'Early-Late' Coordinated Beam-Scheduling Aided MmWave Cellular Networks

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***Abstract*—As a benefit of using highly directional beams in millimeter wave systems the downlink inter-cell interference (ICI) imposed on the users can be mitigated, provided that the beams of neighbor cells do not point towards the user. We exploit this by designing a protocol for network-coordinated time-domain beam scheduling. Specifically, every pair of neighboring cells maintains a beam-collision table for recording the pairs that may inflict ICI upon each other. Then, to avoid beam-collision, the two neighbor cells exchange the necessary information to avoid their simultaneous activation. More explicitly, our protocol supports a distributed cell coordination method without requiring any information exchange between the user and the base station, once the beam collision table has been established. Furthermore, our theoretical analysis and numerical simulations demonstrate that the proposed protocol is capable of efficiently mitigating the ICI between the adjacent cells and hence improves the overall network performance.**

I. Introduction

In millimeter wave (mmWave) communication highly directional beams are adopted for transmission [1], [2], hence downlink inter-cell interference (ICI) is only imposed if the beam of an interferring cell also points towards the served user. Hence, compared to sub-5 GHz systems, which tend to have less sharp radiation patterns, the effect of inter-cell interference (ICI) is typically more severe in mmWave systems. However, to guarantee a high area spectral efficiency (ASE), mmWave systems tend to use a dense set of BSs, which aggravates the ISI effects [3], [4].

Against this background, we conceive coordinated scheduling for the medium access control (MAC) layer in order to mitigate the ICI. Here we continue by briefly reviewing the related contributions. In [5], the beams in each cell are scheduled in the time-domain for maximizing the sum rate, where all users in a cell are assumed to occupy the same time-domain resources. However, in practical systems the service requests of different users tend to be different, which should also be taken into account. As a further deveopment, frequency-domain resource allocation is investigated in [6] with the same objective of maximizing sum rate. Naturally, maximizing the sum rate is desirable, but it requires accurate channel state information (CSI) knowledge between each user and each BS across the entire network, and a central controller for coordinating scheduling in all cells. This would result in an excessively complex implementation. As an alternative solution, in [7] one of two adjacent cells is muted if the beams of the two cells interfere each other. This muting technique is easy to implement and efficiently mitigates the ICI, but the muted time or frequency resources impose a significant throughput loss.

Against the above background, we propose a technique referred to as the Early-Late (EL) protocol for coordinated beam scheduling in the time-domain. Specifically, every pair of neighbor cells maintains a beam-collision table for keeping track of the specific beam pairs potentially imposing ICI on each other. Therefore, we arrange for the neighbor cells to exchange control information if the two beams of a pair will be scheduled in the same time period. Explicitly, this control information ensures that one of the two beams is scheduled early in the N-TS period, while the other one is scheduled late in the N-TS period considered, which significantly reduces the probability of beam collision. Furthermore, an EL balancing mechanism is proposed for roughly equalizing the number of beams scheduled early and late in the N-TS period considered for the sake of further improving the network's performance. In the EL protocol, the coordination between cells is carried out in a distributed manner for ease of implementation in practical systems. As a further benefit, once the beam collision table is established, no further CSI exchange is required. The benefits of our proposal are demonstrated by our theoretical analysis and confirmed by our numerical simulations.

II. System Model

We consider the regular hexagonal cells as shown in Fig. 1(a). The total number of cells in the network is denoted as K. For each cell, we assume that every 60° sector is covered by b beams, and hence there are $B = 6b$ beams in total. Then, we define a time slot as the minimum time duration of a beam scheduling action. Every cell uses a single beam to serve a user during each time slot (TS). The cell coordination is performed once per time period constituted by N TSs.

Since every user is served by a beam of its local base station (BS), we treat the user-scheduling problem as a beam-schedulikng problem, i.e. the scheduling of serving a user is treated as that of the beam serving it. Hence for each N-TS period, we assume that there are M users in each cell served by M different beams. The beam training procedure is assumed to

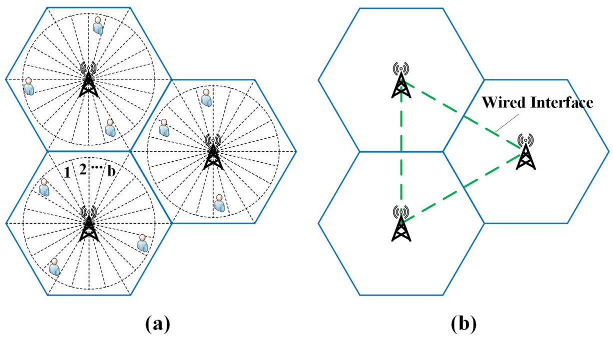


Fig. 1. Regular hexagon cell model. (a) There are b beams in each $60°$ sector and each user in a cell is served by a certain beam. (b) Every two neighbor cells is connected by a wired interface (green dashed line) for information exchanging.

be accomplished, i.e. each user is served by a certain known beam. The resource demand of the mth user in cell k in a specific N-TS period is denoted as $d_{k,m}$, which indicates that cell k should allocate $d_{k,m}$ time slots to the particular beam, which serves the mth user. The sum of resource demands of M users in each cell should be N, which can be written as

$$\sum_{m=1}^{M} d_{k,m} = N, k = 1, \cdots, K. \tag{1}$$

Additionally, we assume that M is a relatively small number compared to B and N, which indicates that the number of users scheduled in an N-TS period is small.

The so-called flat-top beam pattern of [8] is adopted in our model. The directional power gain of a beam is denoted as $G(\phi)$, where ϕ represents the angular offset wrt the boresight of the beam, while $G(\phi)$ can be expressed as

$$G(\phi) = \begin{cases} G_{max}, & |\phi| \leq \frac{\phi_b}{2}, \\ G_{min}, & |\phi| > \frac{\phi_b}{2}, \end{cases} \tag{2}$$

where ϕ_b is the beamwidth, and the power gain is a constant G_{max} if ϕ is within the beamwidth, while it is a constant G_{min}, if ϕ is outside the beamwidth. Given our setting in Fig. 1(a), the beamwidth is $\phi_b = \frac{2\pi}{B}(\frac{\pi}{3b})$.

Similar to the X2 interface of the LTE system, the neighbor cells are fed by optical fibers for example, as shown in Fig. 1(b). Hence the pair of neighbor cells can exchange information via the flawless optical backbone to perform cell coordination relying on a high bandwidth and low latency.

III. 'Early-Late' Protocol

In this section, the EL protocol is proposed for mitigating the mmWave ICI. We firstly introduce thr beam collision table and its maintenance approach. Then, based on the beam collision table, the EL information can be exchanged via the optical fiber to avoid beam collision. Moreover, we propose an EL balancing mechanism for further reducing the probability of beam collision.

A. Beam Collision Table

Since the downlink ICI originates from the coverage overlap of two beams from a pair neighbor cells, we create a beam collision table to record beam pairs in two neighbor cells as and when they are used simultaneously. To exemplify this situation, the beam collision tables of 3 cells are illustrated in Fig. 2. For every two neighbor cells, the adjacent two $60°$ sectors between the two cells contain $2b$ beams, which may interfere with thier neighbor cell, and the $2b$ beams are paired on a one-to-one basis as b beam pairs in the beam collision table. If the two beams that aer deemed to be a pair are used simultaneously within the same time slot, a beam collision event occurs, which again results in strong ICI between two neighbor cells. Therefore, our principle is to minimize the number of beam collisions for mitigating the ICI.

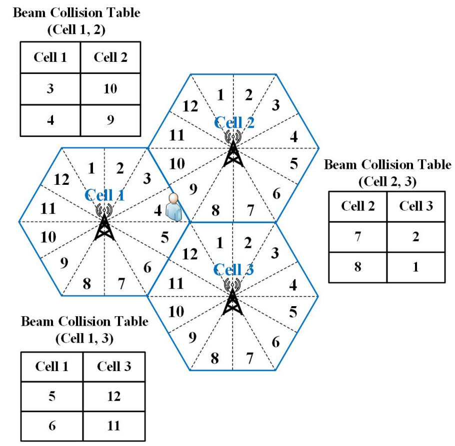


Fig. 2. An example of beam collision table between 3 cells with $b = 2$, where the coverage areas of $B = 12$ beams in each cell are marked by beam indices.

It should be noted that the beam collision table only includes beam pairs, which may inflict strong ICI upon each other, while the remote ICI arriving from other cells is not recorded in the beam collision table. For example, beam 12 of cell 3 may interfere with beam $3, 4$ of cell 1. However, a remote inteferer has a low interference power, hence only imposes a low performance loss, but it is again, it is hard to avoid, when the number cells K is high. By contrast, the power of the strong adjacent-cell ICI is close to that of the serving cell, hence we consider the strong ICI caused by beam collision.

In practical systems the beam collision table can be trained as follows. During an unallocated TS the user can measure the signal arriving from the neighbor cells. By contrast, a non-zero-power reference signal (NZP-RS) can be transmitted for estimating the desired signal power. For example, observe in Fig. 2 that cell 1 can disable its signal transmitted to a local user served by beam 4 for facilitating the above-mentioned interference measurement, while cell 2 sends a NZP-RS by beam 9 and cell 3 disables its transmission through an arbitrary beam. In this way, the user can measure the ICI caused by beam 9 of cell 2, and a strong ICI would be measured and reported to cell 1. Therefore, the BS of cell 1 would conclude that beam 4 collides with beam 9 of cell 2, and hence would enter beam pair $(4, 9)$ into its beam collision table with cell 2.

Since both the localizations of BSs and the directions of beams in each BS are fixed, the beam pairs in beam collision table should remain valid for a long period, unless there is a significant change in the interference environment owing to mobility, for example. Hence the update period of beam pairs can be long, which indicates that the pilot overhead imposed by maintaining the beam collision table remains low.

B. 'Early-Late' Information Exchange

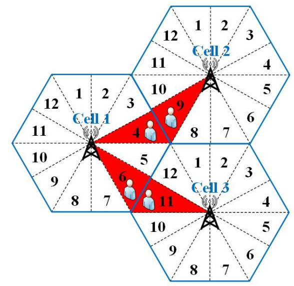
From now on we assume that the beam collision tables between every two neighbor cells have already been established. Then, if two beams experiencing beam collision are scheduled for the same N-TS period, we refer to them as a colliding pair. We then arrange for one of the two beams in a colliding pair to be scheduled at the beginning and the other one to be scheduled at the end of the N-TS period, which requires some information exchange for supporting coordinated beam scheduling.

Firstly, every cell keeps a list of the beams that tend to be scheduled at the beginning and at the end of the N-TS period, respectively. Next, we define two types of EL information, including EL request (REQ) and EL acknowledgement (ACK). For a certain time period, if cell k_1 plans to schedule beam m_1 which may cause beam collision with beam m_2 of a neighbor cell k_2, cell k_1 should send a EL REQ to cell k_2. The EL REQ includes the beam index m_1, and a 1-bit flag indicating, whether beam m_1 tends to be scheduled near the beginning or near the end of the N-TS period. When cell k_2 receives the EL REQ, it should check whether beam k_2 is planned to be scheduled in the N-TS period. If beam k_2 will indeed be scheduled, cell k_2 feeds back a positive EL ACK, which indicates that beam m_2 will be used. Then, the two beams form a colliding pair, so cell k_1 should add beam m_1 either into its early or late list as indicated by the EL REQ, and cell k_2 should add beam m_2 into the other list. If k_2 will not be scheduled, then cell k_2 should feed back a negative EL ACK, which indicates that beam m_2 will not be used. In this case, the two beams do not form a colliding pair, so neither cell k_1 nor k_2 should update the early or late list. Additionally, if cell k_1 has previously fed back an EL ACK to cell k_2, cell k_1 does not have to send an EL REQ to cell k_2.

Following the EL information exchange, the two beams in every colliding pair are respectively added into an early and and a late list. Then, each cell can determine the time-domain sequence of the beams in the N-TS period according to the two lists, i.e. the beams in the early list are scheduled at the beginning and those in the late list are scheduled at the end, where the sequence of beams recorded in the same list can be arbitrary.

C. 'Early-Late' Balancing Mechanism

If there are multiple beams recorded in say the early list, only one of the beams can be scheduled at the beginning of the N-TS period, while the other beams are scheduled late. The late-scheduled beams are more likely to cause beam collision. As demonstrated in Fig. 3, there is a colliding pair $(4, 9)$ between cell 1 and cell 2 and a colliding pair $(6, 11)$ between cell 1 and cell 3. After EL information exchange, we may



	Forward List	Backward List
Cell 1	{4}	{6}
Cell 2	{}	{9}
Cell 3	{11}	{}

(a) FB Balance (Preferred)

	Forward List	Backward List
Cell 1	{4,6}	{}
Cell 2	{}	{9}
Cell 3	{}	{11}

(b) FB Imbalance (Not Preferred)

Fig. 3. Two colliding pairs are between cell 1 and cell 2, cell 1 and cell 3, respectively. (a) Balanced forward list and backward list. (b) Imbalanced forward list and backward list.

arrive at the EL-balanced scenario of Fig. 3(a) or at the EL-unbalanced case of Fig. 3(b). For the EL-balanced case, the colliding pair $(6, 11)$ indeed encounters beam collision, if we have

$$d_{1,6} + d_{3,11} > N. \tag{3}$$

In the EL-unbalanced case, both beam 4 and 6 are scheduled at the beginning. We assume that beam 6 is scheduled after beam 4, and the colliding pair $(6, 11)$ has beam in collision, if

$$d_{1,4} + d_{1,6} + d_{3,11} > N. \tag{4}$$

It is pljusible that the EL-unbalanced scenario is more likely to impose beam collision, because beam 6 is scheduled afterwards. Therefore, our goal is to ensure that the number of beams in the two lists are balanced so that none of the lists would record too many beams. Hence the following EL-balancing mechanism is proposed.

Firstly, every cell should keep a 1-bit EL flag, which determines the next sent EL REQ indicating a beam scheduled at beginning or end. The EL flag is updated, when the early/late lis becomes unbalanced. Explicitly, if the early list records more beams than the late list, the EL flag should indicate that the next EL REQ should be 'late', and vice versa. For each cell, an EL REQ is sent after the EL ACK of the most recent EL REQ is received so that the EL flag can be updated. Furthermore, each cell should sequentially send EL REQs to each neighbor cell, completing one after the other.

Secondly, each N-TS period is preceeded by a time window used for its information exchange with the neighbor cells. Each cell randomly selects an instant within the window to start sending EL REQs to its neighbor cells, where the random instant is generated by cell index to allow the starting instants of nearby cells to be sufficiently separated. However, if a cell feeds back a positive EL ACK to a neighbor cell before its start time, it should ignore the start time, and wait for a short period before starting to send EL REQs to other neighbor cells. This idle period is used for responding to any remaining EL REQs from the former neighbor cell.

This mechanism also allows nearby cells to incorporate beams into their two lists in a serial manner, which provides

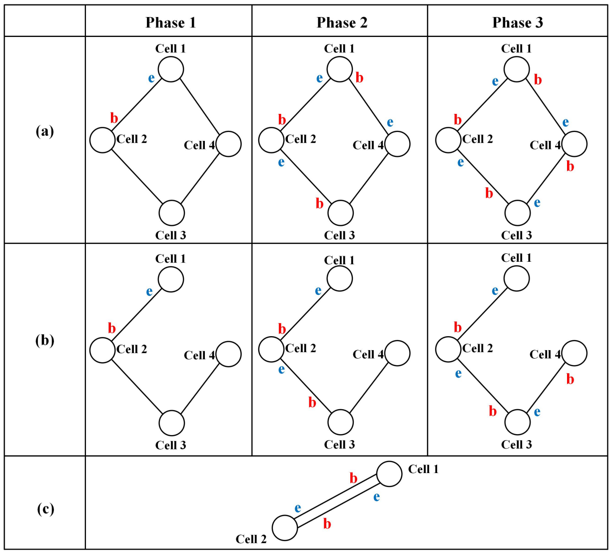


Fig. 4. 3 possible cases for each connected component when $N_k^{(cp)} \leq 2$: (a) a cycle, (b) a path, (c) two cells connected by two edges. For each colliding pair (each edge), marker "b" indicates one beam from the corresponding cell is scheduled at the beginning (recorded in forward list), and "e" indicates the other beam is scheduled at the ending (recorded in backward list).

each cell with an opportunity to balance its two lists. The analysis of this mechanism is provided in Section IV-A.

IV. Performance Analysis

We consider a certain time period, and denote the number of colliding pairs between cell k and its neighbor cells by $N_k^{(cp)}$. The EL information exchanging is assumed to be accomplished, so the sum of the numbers of beam recorded in the two lists of cell k is also $N_k^{(cp)}$.

We assume that the M beams in each cell are randomly selected from B beams with equal probability, so the probability that a beam is selected is M/B. The service demands of M beams in each cell are also randomly generated for satisfying (1), where each of the N time slot has equal probability to be allocated to the service demands of M beams. Since each time slot has $1/M$ probability to be allocated to a resource request, every $d_{k,m}, k = 1, \cdots, K, m = 1, \cdots, M$, is a random variable (RV) with binomial distribution $\mathbb{B}(N, 1/M)$.

A. 'Early-Late' Balancing Mechanism

Firstly, we derive the following proposition for the EL balance mechanism conceived.

Proposition 1. *If $N_k^{(cp)} \leq 2, k = 1, \cdots, K$, the early and late list of each cell both record at most 1 beam.*

Proof: We model the network as a graph, where each cell is represented by a node. If two cells have a colliding pair, the corresponding two nodes are connected by an edge. Two neighbor cells have multiple edges connecting them, if they have multiple colliding pairs. In this model, $N_k^{(cp)}$ is the degree of the node representing cell k.

We separately consider each connected component in the graph. In a connected component, a cell would have the earliest start time to send EL REQs, which triggers the EL information exchange over the whole connected component, and the information exchange is assumed to be finished before the second earliest start time, given the assumption of a perfect optical fibre backbone.

Since $N_k^{(cp)} \leq 2$, there are at most 2 edges connecting two nodes. However, if two nodes have two edges connecting them, they have no other edges and hence they form an isolated connected component. This Scenario is shown in Fig. 4(c). In the figure, we assume that cell 1 is the first one to start sending EL REQs. Due to the EL flag, cell 1 sends two EL REQs to cell 2, indicating the beginning and the end, respectively. Then, the two early lists and two late list of cell 1 and 2 all record only 1 beam, and thus Proposition 1 holds.

Next, we consider that there is at most one edge connecting every two nodes. Then, a connected component only has two possibilities, i.e. it is either a cycle or a path. We firstly assume that the connected component is a cycle. Due to space limitation, we only give a compact illustration of this case in Fig. 4(a), which can be readily extended to an arbitrary cycle. We assume that cell 2 is the first one to start sending EL REQs, and it sends a EL REQ to cell 1 indicating the beginning of phase 1. Then, in phase 2, cell 1 sends EL REQs to cell 4 indicating beginning ???? Meanwhile cell 2 sends EL REQ to cell 3 indicating the end. Finally, in phase 3, cell 3 might send a EL REQ to cell 4 indicating the end, otherwise cell 4 sends EL REQ to cell 3 indicating the beginning. Consequently, these two cases are equivalent to the same early and late lists, as shown in the figure, and hence Proposition 1 holds.

Similarly, it can be verified that Proposition 1 holds if a connected component represents a legitimate path as illustrated in Fig. 4(b). ■

Note that if both lists of each cell have at most 1 beam, then the two beams are scheduled to be activated at the beginning and end of an N-TS period. As a result, the beam collision probabilities of every colliding pair are minimized. However, this proposition requires $N_k^{(cp)} \leq 2$ for each k, and hence we have investigate $N_k^{(cp)}$ subsequently.

B. Distribution of $N_k^{(cp)}$

We consider an arbitrary cell k which has 6 neighbor cells, and denote the M selected beams in cell k as beam $b_1, \cdots, b_M$.

For an arbitrary beam $b_m, m = 1, \cdots, M$, this beam is part of a colliding pair if it is in collision with beam b_m activated by the neighbor cell. Let us denote by A_m as the specific event that beam b_m is not in a colliding pair, and hence the probability of A_m is

$$\Pr(A_m) = 1 - \frac{M}{B} = \frac{B-M}{B}. \tag{5}$$

Note that if two beams b_{m_1}, b_{m_2} are in two different 60° sectors of cell k, the two beams collide with b_{m_1} and b_{m_2} are in two different cells. Hence A_{m_1} is independent of A_{m_2} in this case. On the other hand, if the beams b_{m_1} and b_{m_2} are in the same 60° sector, the probability of A_{m_1} conditioned on A_{m_2} can be derived as

$$\Pr(A_{m_1}|A_{m_2}) = 1 - \frac{M}{B-1} = \frac{B-M-1}{B-1}. \quad (6)$$

Furthermore, the probability of the event that A_{m_1} conditioned on A_{m_2} is not encountered (i.e. beam b_{m_2} is in a colliding pair) is

$$\Pr(A_{m_1}|A^c_{m_2}) = 1 - \frac{M-1}{B-1} = \frac{B-M}{B-1}. \quad (7)$$

Since M is assumed to be a small number compared to B (in Section II), we have $\Pr(A_{m_1}|A_{m_2}) \approx \Pr(A_{m_1}|A^c_{m_2}) \approx \Pr(A_m)$, so A_{m_1} can still be considered to be approximately independent of A_{m_2}. Furthermore, the probability that there are 3 or more selected beams in one 60° sector is very low, given that M is small, hence we can assume $A_m, m = 1, \cdots, M$ to be M independent events. Then, note that $N_k^{(cp)}$ is the number of A_m events which are not encountered, so $N_k^{(cp)}$ has an approximately binomial distribution expressed as

$$N_k^{(cp)} \sim \mathbb{B}(M, 1 - \Pr(A_m)) = \mathbb{B}(M, \frac{M}{B}). \quad (8)$$

The probabilities of $N_k^{(cp)} \leq 2$ derived by the binomial approximation (8) compared to the relevant simulations are listed in Table I, which verifies that the binomial approximation is quite accurate. It can be seen that $\Pr(N_k^{(cp)} \leq 2)$ is high, because M/B is small, which indicates that Proposition 1 holds 'most the time'.

TABLE I
$\Pr(N_k^{(cp)} \leq 2)$ derived by binomial approximation and simulations.

Parameters	$B = 24$		$B = 12$	
	$M = 3$	$M = 4$	$M = 3$	$M = 4$
Binomial Approximation	99.80%	98.38%	98.44%	88.89%
Simulation Results	99.83%	98.47%	98.63%	89.39%

C. Number of Beam Collisions

Next, we compare the expectation of the number of beam collisions caused by a colliding pair operating under our EL protocol to that of random scheduling. We denote the two beams of a colliding pair as beam m_1 of cell k_1 as well as beam m_2 of cell k_2, while the number of beam collisions caused by them is denoted as RV $N_F^{(bc)}, N_R^{(bc)}$ for our EL protocol and for random scheduling, respectively.

We assume that Proposition 1 holds, hence $N_F^{(bc)}$ can be expressed as

$$N_F^{(bc)} = \begin{cases} 0, \text{ if } d_{k_1,m_1} + d_{k_2,m_2} \leq N, \\ d_{k_1,m_1} + d_{k_2,m_2} - N, \text{ otherwise.} \end{cases} \quad (9)$$

Since $d_{k_1,m_1}, d_{k_2,m_2} \sim \mathbb{B}(N, 1/M)$ and they are independent, we have $d_{k_1,m_1} + d_{k_2,m_2} \sim \mathbb{B}(2N, 1/M)$. Therefore, the expectation of $N_F^{(bc)}$ is

$$\mathrm{E}[N_F^{(bc)}] = \sum_{n=1}^{N} n \binom{2N}{N+n} (\frac{1}{M})^{N+n} (\frac{M-1}{M})^{N-n}. \quad (10)$$

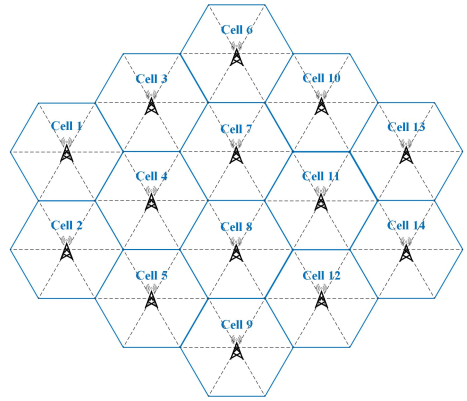


Fig. 5. A 14-cell network scenario for simulation.

Next we consider random scheduling and define the RV $I_n, n = 1, \cdots, N$, to indicate whether the nth time slot has beam collision, which can be written as

$$I_n = \begin{cases} 0, \text{ if the } n\text{th time slot has no beam collision,} \\ 1, \text{ otherwise.} \end{cases}$$

Then, the number of collisions $N_R^{(bc)}$ can be expressed as $N_R^{(bc)} = \sum_{n=1}^{N} I_n$.

For an arbitrary I_n, we have $I_n = 1$ if and only if beam m_1 is scheduled by cell k_1 and beam m_2 is scheduled by cell k_2 at the nth TS. Since the M beams of each cell are symmetrical in random scheduling, each beam has the same probability of $1/M$ to be scheduled at a certain TS. So, the probability that beam m_1 is scheduled at the nth TS and the probability that beam m_2 is scheduled at the nth TS are $1/M$. Hence, we have

$$\mathrm{E}[I_n] = \frac{1}{M^2}, \; n = 1, \cdots, N. \quad (11)$$

Then, we arrive at

$$\mathrm{E}[N_{bc}^{(R)}] = \sum_{n=1}^{N} \mathrm{E}[I_n] = \frac{N}{M^2}. \quad (12)$$

The comparison of the specific values between $\mathrm{E}[N_F^{(bc)}]$ given by (10) and $\mathrm{E}[N_R^{(bc)}]$ given by (12) are shown in Table II. It can be seen that our EL protocol has nearly 0 expectation regardless of the parameters, which is much lower than those of random scheduling, demonstrating that beam collisions may indeed be avoided.

TABLE II
Comparison between $\mathrm{E}[N_F^{(bc)}]$ and $\mathrm{E}[N_R^{(bc)}]$.

Parameters	$N = 20$		$N = 30$	
	$M = 3$	$M = 4$	$M = 3$	$M = 4$
$\mathrm{E}[N_F^{(bc)}]$	0.0156	0.0002	0.0044	1.1755×10^{-5}
$\mathrm{E}[N_R^{(bc)}]$	2.2222	1.2500	3.3333	1.8750

V. Simulation Results

A 14-cell network is setup as our simulation model, as shown in Fig. 5. The carrier frequency is set to 28GHz, and the length of each side of a regular hexagonal cell is set to 50m. We consider the system performance in a single N-TS period, and the M beams in each cell as well as their

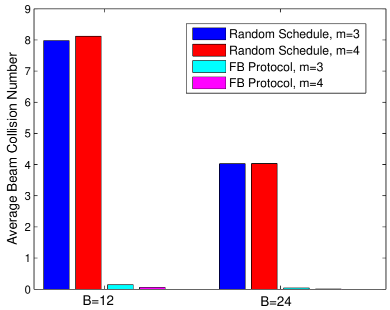


Fig. 6. Average beam collision number with $m = 3, 4$, $B = 12, 24$.

service requests are randomly generated in the same way as in Section IV, where we set $N = 20$. Furthermore, we assume that the user served by each beam is located at the cell edge. The beamforming gain is set to $G_{max} = 13$dB, $G_{min} = 0$ and the 3GPP urban macro path loss model of [9] is adopted.

The average number of beam collisions in the whole network is shown in Fig. 6. As indicated by Table II, the average number of beam collisions in the EL protocol under different parameters are close to 0, which is much lower than that of the random schedulin. Furthermore, when B increases from 12 to 24, the beamwidth becomes narrower and $N_k^{(cp)}$ becomes smaller, so the number of beam collisions in the $B = 24$ scenario is lower than in the $B = 12$ scenario for both our EL protocol and for random scheduling.

Then, in Fig. 7, the network performance of the EL protocol is evaluated in terms of the cumulated distribution function (CDF) of the users' signal-to-interference-plus-noise ratio (SINR) and the network's sum rate.

In Fig. 7(a), there are 6% user SINR values around 0dB for random scheduling, which is owing to the strong ICI caused by beam collisions. When beam collisions occur, the power of ICI received from the neighbor cell is close to the desired power of the serving cell. Hence the users' SINR would be dramatically reduced, which may lead to severe outages. In the figure, the EL protocol eliminates the probability of low user SINRs. Observe furthermore the occurance of mediocre SINRs ranging from 7dB to 17dB, which is caused by the low-power ICI arriving from remote cells. It can be seen that the proportion of users in the mid-SINR region of our EL protocol and of random scheduling are similar. Consequently, the proportion of users in the high-SINR region (from 17dB to 19dB) is increased by our EL protocol.

In Fig. 7(b), the sum rate of our EL protocol and of random scheduling is compared to the interference-free (IF) case, where the beams are randomly scheduled, but all the ICI powers are assumed to be zero in the IF case. Therefore, the sum rate achieved in the IF case is considered as an ideal upper bound of the network's sum rate. By avoiding beam collision, the EL protocol exhibits a substantial sum rate gain compared to random scheduling. Meanwhile, the sum rate gap between the EL protocol and the ideal IF case is attributed to the remote ICI.

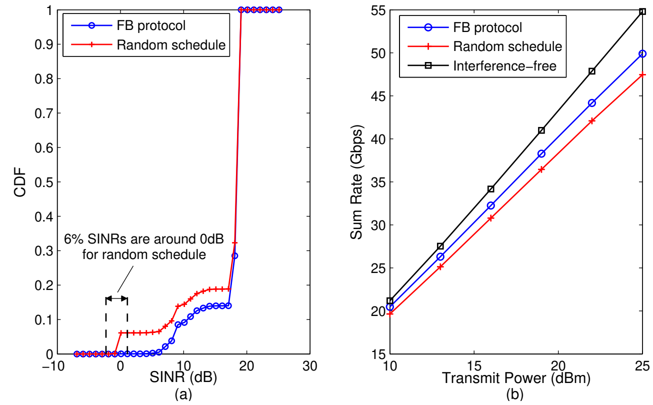


Fig. 7. The network performance simulation with $m = 4$, $B = 24$ and the noise power is set to -80dBm. (a) The CDF of user SINR with 20dBm BS transmit power. (b) Network sum rate.

VI. Conclusions

In this paper, we proposed an EL protocol as a distributed cell coordination method for ICI avoidance. We utilized a beam collision table to record the colliding beam pairs for every two neighbor cells. Based on this beam collision table, EL information was exchanged between the neighbor cells so that one of the beams in a colliding pair was scheduled at the beginning of the N-TS period and the other one is scheduled at the end of the period. Furthermore, an EL balancing mechanism was proposed to balance the number of beams in the two lists and to reduce the probability of beam collision. Based on our theoretical analysis and numerical simulations, we demonstrated that our methodology efficiently eliminates the strong ICI between adjacent cells and improves the network's sum rate.

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