Design Criteria on a mmWave-based Small Cell with Directional Antennas

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***Abstract*—Due to spectrum shortage in the conventional microwave bands, millimeter wave (mmWave) bands have been attracting great attention as an additional spectrum band for 5G cellular networks. In this paper, we show the feasibility of using a mmWave-based small cell with directional antennas. We investigate the effect of the number of antennas, n_{ant}, on the capacity and coverage probability, and propose an antenna clustering scheme (ACS) to utilize the antennas more efficiently. For a given n_{ant}, we also investigate the effect of the number of clusters, $n_{cluster}$, on the capacity and coverage probability. In addition, we propose two design criteria: a capacity-maximization criterion (CapMC) and a coverage-maximization criterion (CovMC), in the mmWave-based small cell. Each design criterion is formulated as a joint optimization problem to find the optimal values of n_{ant} and $n_{cluster}$ to maximize each objective function while satisfying system requirements such as capacity and coverage probability. Performance evaluation shows that CapMC can achieve the highest capacity while satisfying a given coverage probability requirement and CovMC can achieve the highest coverage probability while satisfying a given capacity requirement.**

***Index Terms*—mmWave, small cell, directional antenna, design criterion**

I. INTRODUCTION

Due to the increasing popularity of today's smartphones and tablets, mobile data traffic exhibits unprecedented growth, and many studies have been done to increase the system throughput, including PHY layer enhancements such as orthogonal frequency division multiplexing (OFDM), multiple-input multiple-output (MIMO) antenna technique for a high spectral efficiency [1], and heterogeneous networks (HetNets) [2]. However, these technologies are not sufficient enough to guarantee higher data rates due to a severe spectrum shortage problem in microwave bands. In order to meet the demand for higher data rates, new technologies for future 5G cellular networks have been investigated thoroughly. One of promising candidate technologies is to use a mmWave band. The mmWave band has been attracting great attention, since an enormous amount of bandwidth is available. Actually, the mmWave communication is not a state-of-the-art technique, since the mmWave band has already been used for personal area networking [3], and local area networking [4]. However, the potential of the mmWave for radio access networks has been spotlighted and studied recently [5] - [10].

To verify the feasibility of mmWave networks, Rappaport *et al.* [5] have performed various propagation measurements at 28 GHz in New York City in order to characterize non line-of-sight (NLOS) propagation of the mmWave signals. Moreover, they [6] introduced the motivation for new mmWave cellular systems and showed the possibility that the mmWave cellular networks at 28 GHz and 38 GHz can properly work when using steerable directional antennas.

Since the attenuation and penetration loss at high-frequency carriers are considerable [7], Akdeniz *et al.* [8] investigated the feasibility of broadband mmWave cellular networks and evaluated the capacity of a mmWave-based small cell with a cell radius of $100m$, which has a similar cell density of current 4G LTE systems.

Bai and Heath [9], [10] proposed an analytical framework which includes a blockage effect in order to reflect the propagation of mmWave signals in NLOS links and evaluated the performance of mmWave cellular networks in terms of coverage probability and achievable rate. Especially, in [9], from the viewpoint of a network, they showed that an increase in the base station density exceeding a critical point degrades the SINR and rate performance.

From the viewpoint of small cells, similarly to [9], it is also expected to show that an increase in antenna density beyond a critical point also degrades the system performance such as capacity and coverage probability. However, there have been no studies on this issue. Therefore, it is worthwhile to observe the effect of antenna density on the system performance such as capacity and coverage probability thoroughly.

In this paper, we introduce a mmWave-based small cell structure with directional antennas and propose an antenna clustering scheme (ACS) in order to utilize the antennas more efficiently. And then we investigate the performance of the mmWave-based small cell itself for varying system parameters such as the number of antennas, n_{ant} and the number of clusters, $n_{cluster}$. In addition, we propose two design criteria on the mmWave-based small cell, which are a capacity-maximization criterion (CapMC) and a coverage-maximization criterion (CovMC). Each design criterion can be formulated as a joint optimization problem to find the optimal values of n_{ant} and $n_{cluster}$ to maximize each objective function while satisfying given system requirements such as capacity and coverage probability.

The rest of this paper is organized as follows. In Section II, we describe a system model. In Section III, we introduce performance metrics such as system capacity and coverage probability. In Section IV, we propose two design criteria on a mmWave-based small cell with directional antennas. In Section V, we evaluate the performance in terms of system capacity and coverage probability by using Monte Carlo

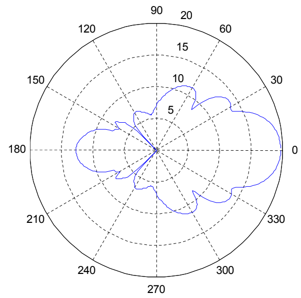


Fig. 1. A beamfomring pattern of the directional antenna

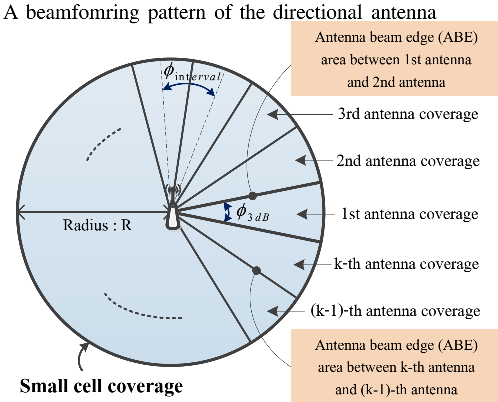


Fig. 2. The proposed small cell with multiple directional antennas, when n_{ant} = k

simulations. Finally, we draw conclusions in Section VI.

II. System Model

In this section, we introduce a mmWave-based small cell with directional antennas and an antenna clustering scheme (ACS) to utilize the antennas more efficiently.

A. Directional Antennas

In order to compensate for a large attenuation loss of mmWave signals, we use directional antennas with a high antenna gain. In [11], they use an idealized piecewise-linear array pattern [12] for simple analysis. In this paper, however, we use a rectangular planar array antenna as a directional antenna [13] in order to consider more practical radiation patterns. We use a narrow directional beamforming pattern obtained through computer simulation. The half-power beamwidth is denoted by ϕ_{3dB} and is assumed to be given by 20° [11]. Fig. 1 shows a beamforming pattern of the used directional antenna.

B. A mmWave-based Small Cell

We consider a single small-cell environment with multiple directional antennas. n_{ant} denotes the number of antennas in the cell, and we assume that all the antennas are arranged with the same interval, $\phi_{interval}$, which is defined as $2\pi/n_{ant}$. Users may suffer from a poor channel condition at the antenna beam-edge, where interference from the other antennas is strong. For convenience, we call this region the antenna beam-edge (ABE) area throughout the paper. Fig. 2 shows a mmWave-based small cell with multiple directional antennas.

C. Antenna Clustering Scheme (ACS)

In Subsection II-B, we mentioned the degradation in the ABE area due to severe interference from the neighboring antennas. The small cell uses spatial degrees-of-freedom (DoF) in order to reuse resources in spatial domain. As a result, it is natural that interference occurs in the ABE area, since multiple antennas transmit different signals (information) by using the same time-frequency resources. Antenna clustering defined here is that a given number of neighboring antennas transmit the same information by using the same time-frequency resources. If we use the concept of antenna clustering, the poor channel condition problem in the ABE area can be overcome efficiently. However, resource reutilization degrades as the number of antennas in a cluster increases since each cluster fully shares all the resources in spatial domain. According to varying user locations or user densities, antenna clustering is assumed to be configured. For simple analysis, however, we here focus on the uniform antenna clustering. The uniform antenna clustering here implies that all the clusters have the same number of antenna beams, therefore, the following equation always holds.

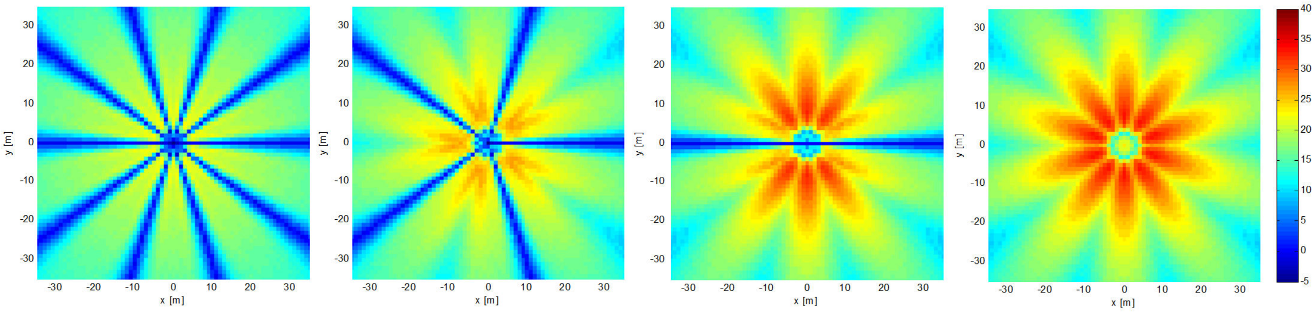
$$n_{ant} = n_{cluster} \times n_{ant}^{cluster}, \quad (1)$$

where $n_{ant}^{cluster}$ represents the number of antennas per cluster. If n_{ant} is given, $n_{cluster}$ and $n_{ant}^{cluster}$ are easily determined. From now on, $A_{i,j}$ respresents an ACS where $n_{cluster}$ is set to i, $n_{ant}^{cluster}$ is set to j, and n_{ant} is given by $i \times j$.

Fig. 3 shows the signal to interference-plus-noise ratio (SINR) distribution map of each ACS. In order to describe the effect of the ACS as an example, we assume that n_{ant} is set to 10. Here in this case, all possible $(n_{cluster}, n_{ant}^{cluster})$ pairs are (10, 1), (5, 2), (2, 5), and (1, 10). Two extreme cases: (10, 1) and (1, 10) show the effect of the antenna clustering clearly. Fig. 3(a) shows the SINR distribution map in case of using $A_{10,1}$, where each antenna beam comprises a single cluster. In this case, since there is only one antenna beam per cluster, resource reuse in space can be maximized, however, the SINR in the ABE area is poor. On the other hand, Fig. 3(d) shows the SINR distribution map in case of using $A_{1,10}$, where all antenna beams are clustered together. In this case, since all antenna beams are clustered into a single cluster, resource reuse in space can be minimized, however, the SINR in the ABE area is effectively improved.

III. System Capacity and Coverage Probability

In this section, we introduce two performance metrics: system capacity and coverage probability. *The system capacity implies an average capacity over the overall coverage area, and the coverage probability is defined as the probability that the received SINR of a user exceeds a certain threshold* [11]. In order to calculate the capacity and coverage probability, the SINR at an arbitrary position should be calculated first. The SINR is defined as the ratio of the received signal power to the sum of the interference power from all the other interfering signals and the noise power. To calculate the received signal



(a) $n_{cluster} = 10$, $n_{ant}^{cluster} = 1$ (b) $n_{cluster} = 5$, $n_{ant}^{cluster} = 2$ (c) $n_{cluster} = 2$, $n_{ant}^{cluster} = 5$ (d) $n_{cluster} = 1$, $n_{ant}^{cluster} = 10$

Fig. 3. The SINR distribution maps, which show the effect of antenna clustering when n_{ant} is set to 10

power, we consider a simple path-loss model as follows:

$$P_r = \frac{\alpha P_t G_t G_r}{r^{\beta}} \ , \ \alpha = \left(\frac{c}{4\pi f_c d_0}\right)^2 , \tag{2}$$

where P_r, P_t, G_t, G_r, r, β, c, f_c and d_0 denote the received signal power of a user equipment (UE), transmit signal power of a BS, transmit antenna gain, receive antenna gain, distance between the BS and UE, path-loss exponent, light speed, center frequency, and a reference distance of $1[m]$, respectively.

The SINR at a point $(r,\ \theta)$ in a polar coordinate is expressed as follows:

$$\gamma(r,\ \theta) = \frac{\sum\limits_{i \in H} S_i(r,\ \theta)}{\sum\limits_{j \in N \setminus H} I_j(r,\ \theta) + \sigma^2} \ , \tag{3}$$

where $S_i(r,\ \theta)$, $\sum\limits_{i \in H} S_i(r,\ \theta)$, $I_j(r,\ \theta)$, $\sum\limits_{j \in N \setminus H} I_j(r,\ \theta)$, σ^2, H, N represent the received signal power from the i-th antenna, the sum of the received signal power from the all the antennas in a home cluster H, interference from the j-th antenna, the sum of interference from the other antennas not belonging to the home cluster H, noise power over the system bandwidth, set of antennas belonging to the home cluster, set of all antennas, respectively. Home cluster represents a cluster which transmits the corresponding signals for point $(r,\ \theta)$.

System capacity can be represented by using the well-known Shannon capacity equation as follows:

$$C = n_{cluster} \int\limits_{A_{cluster}} B \log(1 + \gamma(r,\theta))\, f_{R,\Theta}(r,\theta)\, dr d\theta \tag{4}$$

where $f_{R,\Theta}(r,\theta)$ represents the joint probability density function (PDF) of a random variable r and a random variable θ, which represent the distance from the center of a cell and the rotation angle from the x-axis, respectively. $f_{R,\Theta}(r,\theta)$ can be reduced to $r/\pi R^2$ in case of a uniform distribution. Moreover, $A_{cluster}$ and B represent the coverage area of a cluster and the total system bandwidth, respectively. Since each cluster reuses resources in spatial domain, $n_{cluster}$ is multiplied.

In order to compare the cell coverage, we adopt the concept of the coverage probability, which is expressed as

$$\begin{aligned} p_c &= \Pr\{\gamma(r,\theta) > \gamma_{thresh}\} \\ &= \int\limits_0^{2\pi} \int\limits_0^{R} I(\gamma(r,\theta) > \gamma_{thresh}\,)\, f_{R,\Theta}(r,\theta)\, dr d\theta \end{aligned} \tag{5}$$

where γ_{thresh} represents a given SINR threshold and $I(\cdot)$ represents an indicator fuction which is defined as

$$I(x) = \begin{cases} 1\,, & \text{if } x > 0 \\ 0\,, & \text{otherwise}\,. \end{cases} \tag{6}$$

IV. Design criteria on a mmWave-based small cell

A. Capacity-maximization criterion (CapMC)

CapMC is a criterion which guarantees to achieve the highest system capacity satisfying both a given system capacity requirement and a given coverage requirement. Thus, the CapMC results in the upper bound of system capacity that a small cell yields. The CapMC can be formulated as a joint optimization problem as follows:

$$\begin{aligned} (n_{ant}^*, n_{cluster}^*) &= \underset{(n_{ant}, n_{cluster})}{\arg\max}\ C(n_{ant}, n_{cluster}) \\ s.t.\ \ C &\geq C^{target}\ and\ p_c \geq p_c^{target}\ , \end{aligned} \tag{7}$$

where C^{target} and p_c^{target} represent a given system capacity requirement and a given coverage probability requirement, respectively.

B. Coverage-maximization criterion (CovMC)

CovMC is a criterion which guarantees to achieve the highest coverage probability satisfying both a given system capacity requirement and a given coverage probability requirement. Thus, the CovMC guarantees reliable communication with high probability. The CovMC can be formulated as a joint optimization problem as follows:

$$\begin{aligned} (n_{ant}^*\,, n_{cluster}^*) &= \underset{(n_{ant}, n_{cluster})}{\arg\max}\ p_c\,(n_{ant},\ n_{cluster}) \\ s.t.\ \ C &\geq C^{target}\ and\, p_c \geq p_c^{target}\ . \end{aligned} \tag{8}$$

V. Performance Evaluation

We perform Monte Carlo simulations to evaluate the performance of a mmWave-based small cell for varying system parmameters: n_{ant} and $n_{cluster}$. Table I lists the simulation parameters. We assume that the system capacity requirement is set to $20Gbps$ and the target coverage probability is set to 0.9, which are expressed as sky-blue lines in all figures.

TABLE I
SIMULATION PARAMETERS AND VALUES

Parameters	Values
Transmission	Downlink
Path-loss exponent (β)	3.5 [5]
Transmit antenna gain (G_t)	According to Fig. 1
Receive antenna gain (G_r)	1 (Omni)
Center frequency (f_c)	28 GHz [7]
Total bandwidth (B)	1 GHz [7]
Thermal noise density (σ^2)	-174 dBm/Hz
Transmission power (P_{tx})	100 mW
The number of antennas (n_{ant})	$1 \sim 18$
The number of clusters ($n_{cluster}$)	Divisors of n_{ant}
Resource usage	Fully sharing per cluster

Fig. 4 shows the effect of n_{ant} on system capacity. 'Clustering k antennas' represents that a cluster consists of k antenna beams. For example, 'clustering 1 antenna' implies that a cluster consists of only a single antenna beam and 'clustering 2 antennas' implies that a cluster consists of two antenna beams. In case of a single antenna cluster, there exists an optimal n^*_{ant} which maximizes the system capacity. If we use a smaller number of antennas, then it may not be sufficient enough to cover the overall coverage area of the small cell. However, it is not always good to use a larger number of antennas to cover the entire cell area. Since each antenna shares the resource spatially, the interference among antennas becomes severe as n_{ant} increases, and it degrades the system capacity eventually. Even though more than two antennas are grouped into a cluster, the trend of the graph is not changed, while the optimal n^*_{ant} may vary. Since we can consider a cluster as an aggregated antenna beam, it is natural to observe the similar trend. In other words, we verify that increasing antenna density beyond a critical point degrades the system capacity.

Moreover, the system capacity decreases as $n^{cluster}_{ant}$ increases. For example, when n_{ant} is set to 12, Fig. 4 shows that the system capacity decreases from $50.37Gbps$ to $18.66Gbps$ as $n^{cluster}_{ant}$ increases. $50.37Gbps$ is achieved when $n_{cluster} = 12$, $n^{cluster}_{ant} = 1$, and $18.66Gbps$ is achieved when $n_{cluster} = 3$, $n^{cluster}_{ant} = 4$. As a result, when using the ACS, more antennas are required to achieve a given system capacity requirement, C^{target}. If a single antenna per cluster is used, at least 5 antennas are required. However, a total of at least 8 antennas, at least 12 antennas, and at least 16 antennas are required in case of clustering of 2, 3, and 4 antennas beams, respectively, in order to achieve a system capacity of at least $20Gbps$.

Fig. 5 shows the effect of n_{ant} on the coverage probability. Achieving a high coverage probability implies that users can obtain higher SINR values than γ_{thresh} with high probability. Since a small n_{ant} may not be sufficient enough to cover the target coverage area, this results in low p_c. However, a large n_{ant} also causes low p_c because the ABE area between two antenna beams is affected by the interference from the other antenna, and, thus, the SINR becomes worse. As a result, there also exists an optimal n^*_{ant} that maximizes the coverage probability. Although more than two antennas are grouped into a cluster, the trend of the graph is also not changed, while the optimal n^*_{ant} may vary. Because we can consider a cluster as an aggregated antenna beam, it is natural to observe

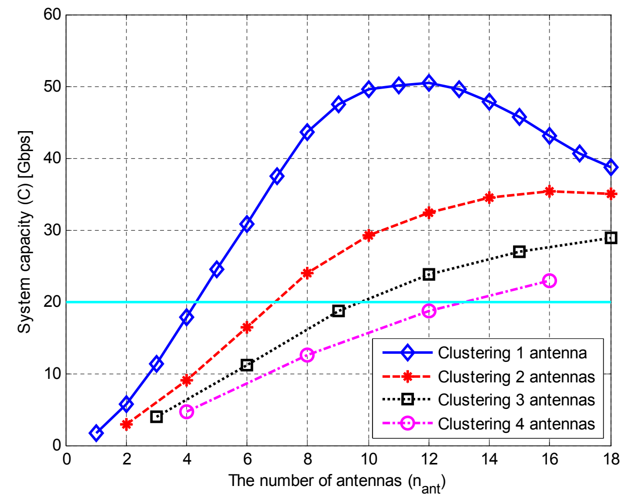


Fig. 4. The effect of the number of antennas on the system capacity

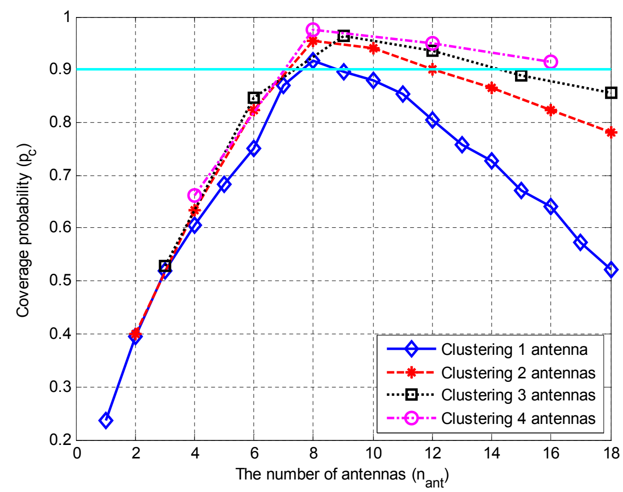


Fig. 5. The effect of the number of antennas on the coverage probability

the similar trend. Moreover, we observe that p_c becomes higher when $n^{cluster}_{ant}$ increases. For example, when n_{ant} is set to 8, Fig. 5 shows that p_c increases from 0.917 to 0.976 as $n^{cluster}_{ant}$ increases. Since the same signals are transmitted through multiple antennas in the same cluster, a diversity gain is achieved in space and the reliability of communication is improved, and, thus, users can achieve higher SINR values by transmitting a signal through multiple antennas in the same cluster. In other words, when n_{ant} is given, the coverage probability increases as $n^{cluster}_{ant}$ increases. As a result, it is better to use the antenna clustering in order to achieve higher coverage probability.

Fig. 6 shows the trade-off relationship between the system capacity and coverage probability. When n_{ant} and $n_{cluster}$ are given, we can obtain p_c and C from Fig. 4 and Fig. 5, and draw (p_c, C) in Fig. 6. It illustrates the result of two design criteria: the CapMC and CovMC. $A_{i,j}(p_c, C)$ represents that the achievable coverage probability is p_c and the achievable system capacity is C Gbps when $n_{cluster}$ is i and $n^{cluster}_{ant}$ is j. When n_{ant} is given, there are several options to cluster the antennas. For example, when n_{ant} is 8, there are four options to make a cluster, which are $A_{8,1}(0.917, 43.52)$, $A_{4,2}(0.955, 23.87)$,

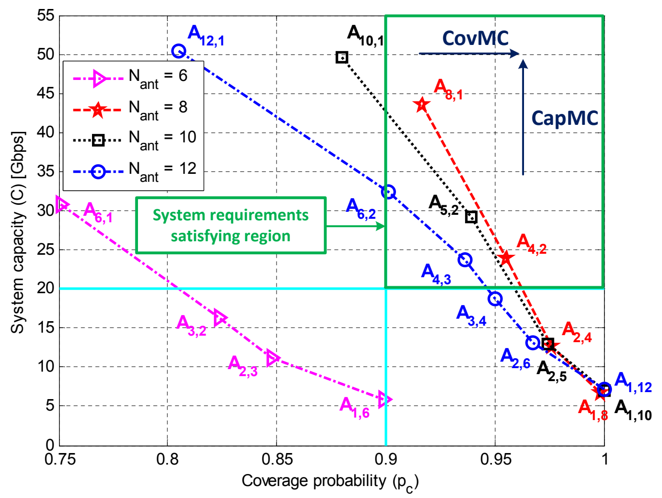


Fig. 6. Trade-off relationship between the system capacity and coverage probability

TABLE II
THE REQUIRED n_{ant} AND $n_{clsuter}$ ACCORDING TO CAPMC

System Requirements		CapMC	
C^{target}	p_c^{target}	$(n_{cluster}, n_{ant}^{cluster})$	(p_c, C)
10	0.9	(8, 1)	(0.917, 43.52)
10	0.95	(4, 2)	(0.955, 23.87)
20	0.9	(8, 1)	(0.917, 43.52)
20	0.95	(4, 2)	(0.955, 23.87)

$A_{2,4}(0.976, 12.57)$, and $A_{1,8}(0.999, 6.648)$. As $n_{cluster}$ decreases, the coverage probability increases, while the system capacity decreases. We have already observed in Fig. 4 and Fig. 5, increasing n_{ant} beyond a critical point degrades both the system capacity and coverage probability regardless of $n_{ant}^{cluster}$. As a result, in Fig. 6, most of ACS with $n_{ant} = 8$ outperforms the others in terms of both the system capacity and coverage probability.

Moreover, the region Λ shown as a green square represents a region which satisfies a given system requirement of both the capacity and coverage probability. All the points in the region Λ can be candidate solutions of the joint optimization problems, since they satisfy both constraints. The CapMC finds the furthermost point from the x-axis in the region Λ, which guarantees the highest capacity. Similarly, the CovMC finds the furthermost point from the y-axis in the region Λ, which guarantees the highest coverage probability.

Tables II and III show the solutions of the CapMC and CovMC, respectively, according to various system requirements. It is worth noting that the CapMC always achieve the highest capacity, while the CovMC always achieve the highest coverage probability. In case of system requirements of 20Gbps and 0.95, all the solutions show that the optimal n_{ant} is 8. We can achieve different objectives (capacity-maximization or coverage-maximization) by adjusting $n_{cluster}$.

VI. CONCLUSION

In this paper, we introduced a mmWave-based small cell with multiple directional antennas and proposed an antenna clustering scheme (ACS) in order to improve the small cell coverage. We investigated the effect of n_{ant} and $n_{cluster}$

TABLE III
THE REQUIRED n_{ant} AND $n_{clsuter}$ ACCORDING TO COVMC

System Requirements		CovMC	
C^{target}	p_c^{target}	$(n_{cluster}, n_{ant}^{cluster})$	(p_c, C)
10	0.9	(2, 4)	(0.976, 12.57)
10	0.95	(2, 4)	(0.976, 12.57)
20	0.9	(4, 2)	(0.955, 23.87)
20	0.95	(4, 2)	(0.955, 23.87)

thoroughly. In addition, we characterized two design criteria: a capacity-maximization criterion (CapMC) and a coverage-maximization criterion (CovMC), in a mmWave-based small cell. Each design criterion was formulated as a joint optimization problem to find the optimal values of n_{ant} and $n_{cluster}$ to maximize each objective function while satisfying a given capacity and a given coverage probability. Finally, we evaluated the performance by using Monte Carlo simulations. The CapMC achieves the highest capacity while satisfying a given coverage probability requirement and the CovMC achieves the highest coverage probability while satisfying a given capacity requirement.

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