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On AP Assignment and Transmission Scheduling for Multi-AP 60 GHz WLAN

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***Abstract*—Millimeter-wave communication in 60 GHz band is considered a promising technology to meet the explosive growth of data demand in Wi-Fi based WLAN. To address potential blockage for 60 GHz signals, multiple APs are proposed for such WLAN. This paper addresses the important problem of AP assignment and transmission scheduling for a multi-AP 60 GHz WLAN. We propose two AP assignment schemes with different complexity and study how to maximize user throughput with joint consideration of AP assignment and transmission scheduling. We advocate to use one-shot AP assignment-based scheduling due to its simplicity for implementation. To address real-time online traffic and human blockage, we propose an online algorithm to implement the one-shot AP assignment scheme without altering the AP assignment for other existing users. Through performance evaluation, we show that the proposed online algorithm is competitive when compared to the offline algorithm.**

***Keywords*-60 GHz WLAN; AP assignment; transmission scheduling.**

I. Introduction

Wi-Fi based WLAN has been widely regarded as a key technology to enable today's information based economy. But with the universal deployment of Wi-Fi and increasing traffic demand from existing and new applications, radio spectrum allocated to Wi-Fi (i.e., 2.4 GHz/5 GHz) has become overloaded. Recently, wireless communications on the mmWave band have been considered for WLAN [18]. In particular, there is 7 GHz of unlicensed spectrum available at 60 GHz, and if utilized efficiently, can fundamentally resolve spectrum shortage for Wi-Fi networks.

Comparing to 2.4 and 5 GHz radio spectrum, radio propagation in the 60 GHz spectrum has some unique properties. First, due to small wavelength, radio propagation in the 60 GHz regime suffers significant loss in free space [12], [15]. To combat such severe attenuation, high-gain directional antennas at both transmitter and receiver are necessary for successful transmission [5]. Further, due to limited diffraction property, 60 GHz signals are vulnerable to blockage (e.g., furnitures, walls, and human body) [11].

A number of approaches have been proposed to address the limitations of 60 GHz for WLAN, including leveraging NLOS signals for data transmission [3], [16], employing relay nodes and use multi-hop communications to get around the blockage [8], [11], and MAC-layer integration of 2.4/5 GHz and 60 GHz spectrum [2], [9] so that users can fall back to legacy Wi-Fi bands when 60 GHz LOS links are not available. In a WLAN environment, one approach that appears most promising is to deploy multiple 60 GHz APs in the same area. There are a number of benefits with this approach. First and foremost, multiple APs offer more potential for a possible LOS path between a user and an AP, which can help address the blockage problem.[1] Second, multiple APs allow concurrent transmissions between users and APs (with directional transmission and reception), which can balance traffic load and improve network throughput.

This paper considers multiple APs for 60 GHz WLAN and addresses two most important problems in this setting: *AP assignment* and *transmission scheduling*. When multiple APs are available, matching between APs and users is critical for network performance. When multiple transmissions can occur simultaneously in a multi-AP WLAN, transmission scheduling is needed for interference management and throughput maximization. This is particular important for an indoor environment. Unlike an outdoor open environment where interference between 60 GHz directional links is negligible [10], mutual interference between links in an indoor environment cannot be ignored due to higher user density and multiplicity of APs in a small area [14]. There have been some separate studies on the AP assignment problem for 60 GHz network [1], [17] and on the transmission scheduling problem for D2D communications in 60 GHz WPAN [8], [13], [14]. Based on the results in these prior efforts, we believe that AP assignment and transmission scheduling are deeply intertwined and an optimal performance of a 60 GHz WLAN can only be achieved when they are jointly considered and optimized.

In this paper, we study AP assignment and transmission scheduling for a multi-AP 60 GHz WLAN under a centralized control architecture. Centralized control architectures have been proposed in [4], [7] and were shown to be feasible to coordinate multiple APs in practice. Under such an architecture, all APs are connected to a centralized controller via high speed wired connection and the centralized controller makes the optimal AP assignment and transmission scheduling decisions based on inputs about active users in the network. Under such an architecture, this paper makes the following contributions:

- We study two AP assignment schemes of different complexity, namely per-time slot AP assignment and one-shot AP assignment. For either AP assignment strategy, we consider downlink communication and

[1] In the case when a LOS path does not exist between a user and any of the APs, the user can fall back to legacy Wi-Fi (i.e., 2.4 GHz or 5 GHz) [18].

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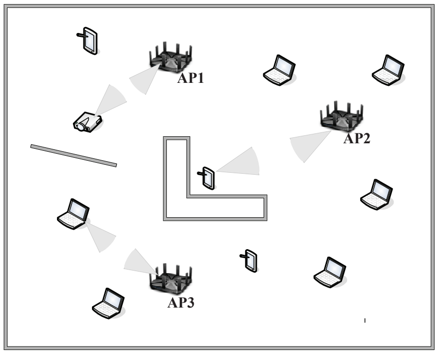


Figure 1: An indoor area that is being served by multiple APs.

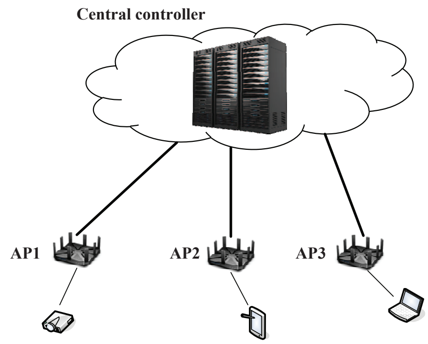


Figure 2: A centralized architecture to control the operation of multiple APs in the area.

develop an optimization problem with the objective of maximizing the minimum throughput among all users. In both schemes, the AP assignment is jointly optimized with transmission scheduling. Interference avoidance is considered as a constraint in all formulations by allowing only non-interfering links to be active simultaneously in a time slot.

- We show that per-time slot AP assignment-based scheduling algorithm only has marginal improvement in throughput performance compared with one-shot AP assignment-based scheduling algorithm. This result is interesting as it suggests that we should adopt one-shot AP assignment in practice due to its low complexity in implementation. Note that per-time slot AP assignment is not practical for implementation due to its extremely high requirement on beam steering for directional antennas.
- To take into consideration of user arrival/departure and potential human blockage over time, we design an online one-shot AP assignment algorithm. The online algorithm optimizes AP assignment for a new arrival or newly blocked user (a change in LOS), while keeping the AP assignment for other existing users intact. We show that the performance of the proposed online algorithm is competitive when compared with the offline algorithm.

The remainder of this paper is organized as follows. In Section II, we present a control architecture for multi-AP 60 GHz WLAN. In Section III, we describe our throughput maximization problem for multi-AP 60 GHz WLAN. In Section IV,we present the mathematical modeling and formulation of two AP assignment strategies. In Section V, we present numerical results and analyze the results. In Section VI, we propose an online algorithm for one-shot AP assignment and present its performance. Section VII concludes this paper.

II. Network Architecture

In this section, we present a system architecture for 60 GHz WLAN with multiple APs. Consider an indoor 60 GHz WLAN shown in Fig. 1, with multiple APs serving the users in the area. Since 60 GHz signals are vulnerable to blockage, we consider obstacles such as cubical walls, furniture, human, etc., as shown in Fig. 1. In 60 GHz channel, NLOS paths suffer severe attenuation and therefore the resulting data rate is not comparable with data rates over the LOS paths. Moreover, the received signal strength is further influenced by complicated multipath effect which is difficult to characterize in a general form. Therefore, we focus on LOS communications in 60 GHz band. That is, an AP can communicate with a user only when there exists a LOS path between them. As a result, some user may not have LOS path to any AP in the area. In these cases, the user will fall back to communications on a lower frequency band (i.e., 2.4 GHz or 5 GHz) [18]. In this paper, we only consider those users that have LOS path to at least one AP in the area.

On the control plane, we employ a centralized controller in the back-end which has direct high speed connection with each of the APs in the area (see Fig. 1). Such centralized control is becoming feasible and popular in recent years (see [4], [7]) due to wide deployment of 10 GHz Ethernet as well as HPC I/O optimized servers. With wide deployment of 10 GHz Ethernet and the emergence of petascale computing, it is expected that many existing applications built on distributed computing will migrate into centralized cloud-based computing and benefit from a centralized control architecture.

During initial AP discovery phase, an AP transmits multiple beacon frames, each on a different sector so as to cover all possible directions. Then users who have LOS path toward the AP can receive the beacon and respond [18]. Subsequently, each AP (user) will have knowledge of the LOS users (APs). Since 802.11ad standard for 60 GHz communication adopts TDMA MAC protocol for data transmission [18], we consider a time-slotted system. Under a centralized control architecture, it is not difficult for the central controller to synchronize the clocks of all APs and users in the network. The central controller will perform all AP assignment and scheduling decisions based on the input from APs. Upon finding an optimal AP assignment and scheduling solution, the central controller will convey this information to all APs, who will then notify all users in the area.

III. Problem Statement

There are some unique challenges for scheduling transmission in the 60 GHz regime.

First, due to directional transmission and the small number of APs, only a small number of users can be served in a time slot. This limitation calls for a scheduling solution for each time slot. Given that each user may have LOS paths to multiple APs, scheduling is not a trivial task.

Second, despite the directionality between 60 GHz transmitter and receiver, interference remains a concern in scheduling and must be addressed by a scheduling solution. This is because that a transmitter's beam may partially collide (overlap) an unintended receiver's reception beam towards another transmitter. Such interference, depending on the amount of beam alignment and overlap, may severely degrade the throughput of the unintended receiver. Therefore, a scheduling solution must also ensure that only non-interfering links are activated in the same time slot.

Finally, a scheduling solution should be designed and optimized for some performance objective, in addition to offering an interference-free matching between the APs and the users in each time slot. In this paper, we focus on throughput maximization.

Note that since 60 GHz communication is directional and sensitive to blockage by obstacles and human body, it is most suitable for a low mobility (static) environment. When there is significant change in topology and blockage, the central controller would have to re-optimize AP assignment and scheduling strategies, as discussed in Section VI.

Under the centralized control architecture, we explore two AP assignment and scheduling schemes:

- *Per-time slot AP assignment:* This is the most complex (and best performing) approach. Under this approach, the central controller decides the optimal matching between an AP and a user in each time slot for transmission. A user may be matched to different AP in different time slot. Clearly, this scheme is not practical for implementation, due to high requirement of beam steering on a very small time scale. So we only use this scheme as an ideal case to show the best possible performance that one could get from 60 GHz WLAN.
- *One-shot AP assignment:* As the name suggests, the "optimal" matching between a user and an AP is done in one-shot and their matching is permanent. That is, a user will communicate to the same AP during its communication session and the user cannot choose a different AP in different time slot. However, scheduling may be optimized in each time slot as it does not pose major technical issue. This approach is simpler than the per-time slot AP assignment and is likely to incur some compromise in performance. So the question is how much performance fall-off it will have (comparing to the per-time slot approach).

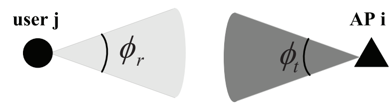


Figure 3: 2D radiation pattern for ideal flat-top antenna.

IV. Mathematical Modeling and Problem Formulation

To understand how the two scheduling algorithms discussed in the last section compare with each other, we study a user rate maximization problem and develop mathematical model for each algorithm. Denote $\mathcal{M}$ as the set of APs in the area and $M = |\mathcal{M}|$ is the number of APs. Denote $\mathcal{N}$ as the set of users in the network and $N = |\mathcal{N}|$ is the number of users. To model blockage, we randomly generate blockage in the network so that each user j only has LOS path to a subset of APs $\mathcal{A}_j$, i.e., $\mathcal{A}_j \subseteq \mathcal{M}$. Thus, user j can communicate with AP i only when $i \in \mathcal{A}_j$. On the AP side, denote $\mathcal{U}_i$ as LOS users for AP i. We employ time-slot based scheduling as in [18], with T time slots in a frame.

A. Per-time Slot AP Assignment

AP Selection Constraints We assume that a user can select at most one of its LOS APs for communication in each time slot. To model this scheduling behavior, we define binary variable $x_{ij}(t)$ to indicate whether or not AP i transmits to user j in time slot t. That is, $x_{ij}(t) = 1$ if AP i transmits to user j, and 0 otherwise. Under per-time slot AP assignment, user j can be served by at most one AP in a time slot. Then we have

$$\sum_{i \in \mathcal{A}_j} x_{ij}(t) \le 1 , \quad (j \in \mathcal{N}, 1 \le t \le T) . \tag{1}$$

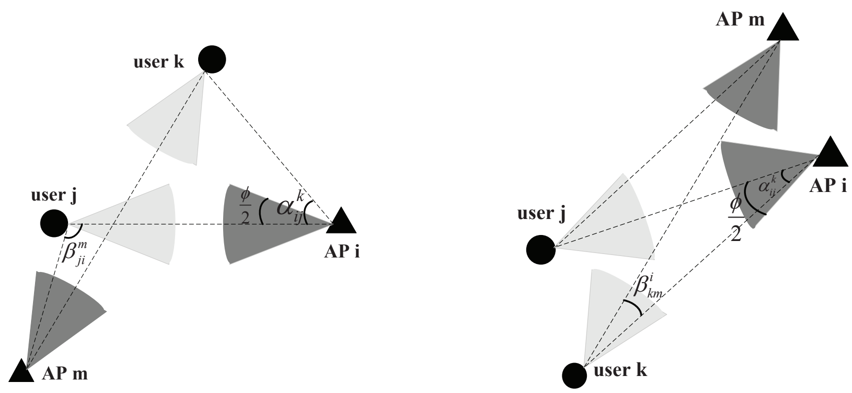
Transmission Scheduling Constraints Likewise, in each time slot, AP i can transmit to at most one of its LOS users. We have:

$$\sum_{j \in \mathcal{U}_i} x_{ij}(t) \le 1 , \quad (i \in \mathcal{M}, 1 \le t \le T) . \tag{2}$$

Interference Constraints Under the flat-top model [10] shown in Fig. 3, the dark gray beam (with a beamwidth of ϕ_t) represents the transmission beam from AP i; the light gray beam (with a beamwidth of ϕ_r) represents the reception beam from user j. In 3-dimension, the flat-top antenna is assumed to be symmetric about its beam-axis. So the horizontal and vertical beam widths are equal. Denote G_t as antenna gain of the transmitter. Then it can be approximated as [6]:

$$G_t = \frac{40000}{\phi_t^2} . \tag{3}$$

Under the ideal flat-top antenna model which has constant transmit/receive gain within its beamwidth and zero gain elsewhere, interference exists only when the receiver and interferer are located within each other's boresight. That is, we say that AP i interferes with an unintended user k *if*



(a) Two non-interfering links. (b) Two interfering links.

Figure 4: An example illustrating interference relationship under directional transmission and directional reception.

and only if the following conditions are satisfied: (i) user k is within the boresight of AP i, *and* (ii) AP i is within the boresight of user k. On the other hand, we say that AP i does not interfere with user k if (i) user k is outside the boresight of AP i, *or* (ii) AP i is outside the boresight of user k. To illustrate such interference relationships, consider the two examples in Fig. 4. In both examples, AP i transmits to user j and AP m transmits to user k. To simplify our discussion, we assume the beamwidth at transmit nodes (AP i and AP m) and receive nodes (user j and user k) are all ϕ.

- In Fig. 4(a), α_{ij}^k represents the angle between AP i to an unintended user k relative to the line connecting AP i and its intended user j. Likewise, β_{ji}^m represents the angle between user j to an unintended AP m relative to the line connecting user j and its intended AP i. As shown in the figure, AP i does not interfere with user k since user k is outside boresight of AP i ($\alpha_{ij}^k > \frac{\phi}{2}$). Likewise, AP m does not interfere with user j since, even though user j is within the boresight of AP m, AP m is outside the boresight of user j (i.e., $\beta_{ji}^m > \frac{\phi}{2}$). Therefore, these two links do not interfere with each other and can be activated in the same time slot.
- In Fig. 4(b), AP i interferes with user k since (i) user k is within the boresight of AP i ($\alpha_{ij}^k \le \frac{\phi}{2}$); and (ii) AP i is within the boresight of user k ($\beta_{km}^i \le \frac{\phi}{2}$). Likewise, AP m's transmission also interferes with non-intended receiver j. Therefore, these two links should not be activated in the same time slot.

To model the interference relationship, we introduce two indicator variables, one from transmit beam side and one from receive beam side. Define $I(\alpha_{ij}^k)$ as a binary variable to indicate whether or not user k is within the boresight of AP i when AP i transmits to user j. That is,

$$I(\alpha_{ij}^k) = \begin{cases} 1 & (\alpha_{ij}^k) \le \frac{\phi}{2}, \\ 0 & \text{otherwise.} \end{cases}$$

Similarly, define $I(\beta_{km}^i)$ as a binary variable to indicate whether or not AP i is within the boresight of user k when user k receives from AP m. That is, $I(\beta_{km}^i) = 1$ if $\beta_{km}^i \le \frac{\phi}{2}$ and 0 otherwise. By definition, AP i interferes with user k if and only if (i) user k is within the boresight of AP i, *and* (ii) AP i is within the boresight of user k. Then we have AP i interferes with user k if and only if $I(\alpha_{ij}^k)I(\beta_{km}^i) = 1$. Otherwise, AP i does not interfere with user k.

To ensure interference-free scheduling between any two transmissions in the area (i.e., two interfering transmissions do not occur in the same time slot), we must have:

$$\text{If } I(\alpha_{ij}^k)I(\beta_{km}^i) = 1, \text{ then } \; x_{ij}(t) + x_{mk}(t) \le 1$$

else, $x_{ij}(t)$ and $x_{mk}(t)$ are unconstrained (can be either 0 or 1). This is equivalent to

$$x_{ij}(t) + I(\alpha_{ij}^k)I(\beta_{km}^i)x_{mk}(t) \le 1 \;, \quad (i \in \mathcal{M}, j \in \mathcal{U}_i, k \in \mathcal{N}, m \in \mathcal{A}_k, 1 \le t \le T) \; . \tag{4}$$

Data Rate Constraints Denote c_{ij} as the achievable data flow rate from AP i to its LOS user j. Then we have:

$$c_{ij} = W \log_2 \left(1 + \frac{P_{ij}}{N_0 W}\right), \quad (i \in \mathcal{M}, j \in \mathcal{U}_i, 1 \le t \le T), \tag{5}$$

where W is the spectrum bandwidth, N_0 is noise power spectral density, and P_{ij} is power of directional transmission and can be obtained by the Friis transmission equation as follows:

$$P_{ij} = P_t G_t G_r (\frac{\lambda}{4\pi})^2 (d_{ij})^{-n}, \quad (i \in \mathcal{M}, j \in \mathcal{U}_i, 1 \le t \le T). \tag{6}$$

In (6), P_t is the transmission power, G_t and G_r are the antenna gain of directional transmit and receive antennas in (3), respectively, λ is the wavelength, d_{ij} is the distance between AP i to user j, and n is the path loss exponent.

Under a time-slotted scheduling system, transmission from AP i to user j may be active only on a subset of time slots in a frame. So the average transmission rate from AP i to user j can be calculated as follows:

$$r_{ij} = \frac{1}{T}\sum_{t=1}^{T} c_{ij}x_{ij}(t) \ , \quad (i \in \mathcal{M}, j \in \mathcal{U}_i, 1 \le t \le T) \ . \ (7)$$

Under per-time slot AP assignment, user j may be served by different APs in different time slots. So its data rate from all APs is,

$$r_j = \sum_{i \in \mathcal{A}_j} r_{ij} \ , \quad (j \in \mathcal{N}, 1 \le t \le T) \ . \qquad (8)$$

Problem Formulation Denote $r_{\min}$ as the minimum rate among all users in the network, then our problem can be formulated as follows:

OPT-P

max $r_{\min}$

s.t $r_{\min} \le r_j$ $(j \in \mathcal{N})$;

AP selection constraints: (1) ;

Transmission scheduling constraints: (2) ;

Interference constraints: (4) ;

Data rate constraints: (7), (8) .

In this formulation, $x_{ij}(t)$ are binary variables, r_{ij}, r_j and $r_{\min}$ are continuous variables. α_{ij}^k, β_{km}^i and c_{ij} are constants. We assume that all the APs and users in the network employ the same beamwidth ϕ, therefore, ϕ is a constant. Although the optimization problem is in the form of a mixed-integer linear program (MILP), a commercial solver such as CPLEX can solve such problem for the scale of a WLAN.

B. One-shot AP Assignment

Different from per-time slot AP assignment, under one-shot AP assignment scheme, the matching between a user and an AP is permanent and does not change on a per-time slot basis. This approach is much easier to implement in practice and has significant benefit on the upper layer as well (e.g., maintaining stability in a communication session).

Denote y_{ij} as a binary variable to indicate whether user j choose AP i for communication, i.e., $y_{ij} = 1$ if user j choose AP i for communication and 0 otherwise. Since user j is permanently assigned to one AP, we have

$$\sum_{i \in \mathcal{A}_j} y_{ij} \le 1 \ , \quad (j \in \mathcal{N}) \ . \qquad (9)$$

Even if $y_{ij} = 1$ (i.e., user j is assigned to AP i for communication), such transmission may not be active in each time slot t. We have

$$x_{ij}[t] \le y_{ij} \ , \quad (i \in \mathcal{M}, j \in \mathcal{U}_i, 1 \le t \le T) \ . \qquad (10)$$

That is, when $y_{ij} = 1$, $x_{ij}[t]$ may be 1 (active transmission) or 0 (idle); when $y_{ij} = 0$ (i.e., user j is not assigned to AP i), then $x_{ij}[t]$ must be 0.

Based on these updates, the problem formulation under one-shot AP assignment can be put forth as follows:

OPT-O

max $r_{\min}$

s.t $r_{\min} \le r_j$ $(j \in \mathcal{N})$;

AP selection constraints: (9) ;

Transmission Scheduling constraints: (2), (10) ;

Interference constraints: (4) ;

Data rate constraints: (7), (8) .

In this formulation, $x_{ij}(t)$ and y_{ij} are binary variables, r_{ij}, r_j and $r_{\min}$ are continuous variables. α_{ij}^k, β_{km}^i, ϕ and c_{ij} are constants.

V. Performance Evaluation

In this section, we compare the performance of two algorithms for AP assignment and transmission scheduling. For comparison, we also simulate a commonly used AP assignment approach where each user is matched to the AP with the strongest signal among all the APs. This is referred to as the strongest-signal AP assignment.

We show that the strongest-signal AP assignment-based scheduling algorithm offers poor performance, while per-time slot AP assignment offers the best performance. This shows that judicious matching between AP and user is critical in throughput performance. We also notice that the performance of one-shot AP assignment based scheduling is very close to per-time slot AP assignment based scheduling.

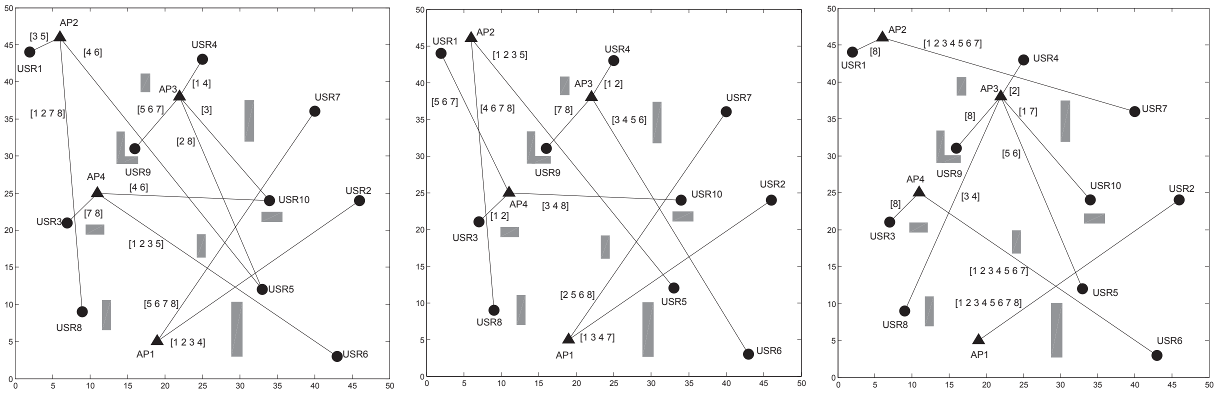
A. Simulation Setting

We consider an indoor environment where multiple 60 GHz APs are randomly deployed in a 50m × 50m area. We assume that each AP can cover this entire area through directional transmission when there is LOS. Following the parameters in [18], the transmission power at AP is 10 dBm, the bandwidth is 2.16 GHz, and the noise spectral density N_0 is -134 dBm/MHZ. The path loss exponent n is 2.3 [12]. We assume the beamwidth of all the APs and users are 30 degrees.

B. A Case Study

Before we present complete results in the following section, we present a case study to show some interesting details. In this case study, we have 4 APs and 10 users as shown in Fig. 5(a)–(c). In the figures, the gray blocks are randomly generated and represent the potential blockage in this area. Therefore, each user in the network may only have LOS access to a subset of APs. For example, user 1 has LOS path to AP 2 and AP 4, while it does not have LOS path to AP 1 and AP 3 due to blockage.

Suppose there are 8 time slots in a time frame. By solving the two optimization problems in the last section, we can find the AP assignment and transmission scheduling solution to each problem. Figures 5(a), (b), and (c) show the solution details under per-time slot AP assignment, one-shot AP assignment, and strongest-signal AP assignment based scheduling algorithms, respectively. The number inside the bracket next to each link represents the time slot in which the link is active. Table I lists the scheduling details for each



(a) Per-time slot AP assignment (b) One-shot AP assignment (c) Strongest-signal AP assignment

Figure 5: A network instance with 4 APs and 10 users.

Table I: Details of scheduling under three AP assignment schemes for a network with 4 APs and 10 users.

User	Per-time slot AP Assignment			One-shot AP Assignment			Strongest-signal AP Assignment		
	Timeslot	AP	rate (Gbps)	Timeslot	AP	rate (Gbps)	Timeslot	AP	rate (Gbps)
1	(3,5)	2	7.3	(5,6,7)	4	6.8	8	2	3.6
2	(1,2,3,4)	1	7.4	(1,3,4,7)	1	7.4	(1,2,3,4,5,6,7)	1	14.8
3	(7,8)	4	6.9	(1,2)	4	6.9	8	4	3.4
4	(1,4)	3	6.8	(1,2)	3	6.8	2	3	3.4
5	(4,6)	2	6.7	(1,2,3,5)	2	6.0	(5,6)	3	3.9
	(2,8)	3							
6	(1,2,3,5)	4	6.8	(3,4,5,6)	3	6.6	(1,2,3,4,5,6,7)	4	11.9
7	(5,6,7,8)	1	6.9	(2,5,6,8)	1	6.9	(1,2,3,4,5,6,7)	2	12.5
8	(1,2,7,8)	2	7.0	(4,6,7,8)	2	7.0	(3,4)	3	3.7
9	(5,6,7)	3	8.9	(7,8)	3	6.1	8	3	2.9
10	3	3	7.2	(3,4,8)	4	6.5	(1,7)	3	4.7
	(4,6)	4							

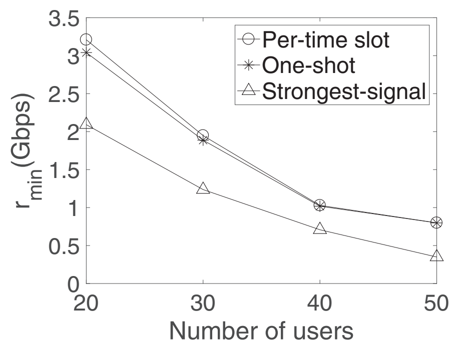


Figure 6: Maximum guaranteed user rate when the number of users increases from 20 to 50.

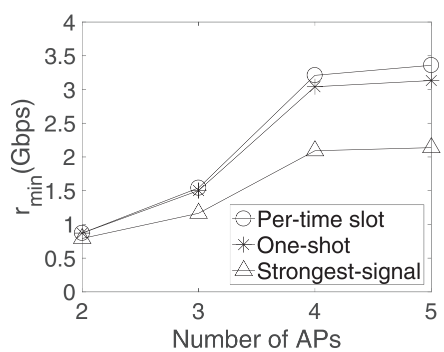


Figure 7: Maximum guaranteed user rate when the number of APs increases from 2 to 5.

user under the three AP assignment schemes, including the time slots in which it is active, to which AP it is assigned to, and its average rate over a frame. Note that under per-time slot AP assignment, a user may be assigned to different AP in different time slot. This is shown for user 5 and user 10, where user 5 is assigned to AP 2 in time slots 4 and 6 and is assigned to AP 3 in time slots 2 and 8; user 10 is assigned to AP 3 in time slot 3 and is assigned to AP 4 in time slots 4 and 6. The average rate for each user under each algorithm is calculated based on (5), (7), and (8) in the optimal solutions. The minimum user rates under per-time slot AP assignment, one-shot AP assignment, and strongest-signal AP assignment are 6.7 Gbps, 6.0 Gbps, and 2.9 Gbps, respectively.

In this case study, we find that both per-time slot AP assignment and one-shot AP assignment have significant advantage over strongest-signal AP assignment in terms of our throughput objective, while there is only marginal improvement of per-time slot AP assignment over one-shot AP assignment. This suggests that we should advocate one-shot AP assignment scheme, which is more amenable to implementation due to its low requirement on beam steering at the user.

C. Complete Results

In this section, we offer extensive results for the two proposed AP assignment and transmission scheduling schemes and the strongest-signal AP assignment based scheduling scheme to substantiate the observations that we had in the case study. For each comparison study, we generate 50

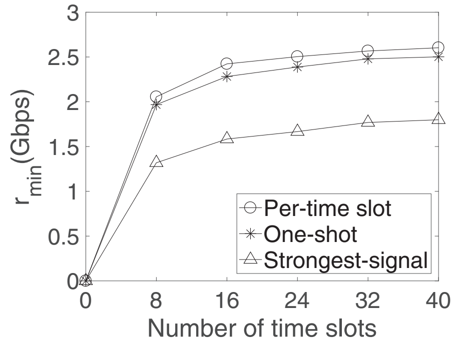


Figure 8: Maximum guaranteed user rate when the number of time slots increases from 0 to 40.

random network instances and take the average from the results. To simulate blockage between an AP and a user, we randomly generate a binary number b_{ij} for each AP i and user j. If $b_{ij} = 1$, we will have a LOS path between AP i and user j; otherwise ($b_{ij} = 0$), there is no LOS between the two. In our comparison study, we vary the number of time slots in a frame, the number of users, and the number of APs in the area.

Varying Number of Users. We compare the objective values obtained by the three AP assignment and transmission scheduling schemes for different number of users in the area. We consider a network with 4 APs and increase the number of users in the network from 20 to 50. Figure 6 shows the trend of objective values as the number of users increases from 20 to 50 when there are 16 time slots in a time frame. Each point on the curve is averaged over results from 50 randomly generated network instances. As shown in the figure, the objective values obtained by all three schemes decreases as the number of users in the network increases, as expected. It is easy to observe that (i) both per-time slot and one shot AP assignment-based scheduling schemes significantly outperform the strongest-signal AP assignment based-scheduling scheme; and (ii) the benefits of per-time slot AP assignment scheme over one-shot AP assignment scheme is marginal.

Varying Number of APs. We now compare the objective values obtained by the three AP assignment and transmission scheduling schemes under different number of APs. We consider a network with 20 users and increase the number of APs in the network from 2 to 5. Figure 7 shows the results when there are 16 time slots in a time frame. Again, we have the same observations.

Varying Number of Time slots. We compare the objective values obtained by the three AP assignment and transmission scheduling schemes under different number of time slots in a frame. We consider a network with 4 APs and increase the number of time slots from 0 to 40. Figure 8 shows the results when there are 20 users. The conclusions are consistent to our earlier observations.

VI. An Online Algorithm for Practical Implementation

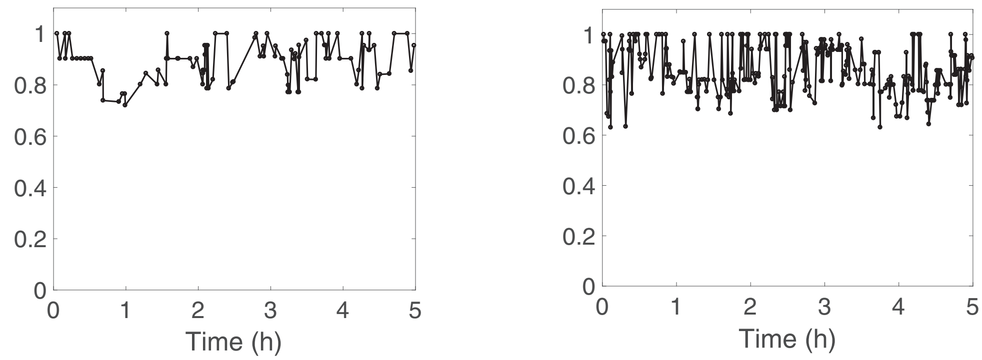
A. Motivation

The results in the last section show that per-time slot AP assignment only has marginal improvement in throughput over one-shot AP assignment. On the other hand, per-time slot AP assignment has substantially more control overhead than one-shot AP assignment. This makes it more attractive to employ one-shot AP assignment in practice. But still, there is more work needs to be done for practical implementation. The one-shot AP assignment based scheduling discussed in Section IV-B takes the instance of the current network as an input. Then it formulates an optimization problem based on this instance and offers an optimal solution for AP assignment and transmission scheduling for each time slot in a frame. Under low human mobility, we assume that the network environment is static within each frame. However, over time, when a new user arrives the network, or an existing user departs the network, the network instance changes. Moreover, since 60 GHz links are vulnerable to blockage by human body [11], the direct path between an existing user and its assigned LOS AP may be blocked due to human activity in the area. Under these scenarios, it is necessary to formulate a new optimization problem and find a new optimal solution for AP assignment and transmission schedule. But changing AP assignment could be disruptive and bring additional control overhead across multiple layers.

We are interested in an online algorithm that performs one-time optimization of AP assignment for a new user and then binds this assignment for this user throughout the life of its communication session until its assigned AP is blocked or it departs the network. This online algorithm will enjoy the same benefits that come with one-shot AP assignment while avoiding the overhead caused by switching AP upon each user arrival/departure or human blockage. As for transmission scheduling, its optimal solution will change whenever a new user arrives, an existing user departs, or the LOS path between an existing user and its assigned AP is blocked. But such change is not disruptive and can be implemented by modern software-based radio.

B. Algorithm Details

There are three types of events that trigger the algorithm, arrival of a new user, departure of an existing user, and human blockage. In the case when the direct path between an existing user and its assigned AP is blocked by a human, we have to enact AP assignment for this user as if it is a new user. That is, transient LOS blockage will be handled as a special case of a user departure followed by a new arrival. Then the design of our online algorithm for one-shot AP assignment and transmission scheduling is centered around solving two optimization problems – one for new user arrival and one for existing user departure. We describe the details as follows.



(a) User arrival rate is 10/hour.

(b) User arrival rate is 30/hour.

Figure 9: Ratio between the objective values obtained by the online algorithm and those by offline algorithm based on one-shot AP assignment.

1) Arrival of A New User: When a new user m enters the network, it can detect the subset of APs that it can communicate with (LOS APs) via the beacon frames sent periodically by these APs. Upon its response, the new user's LOS APs will add user m to their LOS user sets and report to the central controller. The central controller will add user m to the existing user set by updating $\mathcal{N}$ (i.e., $\mathcal{N} \leftarrow \mathcal{N} \cup \{m\}$), and solves the new optimization problem (OPT-A) for AP assignment and transmission scheduling.

Moreover, as for an existing user q in the network, after each successful transmission, user q will send an ACK feedback to its assigned AP i. In the case when direct path between user q and its LOS AP i is blocked due to human activity, there would be no ACK feedback. To avoid feedback errors, we set up a time-out counter. Once the counter expires, AP i identifies a transmission failure. Then AP i deletes user q from its LOS user set and reports to the central controller. Upon receiving this message, the central controller will remove user q from the user set $\mathcal{N}$. Then user q is treated as a new arrival and follows the same LOS AP discovery and assignment procedure as a new user.

OPT-A

max $r_{\min}$

s.t $r_{\min} \leq r_j$ $\quad (j \in \mathcal{N})$;

AP selection constraint only for the new user m: $\sum_{i \in \mathcal{A}_m} y_{im} \leq 1$;

Transmission scheduling constraints for all users: (2), (10) ;

Interference constraints for all users: (4) ;

Data rate constraints for all users: (7), (8) .

In this formulation, α_{ij}^k, β_{km}^i, c_{ij} and y_{ij} ($j \in \mathcal{N} \backslash \{m\}$) are constants, while $x_{ij}(t)$, y_{im}, r_{ij}, r_j and $r_{\min}$ are optimization variables. Upon the central controller solves the optimization problem, the new user is assigned to its optimal AP and each AP adjusts its transmission scheduling to its users following the new optimal solution.

2) Departure of An Existing User: When an existing user k leaves the network, the user sends a termination message to its AP, which relays the message to the central controller. Upon receiving this message, the central controller will remove user k from the user set $\mathcal{N}$, i.e., $\mathcal{N} = \mathcal{N} \backslash \{k\}$. Then it solves the following optimization problem (for optimal transmission scheduling) for the remaining users. Note that the AP assignment for the remaining users are not changed.

OPT-D

max $r_{\min}$

s.t $r_{\min} \leq r_j$ $\quad (j \in \mathcal{N})$;

Transmission scheduling constraints for all users: (2), (10) ;

Interference constraints for all users: (4) ;

Data rate constraints for all users: (7), (8) .

In this formulation, y_{ij}, α_{ij}^k, β_{km}^i and c_{ij} are constants, and $x_{ij}(t)$, r_{ij}, r_j and $r_{\min}$ are variables. Upon solving the optimization problem, each AP adjusts its transmission scheduling to the remaining users following the new optimal solution.

C. Performance Evaluation

To evaluate the performance of the online algorithm, we compare the objective values in real-time for different network instances under the proposed online algorithm and those under the offline algorithm (one-shot AP assignment).

In the comparison study, we use 4 APs and assume there are 20 time slots in a frame. We consider different new user arrival rates (Poisson), i.e., 10 and 30 per hour. The holding time for each user is exponential with an average of 1 hour.

Figure 9(a) and (b) show the ratio between the objective values obtained by our proposed online algorithm and those by the offline algorithm based on one-shot AP assignment when user arrival rates are 10 and 30 per hour, respectively. In Fig. 9(a), there are a total of 97 events during the 5-hour simulation time, among which there are 82 events with ratio over 80%, 59 events with ratio over 90%. The average ratio for all instances is 88.54%. In Fig. 9(b), there are a total of 305 events during 5 hours, among which there are 217 events with ratio over 80%, 118 events with ratio over 90%. The average ratio for all instances is 84.71%. These results show that our proposed online algorithm is competitive when compared to the offline (one-shot AP assignment) algorithm.

VII. Conclusions

In this paper, we studied the important problem of AP assignment and transmission scheduling in a multi-AP 60 GHz WLAN. Two AP assignment schemes were considered, namely per-time slot AP assignment and one-shot AP assignment. Both schemes jointly optimize AP assignment with transmission scheduling, with the objective of maximizing minimum achievable user throughput. We found that there is little difference in performance between per-time slot AP assignment and one-shot AP assignment schemes. Due to its simplicity and lower overhead, we advocate to use one-shot AP assignment-based scheduling in practice. To address potential change in AP assignment under user arrival/departure and dynamic human blockage, we designed an online one-shot algorithm and showed that it performs well when compared to the offline algorithm.

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