Inter-BS Interference-aware Transmission Coordination for Millimeter Wave Networks

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***Abstract*—In millimeter-wave (mmWave) wireless networks, base stations (BSs) are capable of performing beamforming transmissions to deliver downlink data packets to user equipments (UEs). Despite the advantage of spatial diversity (through beamforming), as the number of BSs installed in the network increases, the packet delivery success probability may decrease because of the increasing interference from the beamforming transmissions of neighboring BSs. We propose the downlink transmission coordination methods that allow each BS to decide whether or not to perform a downlink transmission with respect to the level of inter-BS interferences.**

***Index Terms*—Millimeter-wave wireless network, beamforming transmission, downlink coordination.**

I. INTRODUCTION

WITH the explosive growth in wireless traffic demands, the saturation problem in the wireless frequency spectrum ranging from 700 MHz to 2.6 GHz has become very severe. As a means of resolving such a problem, millimeter-wave (mmWave) technology has received considerable attention, and it has become one of the most promising technologies for the future wireless network systems [1]. A mmWave spectrum has a short wavelength and allows the integration of highly-directional antenna arrays into small hand-held devices.

We consider a dense mmWave wireless network where the base stations (BSs) and mobile user equipments (UEs) are densely deployed and share a single wireless channel for directional data transmission. For establishing directional links from the BSs to UEs, the codebook-based beamforming technology is widely used. For example, a sector-sweep based beam selection method was used to enable BSs to select a beam towards destination UEs from a predefined set of beams so as to maximize the received signal strength (RSS) [2].

In a dense mmWave network with multiple BSs, simultaneous beamforming transmissions may interfere with each other, and the interference among highly directional beams results in a significant level of packet delivery failure. For example, as depicted in Fig. 1, let us assume that two BSs BS_i and BS_j perform their downlink beamforming transmissions, where r_T and r_I are the transmission and interference ranges, respectively. Then, UE_i located in area $\mathcal{D}$ may fail to receive the downlink packet successfully owing to the spatial interference incurred by the BS_j's beamforming transmission. Although the beams are selected through a beam selection scheme, coordinating the concurrent transmissions of the BS beams is necessary to avoid the spatial interference among the beams of BSs in dense mmWave wireless networks.

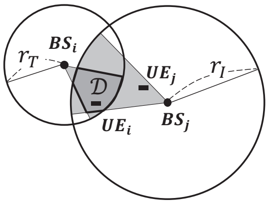

Fig. 1. Example of inter-BS downlink beamforming interference.

One method of preventing the spatial interference is to coordinate the downlink transmissions of the BSs by using the signal-to-interference-plus-noise ratio (SINR) information before transmitting a packet. However, collecting all the channel state information (CSI) and beamforming vectors in every coherence interval to calculate SINR is infeasible, especially in dense networks. In this letter, we propose two transmission coordination methods that exploit the BS-density based throughput analysis and the pairwise beam collision measurement among BSs, respectively. The BS-density based approach derives an optimal transmission probability that maximizes the network throughput for a given density of BSs in the network. The collision-measurement based approach uses the pairwise beam collision measurements among the BSs and performs a threshold-based transmission coordination. To the best of our knowledge, the proposed methods are the first transmission coordination schemes that use inter-BS collision probabilities as an indicator for expected data delivery failure for avoiding the spatial interferences among BSs in dense mmWave wireless networks without computing SINR.

II. SYSTEM MODEL

We consider a downlink scenario of a mmWave wireless network composed of N BSs and their associated mobile UEs. Let $\mathcal{N} = \{n_1, \cdots, n_N\}$ denote a set of BSs. The BSs are equipped with antenna arrays and perform codebook-based beamforming communication. Assume that each BS is capable of performing M directional transmissions. Then, the beamforming codebook, which is a matrix consisting of beamforming weight vectors [2], can be represented as $\mathbf{B} = [\mathbf{b}_1, \cdots, \mathbf{b}_M]$, where $\mathbf{b}_i \in \mathbb{C}^{n_{tx}}$ is the i-th beamforming vector and n_{tx} is the number of BS antennas. Meanwhile, the UEs are equipped with a single antenna and operate in an omnidirectional mode to receive the downlink packets [3]. Based on the beamforming codebook, the BSs adjust the phase of each antenna to send data packets to their respective UEs in

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specific directions. In this letter, we assume that a sector-sweep based beam selection method is used to select a beamforming weight vector that maximizes RSS at the destination UE from the codebook. Further, we assume that the BSs are connected through a backbone network and that they are synchronized with each other. The BSs broadcast their downlink scheduling that indicates the index of the beamforming vectors to be used for transmission, through the backbone network, in order to share the information with each other.

Let $\Gamma_i(u)$ denote the SINR at UE u. $\Gamma_i(u)$ is given by

$$\Gamma_i(u) = \frac{p_t|^T\mathbf{h}_{n_i,u}\mathbf{b}_{n_i}|^2}{\sum_{n_j \in \mathcal{N}\setminus\{n_i\}} p_t|\mathbf{h}_{n_j,u}\mathbf{b}_{n_j}|^2 + N_0 W}, \qquad (1)$$

where p_t is the transmission power of BSs, $\mathbf{h}_{n_i,u} \in \mathbb{C}^{1\times n_{tx}}$ is the channel gain between n_i and u, $\mathbf{b}_{n_i} \in \mathbf{B}$ is a complex beamforming vector of n_i, N_0 is the noise power, and W is the channel bandwidth. We assume that the channel gain matrix is invariant over a single data transmission time. Then, u can successfully receive the downlink data packets when SINR $\Gamma_i(u)$ is greater than a certain threshold Υ. As more BSs are deployed in the network, the successful downlink transmission probability may decrease because of the increasing interference from neighboring BSs. Therefore, it is desirable to coordinate the downlink transmissions of BSs in order to avoid transmission failures due to inter-beam interferences.

III. PROPOSED TRANSMISSION COORDINATION

A. BS-density based coordination approach

First, we propose a BS-density based transmission coordination approach for downlink scenarios. For tractability, we consider a protocol model to derive the successful delivery of a downlink packet. Let $\Gamma_{i,j}(u)$ denote the SINR at UE u where the j-th BS is the only BS that interferes with the downlink transmission of the i-th BS. Under the protocol model, u can successfully receive the downlink data packets when SINR $\Gamma_{i,j}(u)$ is greater than threshold Υ for all $n_j \in \mathcal{N} \setminus \{n_i\}$. Note that although the protocol model is less accurate than the physical model, it is widely used for MAC layer performance analysis because of its simplicity. Recent research results in [4], [5] show that the protocol model is quite accurate in mmWave band because of the mmWave signal characteristics such as high attenuation, directivity, and LoS-oriented propagation.

Let X_n denote the location of n. The interference range r_I is given by $r_I = (\alpha+1)|X_{n_i} - X_u|$ with a positive value for α, which varies according to the SINR threshold Υ [5]. Then, n_i can successfully deliver the downlink data packet to u if the following holds true:

$$|X_{n_i} - X_u| \le r_T \text{ and } |X_{n_j} - X_u| \ge r_I,\ \forall n_j \in \mathcal{O}(u) \setminus \{n_i\},$$

where r_T is the transmission range, and $\mathcal{O}(u) \subseteq \mathcal{N}$ is the subset of the BSs whose beamforming transmission directions are towards u. If r_T, α, and X_u are given, the successful packet delivery to the UE depends solely on the locations of BSs. Let us define a collision between two BSs as a delivery failure to UEs that belong to the BSs. Then, the collision probability between two arbitrary BSs depends on the Euclidean distance between the BSs, assuming that a sufficiently large number of UEs exist on the network.

We analyze the aggregate throughput performance of the mmWave wireless network when the BSs have the transmission probability of δ $(0 \le \delta \le 1)$, and the probability that the BSs use the k-th beamforming vector for transmission is equal to $\frac{1}{M}$ for all $k \in \{1, \cdots, M\}$.

Proposition 1: Under the assumption that the wireless network is a homogeneous Poisson network over a large area $\mathcal{A}$ with a BS deployment intensity λ and that the BSs have the transmission probability δ, the expectation of the aggregate number of successful packet deliveries can be calculated as

$$\mathbb{E}[\Theta(\delta)] = \lambda\mathcal{A}\delta \int_0^{r_T} \prod_{i=1}^{N_c} \left(1 - \delta \int_0^{(\alpha+2)r_T} S(\eta,\psi)\ g_i(\eta) d\eta\right) f(\psi)\ d\psi,$$

where $\mathcal{S}(\eta,\psi)$ is the collision probability at a UE, $g_i(\eta)$ is the pdf of a generalized Gamma distribution, N_c is the number of effective neighboring BSs, and $f(\psi)$ is a pdf of a distance from a BS to its associated UE. Note that ψ and η are the distances from a BS to its UE and neighboring BS, respectively.

Proof: Under a homogeneous Poisson distribution, the pdf of the Euclidean distance from a BS to the i-th nearest neighboring BS is given by a generalized Gamma distribution [6] as follows:

$$g_i(\eta) = \frac{(\lambda\pi)^i \eta^{2(i-1)}}{(i-1)!}\ e^{-\lambda\pi\eta^2}\ 2\eta. \qquad (2)$$

Let $q(\psi)$ denote the transmission success probability when an arbitrary UE is ψ meters apart from its associated BS. Using (2), it is given by

$$q(\psi) = \prod_{i=1}^{N_c} \left(1 - \delta \int_0^{(\alpha+2)r_T} S(\eta,\psi)\ g_i(\eta) d\eta\right). \qquad (3)$$

Here, N_c has a finite value due to the high oxygen absorption in mmWave band, and its value depends on the SINR threshold and BS intensity. In addition, $\mathcal{S}(\eta,\psi)$ is the collision probability at a UE caused by beamforming transmission of its neighboring BS when ψ and η are given. It can be obtained by calculating the interference circular sector within a transmission circle and dividing the angle of interference circular sector by $2\pi M$ as follows:

$$\mathcal{S}(\eta,\psi) = \frac{1}{\pi M} \mathrm{Re}\left\{\cos^{-1}\left(\frac{\eta^2 + \psi^2 - ((1+\alpha)\psi)^2}{2\eta\psi}\right)\right\}.$$

The expectation of the successful packet delivery probability of an arbitrary BS in the network is given by

$$\mathbb{E}[P_s(\delta)] = \delta \int_0^{r_T} q(\psi)\ f(\psi)\ d\psi. \qquad (4)$$

Then, the aggregate number of successful packet deliveries is obtained by $\mathbb{E}[\Theta(\delta)] = \lambda\mathcal{A} \times \mathbb{E}[P_s(\delta)]$. ■

Under the assumption of a homogeneous Poisson network, the optimal δ^* can be numerically obtained by solving optimization problem $\delta^* = \arg\max_{0\le\delta\le1} \mathbb{E}[\Theta(\delta)]$. Note that $f(\psi)$ depends on the association rule adopted in the network. If the UEs are associated with the nearest BS, then $f(\psi) = g_1(\psi)$ in (2) due to the homogeneity of the Poisson network.

B. Collision-measurement based coordination approach

We also propose a practical measurement-based downlink transmission protocol that maximizes the network throughput using collision measurement for each pair of beams transmitted by adjacent BSs. The proposed protocol allows the BSs to exchange their downlink beamforming information determined by a beam selection scheme and to decide whether or not each BS transmits according to a threshold-based transmission policy in a distributed manner.

We define an inter-BS collision matrix (IBCM) to specify the packet delivery failure probabilities for all pairs of beamforming transmissions of the BSs. Let $\mathbf{C}_{i,j} = (c_{i,j}(k,l))_{M\times M}$ denote the IBCM between the i-th and j-th BSs, where $c_{i,j}(k,l)$ is the probability that a downlink packet transmitted by the k-th beamforming of the i-th BS fails to be delivered due to the interference incurred by the l-th beamforming transmission of the j-th BS. The probability $c_{i,j}(k,l)$ can be represented as

$$c_{i,j}(k,l) = \Pr\left[\Gamma_{i,j}(u) \le \Upsilon \,|\, u \in \mathcal{U}_i^k, \mathbf{b}_{n_j} = \mathbf{b}_l\right], \tag{5}$$

where $u \in \mathcal{U}_i^k$ represents the UE for which the i-th BS uses the k-th beamforming vector to perform the downlink transmission.

Based on the IBCM, we define a threshold-based transmission policy. Let τ_{th} $(0 \le \tau_{th} \le 1)$ denote the transmission policy used as a threshold for the packet delivery failure probability. Let us suppose that the i-th and j-th BSs are to transmit to their UEs using the k_i-th and k_j-th beamforming vectors, respectively. If $c_{i,j}(k_i,k_j) \le \tau_{th}$, then the i-th BS is allowed to transmit using the k_i-th beamforming vector. Otherwise, the transmission of the i-th BS is prohibited. Note that this is a pairwise comparison for any pairs of BSs. If more than one interfering BSs exist, the i-th BS is allowed to transmit only when $c_{i,j}(k_i,k_j) \le \tau_{th}$ for all interfering BSs.

In the proposed protocol, a single downlink transmission is divided into a *scheduling session* and a *data session* with p slots as shown in Fig. 2. A detailed procedure of the proposed method is as follows:

(S1) In the scheduling session, each BS chooses a set of UEs for providing the downlink service and carries out the sector-sweep based beam selection operation to decide the beamforming index. Afterward, they broadcast their downlink information about which one of the M downlink beamformings will be performed in each slot.

(S2) After exchanging the entire downlink information with the neighboring BSs, each BS looks up the IBCMs. If $\max_{j\in\mathcal{N}} c_{i,j}(k_q^i, k_q^j) \le \tau_{th}$, the i-th BS performs its downlink transmission in the q-th slot. Otherwise, the i-th BS is prohibited from transmitting its data packet.

The inter-BS collisions are measured by the ratio of the successful transmissions to the total number of transmission attempts for each pair of BSs. Note that the BSs do not need to compute $\Gamma_{i,j}(u)$ to obtain the $c_{i,j}(k_q^i, k_q^j)$ in (S2).

Figure 2 shows an example of how the proposed method operates in a wireless network with three BSs. Let $c_{1,2}(7,3)$, $c_{2,3}(2,3)$, and $c_{3,2}(3,2)$ be greater than τ_{th}. In the first slot, all BSs perform their downlink transmissions because their maximum packet delivery failure probabilities are less than τ_{th}. In the third slot, BS_2 and BS_3 are prohibited from transmitting their packets because of the mutual interference. In the second slot, BS_1 is prohibited from transmitting its packet owing to the interference incurred by BS_2, while BS_2 transmits its packet. This is because $c_{1,2}(7,3) \ne c_{2,1}(3,7)$ and $c_{2,1}(3,7) \le \tau_{th}$. Note that the spatial interference of pairwise beams depends on the relative location of BSs, and the IBCM remains unaffected even though the UEs move on the network.

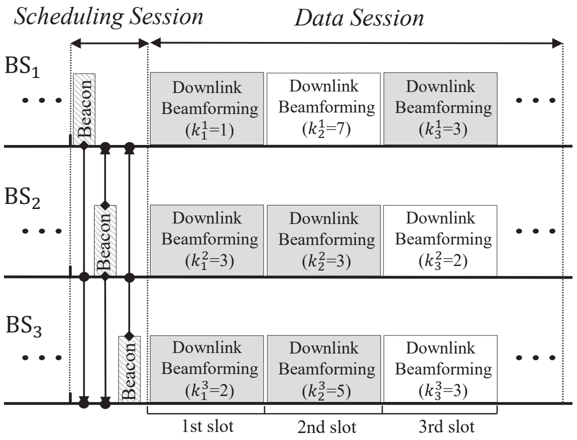

Fig. 2. Example of the proposed downlink transmission method.

Similar to the analysis in Section III-A, we formulate an optimization problem to determine the optimal transmission policy τ_{th}^* that maximizes the network throughput performance. We assume that the UEs are uniformly distributed within the transmission ranges of the BSs and that each BS always has data packets to transmit to its associated UEs. Then, the probability that a BS performs the k-th downlink beamforming transmission is equal to $\frac{1}{M}$ for all $k \in \{1,\cdots,M\}$. For a given threshold τ_{th}, we can derive the successful packet delivery probability of the i-th BS as follows:

$$p_{\text{s},n_i}(\tau_{th}) = \sum_{k=1}^{M} p_{n_i,k}^{\text{tx}}(\tau_{th}) \prod_{n_j\in\mathcal{N}\backslash n_i} \{1 - \sum_{l=1}^{M} p_{n_j,l}^{\text{tx}}(\tau_{th}) q_{i,j}^{k,l}(\tau_{th})\}, \tag{6}$$

where $p_{n_i,k}^{\text{tx}}(\tau_{th})$ is the transmission probability of the k-th beam of the i-th BS, and $q_{i,j}^{k,l}(\tau_{th})$ is the packet collision probability due to the interference incurred by the l-th beam of the j-th BS. Let $\mathcal{A}_{i,j,k}(\tau_{th}) = \{c_{i,j}(k,l) | c_{i,j}(k,l) \le \tau_{th}, \forall l \in \{1,\cdots,M\}\}$ denote the subset of collision probabilities less than or equal to τ_{th}. Then, $p_{n_i,k}^{\text{tx}}(\tau_{th})$ is given by $p_{n_i,k}^{\text{tx}}(\tau_{th}) = \prod_{n_j\in\mathcal{N}\backslash\{n_i\}} \frac{||\mathcal{A}_{i,j,k}(\tau_{th})||}{M^2}$, and $q_{n_i,n_j}(\tau_{th}) = c_{i,j}(k,l)$ if both $c_{i,j}(k,l)$ and $c_{j,i}(l,k)$ are less than or equal to τ_{th}; otherwise, $q_{n_i,n_j}(\tau_{th}) = 0$. Using (6), the aggregate number of successful packet deliveries is obtained as $\Theta(\tau_{th}) = \sum_{n_i\in\mathcal{N}} p_{\text{s},n_i}(\tau_{th})$. Finally, the optimal downlink transmission policy of τ_{th}^* is formulated as an optimization problem as follows:

$$\tau_{th}^* = \arg\max_{0\le\tau_{th}\le 1} \Theta(\tau_{th}). \tag{7}$$

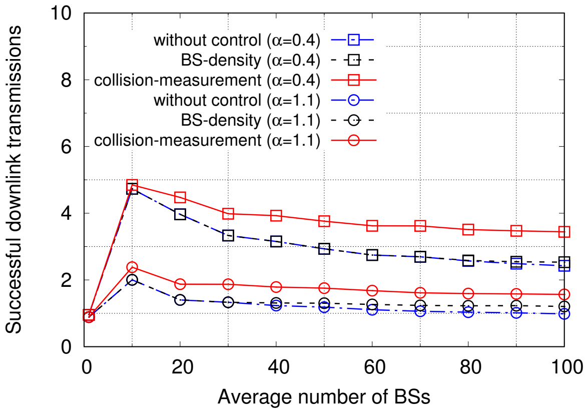

Fig. 3. Simulation results in a homogeneous Poisson network.

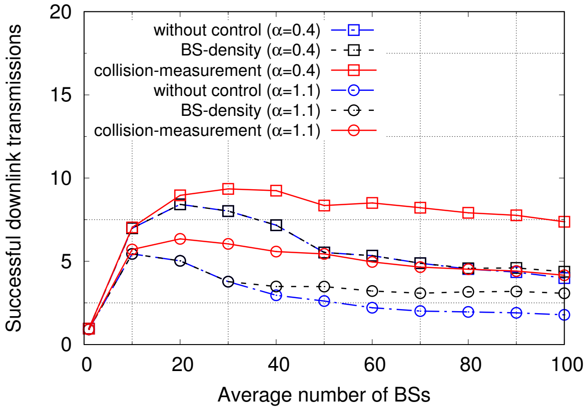

Fig. 4. Simulation results in an inhomogeneous Poisson network.

IV. PERFORMANCE EVALUATION

We conducted extensive simulations using MATLAB. In the simulations, the BSs are randomly deployed according to homogeneous or inhomogeneous Poisson point processes in the network within an area of $\mathcal{A} = 500 \times 500$ m^2. In the homogeneous Poisson network, the intensity of the BSs is constant over the network area. In the inhomogeneous Poisson network, the intensity follows a symmetric bivariate Gaussian model. The UEs are uniformly distributed in the transmission area of the BSs and move slowly so that the beamforming index for the UE does not change within a single downlink slot. We performed our simulations using the SINR model in (1), where the UEs may be affected by more than one interfering BSs. For comparison purposes, a naive method without coordination control is considered where all the BSs transmit their packets in every downlink session.

Figure 3 shows the aggregate number of successful downlink transmissions with respect to the number of BSs in the homogeneous Poisson network, when the transmission range is 150 m, and the number of beamforming vectors is 8. The figure shows that, as more BSs are deployed in the network, the performance of all the methods gradually decreases because of the increase of inter-BS beamforming interference. Nevertheless, the proposed methods achieve better performance than the naive method (without control). The proposed methods successfully alleviate the performance degradation caused by inter-BS beamforming interference by allowing the downlink transmission with relatively low collision probability. The figure also shows that the collision-measurement based approach achieves better performance than the BS-density based approach. This is because the collision-measurement based method allows each BS to exploit the beam selection information for impending transmissions of its neighboring BSs to avoid the inter-BS beamforming interference when it performs its transmission in every transmission session. The practical throughput for data delivery under the collision-measurement based method decreases as the length of the scheduling session increases. Note that the length of the scheduling session is quite short because a wired high-speed backbone network is used for the exchanges of beacon packets among the BSs during the scheduling session.

Figure 4 shows the aggregate number of successful downlink transmissions in the inhomogeneous Poisson network. The figure also shows that the proposed methods achieve better performance than the naive method, and in comparison with the results Fig. 3, the performance discrepancy between two proposed methods becomes larger. The BS-density based method is derived under the assumption of homogeneous Poisson network, which does not hold in this case. On the other hand, the collision-measurement based method successfully characterizes the heterogeneity of the per-beam spatial interference by the IBCM to obtain the optimal transmission policy in heterogeneous network. As a result, the collision-measurement based method achieves an optimal transmission policy that exploits the high spatial diversity of beamforming in realistic network scenarios.

V. CONCLUSION

We proposed two transmission methods for maximizing the aggregate throughput in a dense mmWave wireless network. The BS-density based approach provides an optimal transmission probability of BSs for a given BS density of the network. The collision-measurement based approach allows the BS to perform its downlink transmission only when its maximum collision probability is less than a threshold.

REFERENCES

[1] Z. Pi and F. Khan, “An introduction to millimeter-wave mobile broadband systems,” in *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 101-107, 2011.

[2] J. Wang, Z. Lan, C.-W. Pyo, T. Baykas, C.-S. Sum, M. A. Rahman, J. Gao, R. Funada, F. Kojima, H. Harada, and S. Kato, “Beam codebook based beamforming protocol for multi-Gbps millimeter-wave WPAN systems,” in *IEEE J. Sel. Areas Commun.*, vol. 27, no. 8, pp. 1390-1399, 2009.

[3] H. Shokri-Ghadikolaei, C. Fischione, G. Fodor, P. Popovski, and M. Zorzi, “Millimeter wave cellular networks: A MAC layer perspective,” in *IEEE Trans. Commun.*, vol. 63, no. 10, pp. 3437-3458, 2015.

[4] H. Shokri-Ghadikolaei and C. Fishione, “The transitional behavior of interference in millimeter wave networks and its impact on medium access control,” in *IEEE Trans. Commun.*, vol. 64, no. 2, pp. 723-740, 2016.

[5] S. Singh, R.Mudumbai, and U. Madhow, “Interference analysis for highly directional 60-GHz mesh networks: The case for rethinking medium access protocol,” in *IEEE/ACM Trans. Netw.*, vol. 19, no. 5, pp. 1513-1527, 2011.

[6] D. Moltchanov, “Distance distributions in random networks,” in *Ad Hoc Networks*, vol. 10, no. 6, pp. 1146-1166, 2012.