Impact of Spatial Multiplexing on Throughput of Ultra-Dense mmWave AP Network

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Abstract

The operating range of a single millimeter wave (mmWave) access point (AP) is small due to the high path loss and blockage issue of the frequency band. To achieve a coverage similar to the conventional sub-6GHz network, the ultra-dense deployments of APs are required by the mmWave network. In general, the mmWave APs can be categorized into backhaul-connected APs and relay APs. Though the spatial distribution of backhaul-connected APs can be captured by the Poison point process (PPP), the desired locations of relay APs depend on the transmission protocol operated in the mmWave network. In this paper, we consider modeling the topology of mmWave AP network by incorporating the multihop protocol. We first derive the topology of AP network with the spatial multiplexing disabled for each transmission hop. Then we analyze the topology when the spatial multiplexing is enabled at the mmWave APs. To derive the network throughput, we first quantify the improvement in latency and the degradation of coverage probability with the increase of spatial multiplexing gain at mmWave APs. Then we show the impact of spatial multiplexing on the throughput for the ultra-dense mmWave AP network.

I. INTRODUCTION

The use of millimeter wave (mmWave) frequencies in APs becomes a trend in the emerging fifth generation network [1–6]. Despite the large available bandwidth in mmWave frequencies, the small wavelength experiences a high path loss and a severe penetration loss, which limits the coverage of a single mmWave AP [7]. To achieve the same size of network coverage as the sub-6GHz network, the ultra-dense deployment of APs appears to be the solution for mmWave network [3, 5, 8]. Note that the topology of sub-6GHz AP network is relatively simple, where the area in coverage is divided into macro and micro cells with each cell covered by an AP [9]. Unlike the sub-6GHz network, only a small portion of mmWave APs have direct access to the Internet backhaul. The rest of APs in the ultra-dense AP network are connected to the Internet by following a multihop transmission protocol as shown in Fig. 1. Depending on the
multihop protocol, the topology of mmWave AP network varies, which leads to different network performance.

Several aspects of the ultra-dense mmWave AP network have been studied. In [4], the mmWave modeling was comprehensively studied. The hybrid precoding for mmWave network was proposed in [10]. In [3], the optimal intensity of the ultra-dense mmWave AP network was derived under the impact of blockage. The SINR coverage probability and rate analysis for mmWave network were presented in [2, 5]. We remark that all these previous work assumed mmWave APs to be uniformly distributed in the mmWave network. Such an assumption has been validated for the sub-6GHz network [9]. However, the ultra-density of mmWave APs results in a complicated and flexible network topology, which cannot be captured by simply applying a uniformly distributed spatial model.

We approach the topology of mmWave network by introducing tiers to mmWave APs, where each tier is used to model the APs in one hop of the transmission protocol. For the mmWave AP network, the backhaul-connected APs are considered as the 0th tier. Since the backhaul-connected AP is always the source for any packet transmission. Other AP tier in the mmWave network is used as relay, which extends the coverage of backhaul-connected APs to the whole network. Note that the spatial distribution of backhaul-connected APs is determined by the infrastructure. However, the locations of APs in any other tier depend on the previous tier’s topological structure and the transmission protocol. Consequently, the topology of mmWave AP network has a large flexibility and is dependent on the transmission protocol.

Our key contribution is to incorporate the topology of mmWave AP network with the multihop protocol operated in the network. Specifically, we analyze how the hybrid precoding scheme affects the AP network topology. It follows from [10] that the implementation of mmWave hybrid precoding combines the analog beamforming and baseband spatial multiplexing. Moreover, the rank of spatial multiplexing at a mmWave AP determines the number of streams the AP can support, which is termed as the spatial multiplexing gain in the rest of our paper. In section II, we first introduce the tiered structure for the mmWave APs. We then derive the topology of AP network with respect to the spatial multiplexing gain in section III. The performance analysis is provided in section IV, where we characterize the latency, the coverage probability and the throughput for the mmWave AP network. Due to the page limit we skip the proof in this paper. We refer to the full paper for all the proofs.
The mmWave APs have an inherently tiered structure due to the multihop protocol operated in the network, as shown in Fig. 1. Therefore, instead of modeling the whole network, we model the spatial distribution of mmWave APs for each transmission hop. The APs directly connected to the backhaul are defined as the $0^{th}$ tier. The other mmWave APs are used as relay, which can be further divided into multiple tiers with respect to 'the distance' to the $0^{th}$ tier.

In the mmWave AP network, we measure the distance of an AP to tier 0 by the number of relays between the AP and tier 0, which is termed as hop count. Based on the hop count, the $i^{th}$ AP tier i.e. tier $i$ is defined as the subset of mmWave APs with hop count equal to $i$.

For a mmWave AP network of density $\Lambda_A$, assume that the transmission protocol contains $M$ hops. It follows that mmWave APs can be divided into $M + 1$ tiers, including one backhaul-connected tier and $M$ relay tiers. The locations of mmWave APs in tier $i$ is modeled by the point process $\Phi_i = \{x_1, x_2, \cdots\}, x_j \in \mathbb{R}^2$. We then define the sequence of point processes $\{\Phi_i\}_{i=0}^M$ as the topology of mmWave AP network.

Note that the locations of backhaul-connected mmWave APs are restricted by the network infrastructure. Thus, we model tier 0 by a homogeneous Poison point process (PPP) $\Phi_0$ with intensity $\Lambda_0$. Unlike tier 0, the point distribution of $\Phi_{i+1}$ is determined by $\Phi_i$ and the transmission protocol applied in the mmWave network. Denote $\phi_i$ as the subset of $\Phi_i$, where $\phi_i$ consists of the APs which are scheduled to transmit at the $i + 1^{th}$ hop. From the view of stochastic geometry, $\phi_i$ can be considered as the parent process of $\Phi_{i+1}$. That is, each AP at $x \in \phi_i$ is considered as a parent point, which then generates a cluster of daughter points in $\Phi_{i+1}$.

At hop $i + 1$, the AP at each point $x \in \phi_i$ transmits to a cluster of points $B^x_i = \{y_1, y_2, \cdots\}$
which is centered at \( x \). It follows that tier \( i + 1 \) can be expressed as \( \Phi_{i+1} = \bigcup_{x \in \phi_i} B^x_i \). Here, the points of \( B^x_i \) are assumed to be independently and identically distributed (i.i.d.) around the cluster center \( x \).

### III. TOPOLOGY OF mmWAVE AP NETWORK

Assume that the hybrid precoding is implemented at the mmWave APs, which consists of analog beamforming and spatial multiplexing. Note that analog beamforming is mandatory for a mmWave AP to combat the high path loss. However, the spatial multiplexing is required only when the mmWave AP needs to support multiple data streams.

**Definition 1. Spatial Multiplexing Gain.** The spatial multiplexing gain for a mmWave AP is defined as the number of data streams supported by the AP.

Assume the mmWave AP to be equipped with \( K \) RF chains. Then the spatial multiplexing gain of the mmWave AP is upper bounded by \( K \). Let all the transmitters of the same hop employ the identical hybrid precoding process. It follows that all APs in \( \phi_i \) have the same spatial multiplexing gain, which is denoted by \( k_i \). Next, we characterize the topology of mmWave AP network with respect to the spatial multiplexing gain \( k_i \).

#### A. Topology with Spatial Multiplexing Disabled

Given that the spatial multiplexing is disabled, we then have \( k_i = 1, \forall i \). It implies that for each \( x \in \phi_i \), the cluster \( B^x_i \) contains only one point \( y \in \Phi_{i+1} \), where the probability density function (PDF) of \( y \) conditioning on \( x \) is denoted by \( f_i(y|x) \). Assume that the mmWave APs in \( \phi_i \) transmit at the same power. Let each AP of tier \( i+1 \) to be deployed to receive the maximum average power from \( \phi_i \). Given that \( \phi_i \) is a PPP, we then derive the conditional PDF \( f_i(y|x) \).

**Lemma 1.** In a multihop mmWave AP network, assume \( x \in \phi_i \) and \( y \in \Phi_{i+1} \) to be a pair of transmitter and receiver at the \( i+1 \)th hop. If \( \phi_i \) is a PPP with intensity \( \lambda_i \), then \( y \) is isotropically distributed around \( x \) with the conditional PDF:

\[
f_i(y|x) = f_L(y|x)e^{-2\pi\lambda_i \int_0^{||y-x||/\alpha_L} P_L(r)dr} + f_N(y|x)e^{-2\pi\lambda_i \int_0^{||y-x||/\alpha_N} P_N(r)dr},
\]

where

\[
f_L(y|x) = 2\pi|y - x|\lambda_i P_L(||y - x||)e^{-2\pi\lambda_i \int_0^{||y-x||} P_L(r)dr},
\]

\[
f_N(y|x) = 2\pi|y - x|\lambda_i P_N(||y - x||)e^{-2\pi\lambda_i \int_0^{||y-x||} P_N(r)dr}.
\]
Here, the constant $\alpha_L$ and $\alpha_N$ represent the path loss exponent for line-of-sight (LOS) and non-line-of-sight (NLOS) mmWave link, respectively. $P_L(r)$ refers to the probability with that a mmWave link of length $r$ is LOS. It follows the NLOS probability $P_N(r) = 1 - P_L(r)$.

Lemma 1 implies that each point $y \in \Phi_{i+1}$ can be considered as the isotropic displacement of some point $x \in \Phi_i$, where the distance between $y$ and $x$ follows the PDF $f_i(y|x)$ in (1). It follows from (11) that if $\Phi_i$ is a homogeneous PPP, then $\Phi_{i+1}$ is a PPP with the same intensity as $\Phi_i$.

Consider a mmWave AP network of density $\Lambda_A$, where all APs are scheduled to transmit to the following tier i.e. $\phi_i = \Phi_i$, $\forall i$. By repeatedly using the displacement property of the PPP (11), the topology of mmWave AP network can then be written as $\{\Phi_i\}_{i=0}^M$, where $\Phi_i$ is a homogeneous PPP of intensity $\Lambda_0$, $\forall i$. It follows that the total number of transmission hops

$$M = \frac{\Lambda_A}{\Lambda_0} - 1.$$  

Note that $\bigcup_{i=0}^M \Phi_i$ is the superposition of $M + 1$ homogeneous PPPs, thus is also a homogeneous PPP. It implies that the mmWave APs are uniformly distributed in the network if the spatial multiplexing at APs are disabled by the transmission protocol.

**B. Topology with Spatial Multiplexing Enabled**

By enabling the spatial multiplexing of APs in $\phi_i$, the cluster $B^x_i, x \in \phi_i$ becomes a sequence of i.i.d. points $\{y_1, \cdots, y_{k_i}\}$ with the PDF $f_i(y_j|x)$. Following Lemma 1, if $\phi_i$ is a PPP of

![Fig. 2: The spatial distribution of mmWave APs in the network with spatial multiplexing disabled (left) and enabled (right).](image-url)
intensity $\lambda_i$, then $y_j$ is isotropically located around $x$ with $f_i(y_j|x)$ in (1). We remark that the location distribution of $y_j$ only depends on $x$, which is irrelevant to the size of $B^x_i$.

For tier $i + 1$, the mmWave APs are spatially distributed following the point process $\Phi_{i+1} = \bigcup_{x \in \phi_i} B^x_i$. Given that $\phi_i$ is a PPP of intensity $\lambda_i$, we then have that $\Phi_{i+1}$ is a Poisson cluster process (PCP), more specifically, a Neyman-Scott process with intensity $\Lambda_{i+1} = k_i \lambda_i$ [11].

Note that $\Phi_i$ is a collection of cluster $B^x_{i-1}$ with size $k_{i-1}$. Assume that $\phi_i$ is generated by taking one point from each cluster $B^x_{i-1}, x \in \phi_{i-1}$. It follows from Lemma [1] that if $\phi_{i-1}$ is a PPP, then $\phi_i$ is a PPP, where $\phi_i$ and $\phi_{i-1}$ are of the same intensity. Note that $\Phi_0$ represents the transmitters at hop 1, which is a PPP of intensity $\Lambda_0$. Therefore, each $\phi_i$ is a PPP with intensity $\Lambda_0$. It follows that $\Phi_{i+1}$ is a Neyman-Scott point process with intensity $k_i \Lambda_0$ for all $i$.

In Fig.2b we illustrate the spatial distribution of mmWave APs with spatial multiplexing enabled. Note that the mmWave AP network in Fig.2a and Fig.2b are of the same density $\Lambda_A$. Moreover, tier 0 is assumed to be identical for the two AP networks. However, the spatial multiplexing is disabled in Fig.2a. It can be observed from Fig.2 that given $k_i = 1, \forall i$, the mmWave relays are uniformly distributed in the area. By enabling the spatial multiplexing, the locations of mmWave relays become clustering. Such a clustering pattern is consistent with the distribution of Neyman-Scott point process.

IV. PERFORMANCE OF MMWAVE AP NETWORK

To characterize the impact of spatial multiplexing on the throughput, we first derive the latency and coverage probability for the mmWave AP network. Note that the latency of AP network indicates the delay of packet transmission. While the reliability of packet transmission can be captured by the coverage probability.

A. Network Latency

In a mmWave AP network, tier 0 is always the source tier for a packet, whereas the destination of the packet can be a mmWave AP in any tier. Note that the delay of a packet depends on the hop count from the source AP to the destination AP. Accordingly, the worst-case delay of a packet is equivalent to the maximum hop count of APs in the network. It follows that the latency of a mmWave AP network can be defined as the total number of transmission hops $M$ in the network.
Theorem 1. For a mmWave AP network of density \( \Lambda_A \), the latency \( M \) is bounded by

\[
\frac{\Lambda_A}{K \Lambda_0} - \frac{1}{K} \leq M \leq \frac{\Lambda_A}{\Lambda_0} - 1,
\]

where \( \Lambda_0 \) is the intensity of tier 0. Each mmWave AP is equipped with \( K \) RF chains, thus \( K \) represents the maximum spatial multiplexing gain for each transmission hop.

It follows from Theorem 1 that the latency of mmWave AP network decreases linearly with the increase of \( k_i \). Note that the network latency reaches its upper bound when the the spatial multiplexing is disabled. By setting the spatial multiplexing gain to \( K \) for each transmission hop, the minimum latency of mmWave AP network can be achieved.

B. Coverage probability

To calculate the coverage probability for tier \( i + 1 \), we need to first derive the signal-to-interference-noise ratio (SINR) for APs in \( \Phi_{i+1} \). Note that \( \phi_i \) and \( \Phi_{i+1} \) represent the transmitters and receivers of the \( i \)th transmission hop, respectively. At hop \( i \), the hybrid precoding is employed by two stages [4]. In the first stage, the mmWave AP located at \( x \in \phi_i \) assigns a unique analog beam to each AP in \( B^x_i \). Denote \( \theta_A \) as the main lobe width of the analog beam, where the beamforming gain within and outside the main lobe are denoted by \( G_A \) and \( g_A \), respectively. We use \( G(k_i) \) to denote the tranceiver beamforming gain between two APs. It follows that \( G(k_i) \) equals to \( G_A^2 \), \( G_A g_A \) and \( g_A^2 \) with probabilities \( \left( \frac{\theta_A k_i}{2 \pi} \right)^2 \), \( \left( \frac{\theta_A k_i}{\pi} \right) \left( 1 - \frac{\theta_A k_i}{2 \pi} \right) \) and \( \left( 1 - \frac{\theta_A k_i}{2 \pi} \right)^2 \), respectively.

In the second stage of hybrid precoding, the spatial multiplexing is performed in the baseband, where the AP at \( x \in \phi_i \) transmits a different data stream for each \( y \in B^x_i \) as well as cancels the inter-stream interference. Let a randomly selected AP at \( y \in \Phi_{i+1} \) be the origin of the coordinate system, where \( y \) belongs to the cluster \( B^y_0 \). It follows that the coordinate of \( x \) becomes \( x_0 = x - y \). The SINR of AP at the origin can then be expressed as

\[
\text{SINR}(k_i) \triangleq \frac{h_0 G_A^2 \ell(|x_0|)}{\sigma^2 + \bar{I}_i(k_i)} = \frac{h_0 G_A^2 \ell(|x_0|)}{\sigma^2 + \sum_{x_b \in \phi_i \setminus \{x_0\}} h_b G_b(k_i) \ell(|x_b|)},
\]

where \( h_b \) represents the channel fading from \( x_b \) to the origin; \( G_b(k_i) \) is the transceiver beamforming gain between \( x_b \) and the origin; \( \sigma^2 \) denotes the noise power; \( \ell(\cdot) \) denotes the path loss of the mmWave link [4]

\[
\ell(r) = \begin{cases} 
\beta r^{-\alpha_L}, & \text{with probability } P_L(r) \\
\beta r^{-\alpha_N}, & \text{with probability } P_N(r)
\end{cases},
\]
where $\beta$ is a constant representing the intercept of path loss model \[4\]; the LOS probability $P_L(r)$ and NLOS probability $P_N(r)$ are introduced in Lemma \[1\].

As discussed in Section III, $\phi_i$ is formed by taking one point from each cluster of $\Phi_i$. Thus, $\phi_i$ is always a PPP with intensity $\Lambda_0$ regardless of the intensity of $\Phi_i$. It follows that the SINR expression in \[3\] can be applied for any tier in the network. For a mmWave AP network, the coverage probability of tier $i+1$ is defined as

$$C(\tau, k_i) \triangleq \mathbb{P}\{\text{SINR}(k_i) > \tau\}$$

(5)

with that the AP in tier $i+1$ has a SINR larger than the threshold $\tau$. To calculate the coverage probability, we first provide the characteristic function of the interference at the origin. Given that the AP at the origin is connected to a LOS AP located at $x_0$, the characteristic function can be written as

$$L_{\mathcal{I}_L}(s, k_i) = \exp \left( -2\pi \Lambda_0 \int_{|x_0|}^{\infty} \left[ 1 - G_L(s, r, k_i) \right] P_L(r) r \, dr \right) \times \exp \left( -2\pi \Lambda_0 \int_{|x_0|^\alpha_L/\alpha_N}^{\infty} \left[ 1 - G_N(s, r, k_i) \right] P_N(r) r \, dr \right),$$

(6)

where $s$ is the value on that the characteristic function is evaluated and $G_L(s, r, k_i) = \mathbb{E}_{h, G} \left[ e^{-s \beta h G(k_i)} r^{-\alpha_L} \right]$.

If the AP at $x_0$ is in the NLOS state, the characteristic function of the interference is given as

$$L_{\mathcal{I}_N}(s, k_i) = \exp \left( -2\pi \Lambda_0 \int_{|x_0|}^{\infty} \left[ 1 - G_N(s, r, k_i) \right] P_N(r) r \, dr \right) \times \exp \left( -2\pi \Lambda_0 \int_{|x_0|^\alpha_N/\alpha_L}^{\infty} \left[ 1 - G_L(s, r, k_i) \right] P_L(r) r \, dr \right),$$

(7)

with $G_N(s, r, k_i) = \mathbb{E}_{h, G} \left[ e^{-s \beta h G(k_i)} r^{-\alpha_N} \right]$.

Next, we show the main result on the coverage probability of tier $i+1$ for a mmWave AP network.

**Theorem 2.** In a mmWave network, the coverage probability of a randomly selected AP in tier $i+1$ is given by

$$C(\tau, k_i) = \int_{r>0} \frac{f_L(r) f_N(r^{\alpha_L/\alpha_N})}{2\pi r^{\alpha_L/\alpha_N} \Lambda_0 P_N(r^{\alpha_N/\alpha_L})} C_L(\tau, r, k_i) \, dr$$

$$+ \int_{r>0} \frac{f_L(r^{\alpha_N/\alpha_L}) f_N(r)}{2\pi r^{\alpha_N/\alpha_L} \Lambda_0 P_L(r^{\alpha_N/\alpha_L})} C_N(\tau, r, k_i) \, dr,$$

(8)

(9)
where \( k_i \) is the spatial multiplexing gain at hop \( i \); \( f_L(\cdot) \) and \( f_N(\cdot) \) are the PDF of distance distributions given in (1). Assume that channel follows the Rayleigh fading model, then

\[
C_L(\tau, r, k_i) = \exp \left( -\frac{r^{\alpha_L} \sigma^2}{G_A^2 \beta} \right) \mathcal{L}_{\mathcal{L}} \left( \frac{r^{\alpha_L} \tau}{G_A^2 \beta}, k_i \right),
\]

\[
C_N(\tau, r, k_i) = \exp \left( -\frac{r^{\alpha_N} \sigma^2}{G_A^2 \beta} \right) \mathcal{L}_{\mathcal{N}} \left( \frac{r^{\alpha_N} \tau}{G_A^2 \beta}, k_i \right).
\]

In Fig. 3 we numerically evaluate the expression of coverage probability \( C(\tau, k_i) \) derived in Theorem 2. Here, the main lobe width of analog beam is set as \( \theta_A = 30^\circ \) with the main lobe gain \( G_A = 20 \) dB and side lobe gain \( g_A = 0 \) dB. The noise power is assumed to be negligible. Each mmWave AP is assumed to be equipped with \( K = 12 \) RF chains, which indicates the spatial multiplexing gain \( k_i \leq 12 \). We remark that the intensity of \( \phi_i \) is equal to \( \Lambda_0 \), which is represented by the inter-APs distance \( r_0 = \sqrt{\frac{1}{\pi \Lambda_0}} \) [5]. For the path loss model, we use \( \beta = 1 \), \( \alpha_L = 2 \) and \( \alpha_N = 4 \) [6]. It can be observed from Fig. 3 that given the SINR threshold \( \tau \), the decrease of coverage probability \( C(\tau, k_i) \) is close to linear with the increase of \( k_i \). The other observation is that \( \phi_i \) with \( r_0 = 100 \) m and \( r_0 = 200 \) m result in the similar coverage probability of tier \( i+1 \). Since a higher density of transmitters results in a higher power of desired signal, but leads to a higher strength of interference.


C. Network Throughput

For a mmWave AP network, we define the throughput as the aggregate data rate of all relay tiers i.e. $\bigcup_{i=1}^{M} \Phi_i$. Consider the network, where each transmission hop follows the same protocol. It follows that $k_i = k, \forall i$. Consequently, the coverage probability of each tier is equal to $C(\tau, k)$. Assume that each AP in the network is assigned with the same bandwidth. We then derive the network throughput with respect to spatial multiplexing gain.

Theorem 3. Consider a mmWave AP network of density $\Lambda_A$, where the distribution of backhaul-connected APs follows a homogeneous PPP with intensity $\Lambda_0$. Assume that each hop follows the identical transmission protocol with the spatial multiplexing gain $k$, the network throughput is then given by

$$T(k) = \frac{(\Lambda_A - \Lambda_0)C(\tau, k) \log_2(1 + \tau)}{M} = Wk\Lambda_0 C(\tau, k) \log_2(1 + \tau),$$

where $\tau$ is the SINR threshold; $M = (\Lambda_A - \Lambda_0)/k\Lambda_0$ is the network latency; $W$ denotes the bandwidth of each AP; the coverage probability $C(\tau, k)$ is given in (9).

We remark that the throughput of a mmWave AP network $T(k)$ is dependent on the intensity of backhaul-connected APs i.e. $\Lambda_0$. However, $T(k)$ is independent of $\Lambda_A$.

In Fig.4, we show the network throughput derived in Theorem 3. The parameters used in Fig.3 and Fig.4 are the same. For a fixed intensity $\Lambda_0$, Fig.4 demonstrates the trade-off between the latency and coverage probability when choosing the spatial multiplexing gain $k$. It can be observed from Fig.4 that the network throughput is not monotonically varying with the spatial multiplexing gain. As the network latency can be improved by increasing $k$ whereas the degradation of coverage probability is considerable as $k$ increases. Moreover, the optimal spatial multiplexing gain is different depending on the SINR threshold. When the SINR threshold is low, the latency dominates the network throughput. Thus the higher spatial multiplexing gain corresponds to a higher throughput. In the region of high SINR threshold, the coverage probability becomes the bottleneck of performance. Therefore, the smaller spatial multiplexing gain results in a higher network throughput. By comparing the throughput of network with different $\Lambda_0$, Fig.4 then illustrates that the mmWave AP network can be benefit from the densification of tier 0.
V. CONCLUSION

We proposed to incorporate the multihop transmission protocol in modeling the ultra-dense mmWave AP network, where we introduced the tier to represent the APs belonging to one transmission hop. We then characterized the spatial distribution for each tier with respect to the spatial multiplexing gain. Our analysis indicated that the mmWave APs are uniformly distributed in the network if spatial multiplexing is disabled. However, the topology of mmWave AP network showed clustering pattern when the spatial multiplexing is enabled. From our performance analysis, the latency of mmWave AP network decreases as the spatial multiplexing gain increases, while the SINR coverage probability drops with the increase of spatial multiplexing gain. The numerical results showed the optimal spatial multiplexing gain to maximize the throughput of mmWave AP network.

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