}}+\frac{\lambda_l\overline{S^2}}{2N(2-\rho_l)} + \overline{S} + \frac{(N-2)}{2}T_{transit} + \frac{N}{2}T_{prop}. \quad (8)$$

Proof. The indoor local packets experiences the same queuing latency as the uplink packets in (7), except that at the m-th ONU-FBS, only local packets are sent into the ring. ■

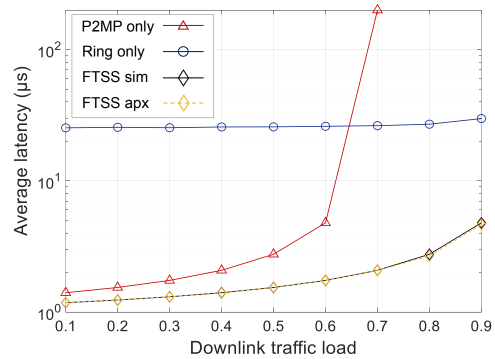
The results in (6) and (8) indicate the latency and capacity when one ONU-FBS aggregates and delivers uplink traffic to the OLT given a long T_s duration. We extend the discussion on the impact of T_s. The T_s setting changes the uplink traffic load on the ring as it determines the TDM latency. When TDM delay is large, ONU-FBSs would split more uplink traffic to the ring. This helps reduce the uplink latency, but as a trade-off, the ring capacity is consumed and the latency of local traffic may increase. Simulation evaluation is presented next.

III. Simulation Evaluation

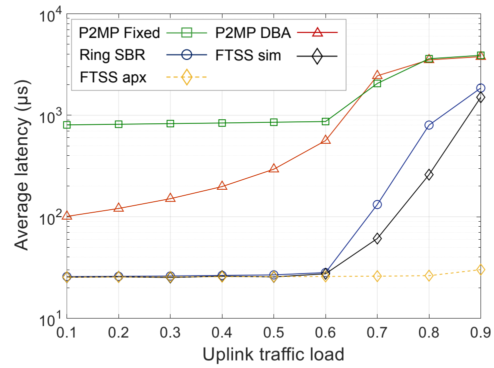
In event-driven network-level simulations in MATLAB, we evaluate the performance of the hybrid network with FTSS. We simulate a symmetric 10G-EPON with $N = 8$ ONU-FBSs. The propagation time in individual links is $T_{prop} = 0.5\mu s$, i.e., $100m$ link distance. The guard time $T_{guard} = 5\mu s$ in uplink transmissions and a transit time $T_{transit} = 5\mu s$ in the ring are considered. Packets are within 64 bytes - 1518 bytes. The hybrid network with FTSS is compared with the P2MP and a pure ring network. In the P2MP network, two bandwidth allocation schemes are considered, i.e., classic DBA in gated service [15] and TDM in a fixed T_s as in FTSS.

Fig. 3 shows the latency and capacity performance, where a fixed indoor local traffic load $\rho_l = 0.3$ and downlink and uplink loads from 0.1 to 0.9 are considered. A $T_s = 2ms$ is adopted in FTSS. The average downlink latency is presented in Fig. 3a. In the P2MP network, local traffic consumes downlink bandwidth, causing higher latency than in the hybrid network. The pure ring network has the highest downlink latency, primarily because packets have to transit through ONU-FBSs. With $\rho_l = 0.3$, the P2MP network carries downlink traffic loads up to 0.7, less than that in the ring and hybrid network. The result in (4) accurately characterizes the downlink latency.

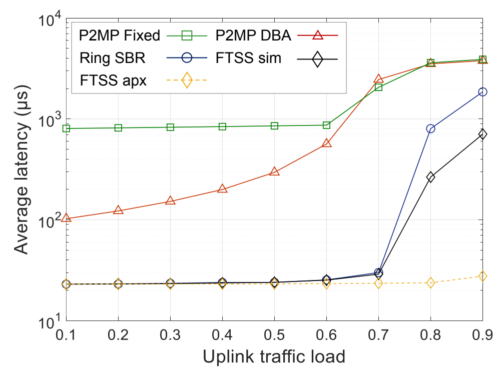
Figs. 3b and 3c present the average uplink and indoor local traffic latency, which also reflect the capacity performance of the compared solutions to carry different traffic loads. First, the latency is the highest in the P2MP network in fixed TSs due to the long waiting time of packets for slots. DBA helps reduce the latency, which is still higher than that in the ring and hybrid network due to the report-grant process. The ring and hybrid



(a) downlink traffic latency



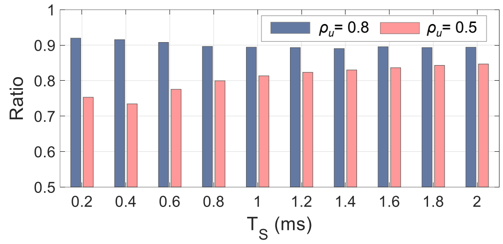
(b) uplink traffic latency



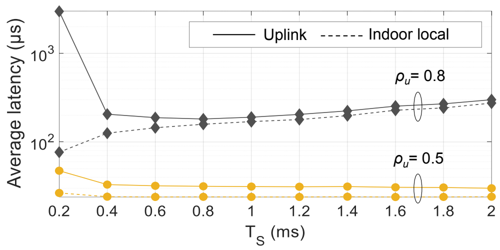
(c) indoor local traffic latency

Fig. 3. Latency and capacity performance comparisons. (ρ_d, ρ_u from 0.1 to 0.9 and $\rho_l = 0.3$; $T_s = 2ms$)

networks show similar latency in light and medium loads up to 0.6. As the uplink loads increase, FTSS keeps a lower latency. Overall, the FTSS reduces uplink latency by over 5 times than the use of DBA for indoor FiWi networks. Regarding the capacity performance, given 0.3 load local traffic, the P2MP network saturates when the uplink load is 0.7. The hybrid network with FTSS is capable to carry about 0.9 uplink load together with the local traffic attributed to the spatial reuse of the ring. The theoretical results in (6) and (8) closely approximate the simulated latency under traffic loads less 0.6. In heavy loads, queuing processes at ONU-FBSs deviate from the M/G/1 model when long packet sequences occupy the ring



(a) ratio of uplink traffic in ring



(b) latency performance

Fig. 4. Ratio of uplink traffic in ring and latency in FTSS with different T_s. ($\rho_l = 0.3$ and $\rho_u = [0.5, 0.8]$)

[24]. Thus, the model results deviate, which is similar to the findings reported in studies [18], [19].

Fig. 4 details the impacts of T_s in FTSS. Two uplink traffic load cases, i.e., $\rho_u = 0.5$ and 0.8 are considered for illustrative purposes. As above analyzed, T_s impacts the ratio of uplink traffic that transits in the ring. Fig. 4a shows that a T_s too small or too large may increase this ratio. This is because a small T_s can lead to long packet queues at ONU-FBSs, while a large T_s means a long waiting time for an available slot. In Fig. 4a, the ratio under $\rho_u = 0.8$ is higher due to heavy queues. The average latency of uplink traffic and indoor local traffic are shown in Fig. 4b. A $0.2ms$ T_s is not enough to cater to $\rho_u = 0.8$ and thus increasing T_s at first reduces the uplink latency. To keep increasing T_s increases both the uplink and indoor local traffic primarily due to the long packet train in the ring. In comparison, in $\rho_u = 0.5$, longer T_s reduces the uplink latency with negligible local traffic latency increase.

IV. Conclusions

This paper studied a hybrid fiber-femtocell network towards supporting B5G low-latency and high-capacity communication performance in indoor application scenarios. With short inter-ONU-FBS connections in a ring form and the FTSS scheme, efficient local traffic exchange and collaborative uplink traffic delivery by ONU-FBSs to reduce uplink latency are facilitated. Extensive simulations verified the ability of the hybrid network to support higher network traffic loads at lower latency compared to the typical solutions.

V. Acknowledgement

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