On the Potential Benefits of Mobile Access Points in mmWave Wireless LANs

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***Abstract*—Millimeter-wave communication is a highly promising technology to deliver multi-gigabit-per-second transmission rates for next-generation wireless LANs (WLANs). To achieve such ultra-high throughput performance in indoor scenarios, line-of-sight (LoS) connectivity becomes a critical requirement. Prior work has proposed access point (AP) mobility as an approach to improve LoS conditions and, thereby, approach optimum mmWave WLAN performance. In this work, we present a comprehensive simulation study of linear AP mobility that investigates various dimensions, including the number of mobile APs, the placement of the mobile AP platforms, and the length of the platforms. The results show how WLAN performance varies across these dimensions and also compares the results against a varying number of static APs to quantify the performance gains achievable from mobility. The results show that even 2 or 3 mobile APs can significantly outperform a much larger number of static APs and that deploying up to 3 mobile APs in a room brings substantial performance gains.**

***Index Terms*—Millimeter wave, line-of-sight, AP mobility, blockage effects, wireless LAN, multiple APs**

I. Introduction

According to the Cisco Visual Networking Index report [1], global data traffic will increase threefold in five years due to the widespread use of bandwidth-intensive applications such as virtual reality, augmented reality, and real-time high definition video. However, the spectrum allocated to conventional WiFi operating on 2.4 and 5 GHz frequencies has become congested. Given the large available unlicensed bandwidth, millimeter-wave (mmWave) communication is regarded as a promising technology for next-generation WLAN scenarios, which has the capability of delivering the multi-gigabit-per-second (Gbps) data rates needed for bandwidth-hungry applications [2]. In recent years, several standardization efforts, specifically IEEE 802.11ad/ay [3] [4], operating in the 60 GHz mmWave frequency band have been undertaken and link rates of around 7 Gbps have been demonstrated with 802.11ad technology [5].

To fully realize this promising wireless technology in WLANs, line-of-sight (LoS) connectivity is extremely important, because 1) mmWave signals are vulnerable to blockage effects from obstacles [6] such as walls, cabinets and even human beings in indoor settings, and 2) it is hard to exploit non-LoS (NLoS) paths for link recovery due to the use of narrow-beam directional antennas and the sparsity of mmWave multi-path channels. To illustrate the importance of LoS for mmWave links, consider [7], where experiments were conducted to compare the throughput performance of 60 GHz transmissions under LoS and NLoS conditions. The results of [7] show that in an open LoS area, 60 GHz WLAN can achieve more than 1.5 Gbps data rates even beyond typical AP-client separation distances; however, the throughput drops to almost zero in the NLoS area, which means that obstacles essentially disconnect mmWave links. These measurements demonstrate that LoS links between access points (AP) and clients are necessary to achieve high link data rates in typical indoor settings.

To improve LoS conditions in mmWave WLANs, there are four main approaches: 1) the use of reflected signals, 2) the use of relay nodes, 3) infrastructure diversity, i.e., multiple static APs, and 4) infrastructure mobility, i.e., mobile APs. Historically, the design of networking techniques has been based on the assumption that clients are mobile and APs are static. Thus, a number of prior works have focused on the first three candidate solutions (see Section II for more discussion). With significant advancements in robotics and embedded systems in recent years, AP mobility becomes a realistic approach to consider when optimizing network performance. Specifically considering the mmWave WLAN scenario, a mobile AP can actively move to an optimal location to circumvent obstacles that block original mmWave links, and thereby provide significantly better network performance through LoS connectivity for clients. To our knowledge, only a few prior works studied the use of AP mobility in mmWave WLANs [8], [9], and these were solely focused on the performance of a single mobile AP. Our work herein presents a more comprehensive study of linear AP mobility including the performance gains provided by multiple mobile APs and the effects of mobility platform placement and length. Our evaluation yields insights on selecting mobile AP configurations to improve network performance in mmWave WLANs.

Fig. 1 shows an example of the AP mobility scenarios we consider in this paper. The mmWave APs are mounted on the ceiling of the room and move on linear actuators (the blue lines in the figure), which aims to maximize LoS performance for randomly located clients in the presence of multiple obstacles. Although we have done some preliminary work using an experimental platform [9], it is difficult to investigate a wide range of mobile AP scenarios with a single experimental platform. Thus, in this paper, we perform a simulation-only study, which allows us to better explore the space of mobile AP solutions by, for example, extensively varying the number of mobile APs, and the lengths and placements of the mobility platform.

As compared to optimally-placed static APs, our results show that a single mobile AP provides similar network performance to 3 or 4 ceiling-mounted static APs. However, with *multiple* mobile APs, the results show that only 2 or 3 APs with mobility can significantly outperform any reasonable number of optimally-placed static APs, and deploying 3 mobile APs could be a cost-effective choice that provides tremendous performance benefits. Our results also yield insights on the best configurations of mobile APs through studies of the impacts of length and placement of the AP mobility platforms.

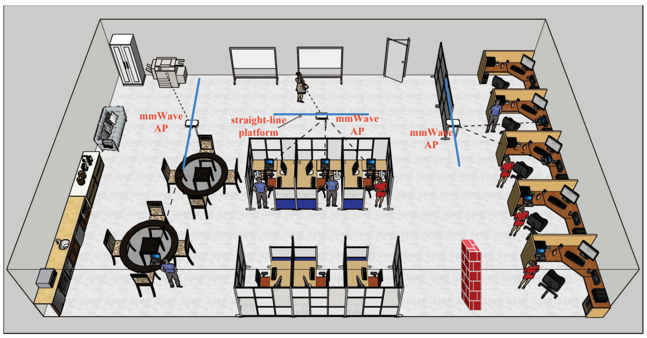

Fig. 1. A mmWave WLAN scenario with AP mobility and diversity.

The remainder of this paper is organized as follows. Sec. II discusses related works to this research. In Sec. III, we introduce the system models used in this work. Sec. IV introduces the performance study on multiple mobile APs in mmWave WLANs. Finally, the conclusion is given in Sec. V.

II. Related work

To improve LoS conditions and overcome potential blockages in mmWave WLANs, some previous works, e.g. [10]–[12], use reflections to steer around obstacles, thereby avoiding a blockage. For example, [11] showed that the use of reflected signals from the ceiling and walls can improve link quality in a 60 GHz WLAN system, and [12] proposed a solution where 60 GHz signals bounce off data center ceilings to avoid obstacles. However, reflections only maintain high signal-to-noise ratio off certain materials, such as glass and certain metals, while for most surfaces, the reflection loss is severe at 60 GHz [13], which means that link quality will be significantly below that of a LoS path.

To make use of alternative LoS links for blockage avoidance, some other works, e.g. [14]–[16], use relay nodes to maintain LoS connectivity. Specifically, the 802.11ad specification [3] includes the capability to opportunistically use a node in the network as a single relay when the LoS path between two other nodes is blocked. In [14], a directional MAC scheme for wireless personal-area networks is proposed, which selects and schedules these opportunistic relays, while [16] presents an algorithm for fast selection of a suitable relay node in this context. Opportunistic relays can improve network performance when they are available. Unfortunately, they can not be relied upon to solve the LoS problem, because they are not always available when needed.

With the trend of dense deployment of APs, several prior works propose the use of multiple static APs in the same room to address the LoS problem. In multi-AP mmWave WLANs, some works have focused on protocol design or resource allocation, such as [17]–[19], which designed AP-client association and fast AP switching algorithms to ensure seamless high-rate LoS connectivity. As severe blockage effects can be mitigated with a good deployment strategy of APs in indoor environments, a few works studied the multi-AP placement issue in mmWave WLANs [20]–[22]. Specifically, [22] did a concrete analysis on blockage effects and investigated optimal placement approaches with a varying number of static APs. It is true that, as shown in these prior works, network performance can be improved when using multiple APs instead of a single AP. However, in cases where a limited number of static APs are available, performance benefits are lower than desired, especially as obstacle density increases.

In recent years, several works began to consider the use of AP mobility to boost network performance. Considering conventional WiFi networks operating on lower frequency bands, some works [23]–[26] studied robotic APs that adaptively adjust their position based on the network conditions to deliver improved network performance. For mmWave WLANs, [8] explored a ceiling-mounted mobile AP model and studied the optimal configurations of AP mobility platform. Furthermore, based on this mobile-AP model, [9] presented a LoS prediction algorithm that addresses the location discovery problem of mobile AP, which identifies the target position on the mobility platform to maximize LoS connectivity. All of these prior works considered the use of only a *single* mobile AP. In this work, we focus on *multiple* mobile APs, and study how much benefit can be achieved with varying numbers of APs and different platform configurations, as compared to a varying number of static APs.

III. Network and environment models

In this section, we introduce the network models and configurations for both static APs and mobile APs used in the remainder of the paper.

A. Ceiling-mounted static AP model

With multiple static APs (S-APs) in a mmWave indoor WLAN, we assume that S-APs are mounted on the ceiling, because this achieves better LoS performance with larger coverage as compared to placing APs at a lower height, e.g. on the wall or on a desk or table [22]. In [22], it was also shown that the position of the S-APs on the ceiling can have a significant impact on the LoS coverage and network performance, and optimal placements were derived as a function of the dimensions of a room. Here, we adopt the optimal S-AP placements from [22] as a comparison point to assess the potential benefits of mobile APs. As an example, in a 12m×8m room, a single ceiling-mounted S-AP should be placed in the center of the room, and when there are multiple S-APs (e.g., 3∼5 APs), the optimal placements are shown in Fig. 2 (a)-(c).

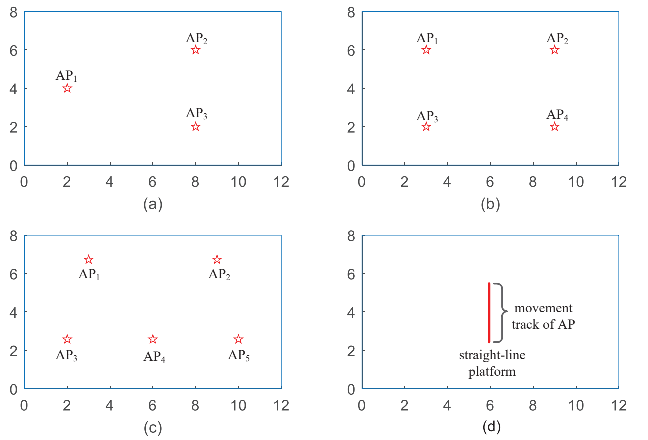

Fig. 2. Examples of optimal placements for multiple static APs and a single mobile AP: (a) 3 S-APs; (b) 4 S-APs; (c) 5 S-APs; (d) a single M-AP.

B. Ceiling-mounted linear mobile AP model

AP mobility is another attractive technology in mmWave WLANs, where the mobile AP (M-AP) can proactively move its location to offer the best performance for clients, which takes advantage of both flexibility and spatial diversity. In this work, we adopt a ceiling-mounted, straight-line M-AP model, where an AP moves on a 1-dimensional linear actuator. Several prior works studied this linear AP mobility model [8], [9], and two results are worth mentioning. First, the performance of the straight-line platform was demonstrated to be better than that of other common platform shapes with the same length, such as cross straight-line platform with two perpendicular lines, square-shaped or compressed square platforms. Second, in order to maximize the LoS performance, a single straight-line platform should be placed parallel to the shorter edges of the room and bisecting the longer dimension (e.g., as shown in Fig. 2 (d)).

In [9], an experimental prototype implementation of the linear mobile AP was described and evaluated. This prior work considered the practical implementation details and provided a proof of concept of this approach. In this paper, we focus on the number, arrangement, and length of mobile AP platforms to better evaluate the range of performance that can be expected with AP mobility.

C. Obstacle and client models

The obstacle model we use is as follows: 1) obstacles are modeled as cuboids and placed on the floor; 2) the center of each obstacle follows a Poisson point process with a specific density λ, where λ is the mean number of obstacles in a unit area; 3) the width, length, and height of each obstacle follow truncated normal distributions W$\sim \mathcal{TN}$(0.56, 0.08, 0.25, 1.25), L$\sim \mathcal{TN}$(1.08, 0.18, 0.5, 1.75), H$\sim \mathcal{TN}$(1.2, 0.6, 0.5, 1.9), respectively; 4) each obstacle's orientation follows the uniform distribution $\Theta \sim \mathcal{U}(0, \pi)$.

Each client, i.e. wireless device, is viewed as a random and uniformly distributed point in the 2-D area of a room and its height follows the uniform distribution $\mathcal{U}(0.3, 1.5)$.

The distribution parameters for obstacles and clients were chosen by using a real-life lab environment as a guiding example. All length units are in meters throughout the paper.

D. Channel and physical-layer models

To build an accurate channel model for indoor mmWave communication, we adopt a widely-used log-distance path loss model extended to include multipath and shadowing components:

$$L(d) = L(d_0) + 10 \cdot n \cdot \log_{10}(\frac{d}{d_0}) + X_\Omega + X_s \quad [\text{dB}]. \quad (1)$$

In Eq. (1), $L(d)$ is the path loss in decibels at separation distance d, $L(d_0)$ represents the path loss at a reference distance d_0, n is the path loss exponent, X_Ω represents the normal distribution of multipath fading, where Ω is the standard deviation, X_s represents a shadowing term resulting from the penetration loss of the signal traveling through an obstacle. Note that X_s is 0 when the communication link is in LoS condition. Here, we used the average of 5 sets of experimental estimations of path loss (including the path loss exponent and distribution of multi-path fading), where all experiments are performed with LoS connections in the lab environment [27], and n and Ω are set as 2 and 2.24, respectively. The shadowing term X_s is determined from obstacles' locations, dimensions, and materials, based on [28].

IV. Performance study with AP mobility

In this section, we investigate the performance of multiple M-APs in mmWave WLAN scenarios, and the results are compared against multiple S-AP deployments with the optimal configurations from [22]. All evaluations are done at the mmWave frequency of 60 GHz with a 2.16 GHz bandwidth[1], and a transmission power of 10 dBm on each AP.

To give a basic overview of the solutions we are comparing, we begin with a simple example. For a room configuration of 12m×8m×3m, Fig. 3 (a) shows a randomly generated scenario with a number of obstacles and clients (see blue asterisks and green triangles with their heights, respectively), where some of the clients may attach on/to those obstacles. For 3 static APs with optimal placements in Fig. 3 (b), we observe that some of clients may fail to have LoS connections with any of the placed APs. However, when we exploit linear AP mobility in Fig. 3 (c), APs can move along their respective platforms based on where the clients are located, thus all clients can have LoS connectivity for high-rate data transmissions. Even when some of the clients move around within the room (see Fig. 3 (d)), the

[1] While 60 GHz is used to derive specific throughput values, our results focus on maximizing LoS conditions, which will improve performance at any frequency in the mmWave bands.

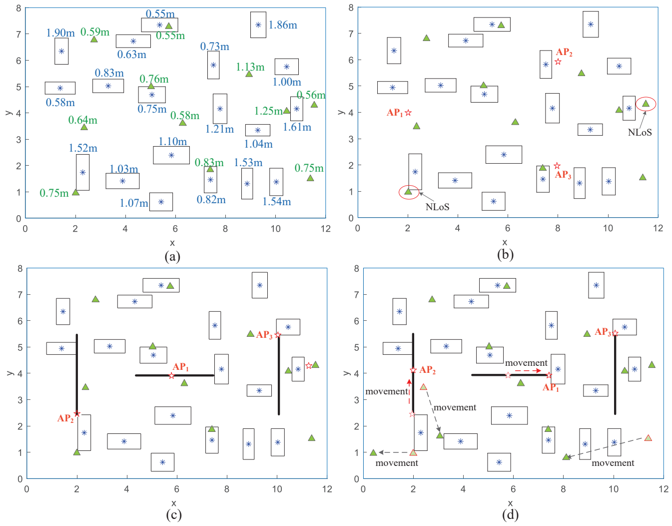

Fig. 3. An example of mmWave WLAN scenario with multiple static/mobile APs: (a) An indoor scenario; (b) 3 static APs; (c) 3 mobile APs; (d) 3 mobile APs with the movement of clients.

APs can also move to new positions on their platforms such that LoS connections are still maintained. Note that here we assume users remain stationary for several minutes in between short mobility periods so that the positions of mobile APs do not have to be changed frequently.

A. Single mobile AP vs. multiple static APs

First, we investigate the performance of a single mobile AP (M-AP) and multiple static APs (S-APs) in WLAN scenarios, where the network models and AP placement approaches in Sec. III are adopted (see Fig. 2). For M-APs, the platform length (PL) is fixed at 3m. Here, we evaluate the LoS performance and aggregate throughput over different scenarios. The aggregate throughput is evaluated based on the channel model in Sec. III-D and the IEEE 802.11ad protocol, where the single carrier PHY is adopted that supports 12 modulation and coding schemes (MCSs) [3]. To be specific, we first calculate the received power, which then determines the specific MCS that can be supported, which finally maps to the achievable link rate. Each data point collected was the result of generating 384 client locations distributed over the area of the room and the LoS performance is the percentage of locations where the client has an LoS connection to at least one AP. The results are reported in Fig. 4-5.

In Fig. 4, it is observed that the LoS performance of a single M-AP is comparable to that of 3–4 S-APs, and the performance gaps between a single M-AP and 4–5 S-APs become larger when the obstacle density increases. The same results are reflected in Fig. 5, where a single M-AP and 3–4 static APs offer similar throughput performance. From these two figures, we see that the throughput is highly correlated with LoS performance, which confirms that LoS is a critical requirement for indoor mmWave communication. Therefore, in what follows, we focus solely on LoS performance.

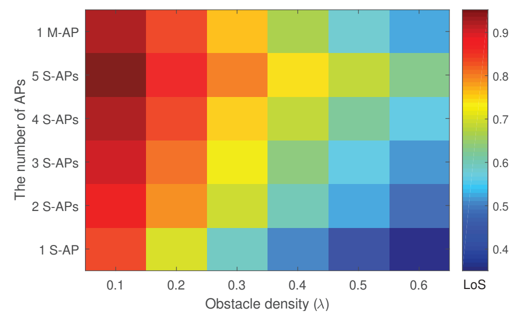

Fig. 4. LoS performance with a single M-AP and multiple S-APs.

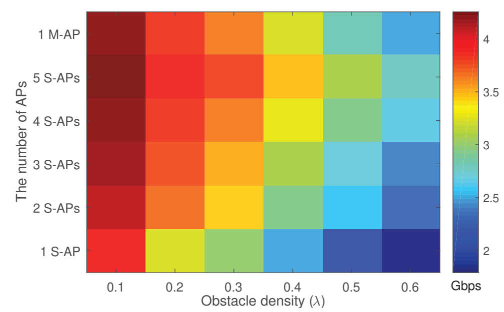

Fig. 5. Throughput performance with a single M-AP and multiple S-APs.

The above result reveals that a single M-AP with a 3m platform length performs as well as a small number of static APs, which does not clearly show strong benefits for AP mobility. Thus, in the remainder of the paper, we investigate varying numbers of mobile APs and different platform configurations to see under what conditions AP mobility provides substantial benefits relative to a small number of static APs.

B. Multiple mobile APs vs. multiple static APs

Considering multiple M-APs, we first compare the performance of 2 and 3 M-APs with that of multiple S-APs. In this part, the S-APs adopt the optimal placements (see Fig. 2 and [22]), and the platform placement approaches for different number of M-APs are as shown in Fig. 6, where the PL for each straight-line platform of mobile AP is fixed at 3m.

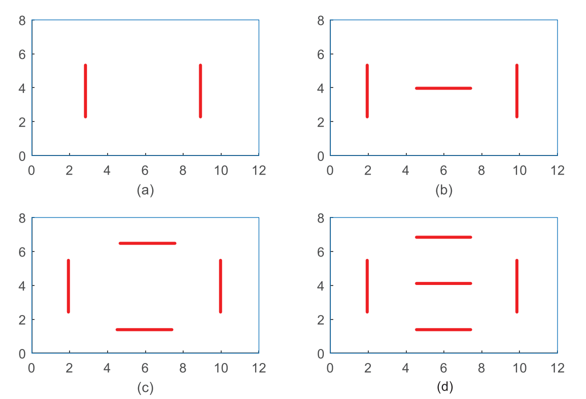

Fig. 6. Initial platform placement approaches for 2–5 M-APs.

As shown in Fig. 7, we observe that 2–3 M-APs outperform 7 S-APs, which clearly shows the advantage of AP mobility for improving LoS conditions. Since the performance benefits brought by higher numbers of S-APs diminish rapidly after 5 S-APs, it is safe to say that 2 or 3 M-APs can easily outperform any practical number of S-APs in typical indoor scenarios.

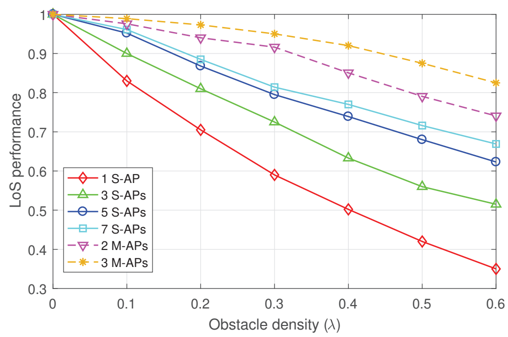

Fig. 7. Performance comparison of multiple S-APs and 2–3 M-APs.

Next, we do a more extensive investigation of the impact of the number of M-APs, where we consider different number of mobile APs with the placements shown in Fig. 2 and Fig. 6.

Fig. 8 shows the LoS performance for 1–5 M-APs. First, we observe that the performance is improved when more M-APs are used in the network, while as the number of M-APs increases beyond 3, the performance improvement brought by higher numbers is marginal. The average performance increases over different obstacle densities from the 2^{nd} M-AP to the 5^{th} M-AP are 15.17%, 5.05%, 1.14% and 0.58%, respectively. Thus, this data suggests that 3 M-APs are a good choice for AP mobility in areas of around the size studied herein, which reflects many shared office and small- to medium-sized lab environments.

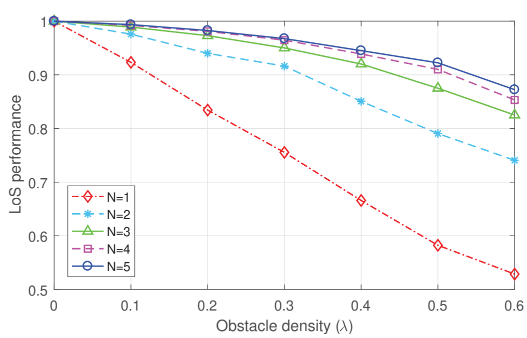

Fig. 8. Performance comparisons for different number of M-APs.

C. The impact of platform length

In this part, we investigate how the platform length (PL) affects the performance provided by M-APs. Fig. 9 shows the performance of 3 M-APs with fixed platform centers and platform lengths of 1–8 meters (dashed lines in figure). For comparison, we again show the S-AP performance with 1–7 S-APs (solid lines). Observe that even with a quite short platform of 1 meter, 3 M-APs still outperform multiple S-APs. In addition, it is evident that much higher performance gains are obtained as the platform length increases, where the LoS performance exceeds 94% even with a very high obstacle density.

The much better performance for longer platforms is because they allow significantly increased diversity of AP locations, such that APs have more potential to provide LoS connectivity for clients. As an example shown in Fig. 10 (b), AP_2 and AP_3 can move to the end of longer platforms to provide LoS connections for clients who were under NLoS conditions in Fig. 10 (a), where the platforms are much shorter.

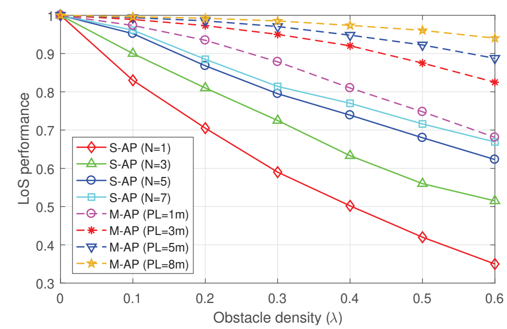

Fig. 9. Performance comparison for multiple S-APs and 3 M-APs with different platform lengths.

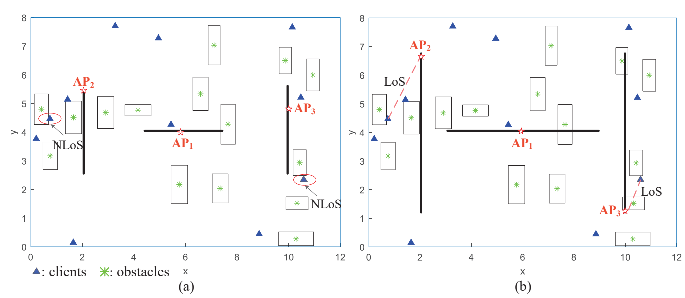

Fig. 10. An example case with 3 M-APs having shorter and longer platforms.

In addition, we note that the performance of 3 M-APs with platform lengths of 5 meters (see blue dashed line in Fig. 9) is very similar to that of 5 M-APs with platform lengths of 3 meters (see blue solid line in Fig. 8). This indicates that increasing the platform length is an effective approach to improve network performance without the use of additional APs.

D. The impact of multiple M-AP platform configurations

Since multiple M-AP platforms with different configurations will impact the diversity of AP locations, here we investigate the impact of different AP-mobility platform configurations on the network performance. From the conclusion of Sec. IV-B, we know that deploying 3 M-APs offers the best cost-performance for the room types we are considering. Thus, we focus on the 3 M-AP case and evaluate the performance of six common placement approaches as shown in Fig. 11. These include linear arrangement (L_1), H-shaped configuration (H), N-shaped configuration (N), and their respective 90°-rotated versions (see Fig. 11 (d)-(f)).

With the length for each straight-line platform fixed at 3m, Fig. 12 shows the performance comparison among these

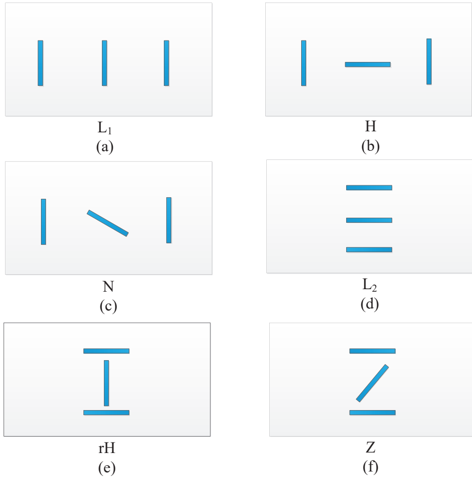

Fig. 11. Three M-AP configurations studied.

different configurations. It is observed that the H-shaped configuration offers the best performance, and "L_1", "H" and "N" configurations outperform their 90°-rotated versions. In particular, the performance of "N" ("Z") configuration falls between that of "H" ("rH") and "L_1" ("L_2") configurations, which indicates that the performance will be improved when we rotate the middle straight-line platform from the vertical direction to horizontal direction.

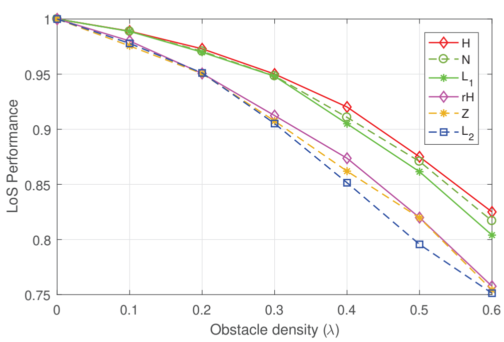

Fig. 12. Performance comparisons among different plactform configurations.

V. Conclusion

In this paper, we studied the potential benefits of AP mobility in mmWave WLANs, and the performance of mobile APs based on the ceiling-mounted, straight-line mobility platform was investigated. Through extensive simulations, we showed that the performance benefits brought by a single mobile AP are not as large as we would like, but that 2 or 3 mobile APs can greatly outperform a much larger number of static APs. Specifically, we demonstrated that deploying up to 3 mobile APs can offer substantial performance gains from mobility. With the evaluation of different mobility platform configurations, we showed that increasing the platform lengths of mobile APs can further improve the network performance, and the H-shaped configuration is a good choice for 3 mobile APs.

Acknowledgement

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