MAC-Layer Concurrent Beamforming Protocol for Indoor Millimeter-Wave Networks

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***Abstract*—In this paper, we study concurrent beamforming issue for achieving high capacity in indoor millimeter-wave (mmWave) networks. The general concurrent beamforming issue is first formulated as an optimization problem to maximize the sum rates of concurrent transmissions, considering the mutual interference. To reduce the complexity of beamforming and the total setup time, concurrent beamforming is decomposed into multiple single-link beamforming, and an iterative searching algorithm is proposed to quickly achieve the suboptimal transmission/reception beam sets. A codebook-based beamforming protocol at medium access control (MAC) layer is then introduced in a distributive manner to determine the beam sets. Both analytical and simulation results demonstrate that the proposed protocol can drastically reduce total setup time, increase system throughput, and improve energy efficiency.**

***Index Terms*—Beamforming, concurrent transmissions, medium access control (MAC), millimeter wave (mmWave) communications, setup time.**

I. Introduction

MILLIMETER-WAVE (mmWave) band communications, particularly the 60-GHz band, has received considerable attention for short-range indoor applications, such as wireless personal area networks (WPANs) [1]–[3] and wireless local area networks (WLANs) [4]–[7]. The most attractive advantage of mmWave communications is its capability to achieve multi-gigabit-per-second rate to support bandwidth-intensive multimedia applications. However, mmWave communications suffers high propagation loss due to its high frequency band. To compensate for the tremendous propagation loss and to reduce the shadowing effect, a high-gain directional antenna array is favored to improve the system efficiency and transmission range, particularly for non-line-of-sight (NLOS) channels [8]. Since the dimensions and necessary spacing of 60-GHz antennas are on the order of millimeters [9], multiple antennas can be integrated into portable devices.

Manuscript received December 6, 2013; revised February 28, 2014; accepted March 28, 2014. Date of publication April 29, 2014; date of current version January 13, 2015. This work was supported in part by a Discovery Grant from the Natural Science and Engineering Research Council (NSERC) of Canada and in part by the International Cooperative Program of Shenzhen City under Grant ZYA201106090040A. The review of this paper was coordinated by Prof. N. Kato.

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Digital Object Identifier 10.1109/TVT.2014.2320830

Beamforming determines a beam toward a certain direction formed by multiple antennas to maximize the transmission rate. The antenna gains of the transmitter and the receiver have a significant impact on the transmission data rates. Thus, a beamforming protocol is required to select the best transmission and reception beams, according to the selection metric [10], [11], e.g., SNR. Because of the directional antennas and the high propagation loss, multiple communication links can operate simultaneously to exploit the spatial reuse potential [1], [12]. Appropriate concurrent transmissions are desirable in directional mmWave networks to improve the network capacity [2], [13]. The high propagation loss accompanying the limited penetration and diffraction capability confines the network coverage in a shorter range. The mutual interference generating from the concurrent links in short coverage area can greatly affect the concurrent throughput. Beamforming for multiple concurrent links (named as concurrent beamforming) should consider the mutual interference to decide the best transmission/reception beam for each link, instead of enabling the beamforming for each link in isolation. The best transmission beam can improve the link rate while it generates the interference to other receivers to reduce the rates of other links. How to select appropriate beams for concurrent links to optimize sum rates is an important and challenging issue.

Concurrent beamforming in the 60-GHz band has several challenges. First, the antenna array forms a specific beam pattern according to the weight vector calculated based on the measuring signals' angle of departure (AOD)/angle of arrival (AOA) or acquisition of the entire channel state information (CSI) matrices. It introduces high calculation load and large overhead. Second, the concurrent links make beamforming even more difficult because the mutual interference is unknown until the best transmission and reception beam patterns for all the concurrent links are finalized. Finally, no complete medium access control (MAC) protocol to setup multiple directional communication links is available.

To reduce the realization complexity on beamforming, this paper adopts the beam-switching operations based on the predefined beam steering vectors (i.e., a codebook) without the necessity of AOD/AOA or CSI estimation. This paper has the following main contributions. First, the codebook-based concurrent beamforming problem is formulated as an optimization problem by maximizing the sum rates. Second, to reduce the complexity and the total setup time (meaningful on reinforcing transmission efficiency and reducing energy consumption), we decompose concurrent beamforming into multiple single-link beamforming and propose an iterative searching algorithm to quickly achieve the suboptimal beam sets. Third, with the proposed algorithm, a comprehensive beamforming protocol is proposed to determine the transmission/reception beam sets operating on MAC layer in a distributive manner. Finally, the analytical evaluation demonstrates that the proposed protocol can significantly reduce the searching space.

The remainder of this paper is organized as follows. In Section II, related works are presented. The network topology, the timing structure, and the beamforming model are provided in Section III. In Section IV, an optimization model for concurrent beamforming is presented, and an iterative searching algorithm is proposed to solve it. A complete beamforming protocol is proposed in Section V. The performance is analyzed in Section VI and evaluated by simulations in Section VII, followed by concluding remarks in Section VIII.

II. Related Works

Beamforming techniques at the 60-GHz band have been actively studied in [10], [11], [15], [16], and [18]–[20] and specified in standards, including IEEE802.15.3c (TG3c) [21] for WPANs, and IEEE802.11ad (TGad) [22] and Wireless Gigabit Alliance (WiGig) for WLANs. One type of beamforming for mmWave networks is in accordance with the measurement of signals' AOD/AOA and the entire CSI to decide the beam direction [15], [16], [18]–[20]. A general beamforming problem is formulated in [17], and an automatic alignment mechanism is provided to adaptively track the transmitter location and to steer the beam to maximize the received power. In [15], experimental results on AOD estimation and optimal beamforming are presented for 60-GHz smart antennas. Beamforming is accomplished with the control of amplitudes and phases of mmWave signals by means of a maximum directivity beamforming algorithm. The main challenge on this type of beamforming methods is that the channel sounding procedure based on transmission and reception between all pairs of individual elements is not always possible due to the high propagation loss in the mmWave band. In addition, the high calculation loads increase the setup time of beamforming and hinder the applications sensitive to delay (e.g., wireless display).

Recently, another type of beamforming protocols realized on the MAC layer has been proposed in [10], [11], [14], [19], and [20], based on switched antenna array with a structured codebook. In [10], by enabling sector-level and beam-level searching, the proposed beamforming protocol targets to minimize the setup time and to mitigate the high path loss of 60-GHz WPAN systems. In [11], multilevel heuristic searching algorithms are proposed to determine the best transmission/reception beam pattern while reducing the setup time considerably in comparison with exhaustive search. A simple and efficient antenna weight vector training algorithm is proposed in [20] using only one antenna weight vector feedback to obtain the best transmission and reception antenna weight vector pair. In [14], the beam switching process with prespecified beam codebooks is described to identify the best beam pair for data transmissions. The Rosenbrock numerical algorithm is used to implement beam searching, which can reduce the searching spaces and improve the probability of success.

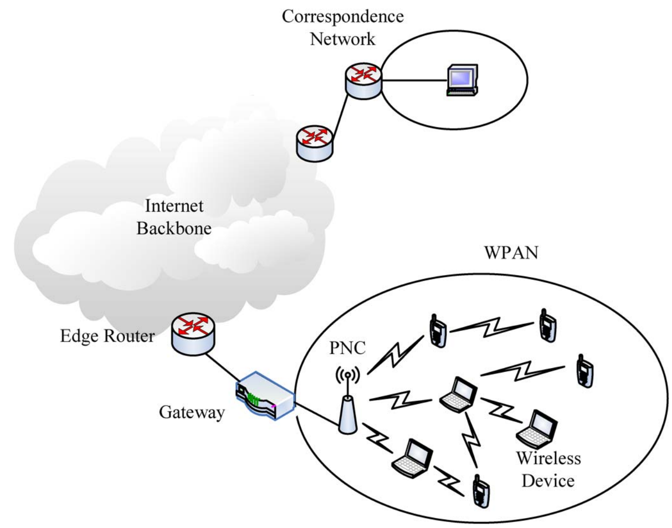

Fig. 1. Indoor mmWave network architecture.

To the best of our knowledge, the previous works on beamforming protocols for indoor mmWave networks are designed for one pair of a transmitter and a receiver (i.e., a single link). Concurrent beamforming is highly required since concurrent transmissions are desired in indoor mmWave networks to increase network capacity, provide higher transmission rates, and support more users, particularly for the densely populated networks. It is necessary to jointly consider the beamforming for all the transmission links operating simultaneously, to mitigate the mutual interference and achieve better system performance.

III. System Model

For presentation clarity, in what follows, we use IEEE 802.15.3c mmWave WPANs to describe the concurrent beamforming problem, which is also applicable to other mmWave indoor networks, such as WLANs. As shown in Fig. 1, a WPAN consists of several wireless devices (WDEVs) and a single piconet controller (PNC), which schedules device-to-device communications between WDEVs. All the WDEVs are equipped with directional antennas, which are favorable to support concurrent transmissions. Concurrent beamforming is defined as the training process to determine the best transmission/reception beam set for multiple transmitters/receivers to form the concurrent links. Concurrent beamforming chooses specific beam for all the WDEVs active at the same time to achieve the best system performance.

A. Timing Structure

As shown in Fig. 2, time is partitioned into superframes composed of three phases: the beacon period (BP) for network synchronization, control message broadcasting, and scheduling decision distribution; the contention access period (CAP) for applications without performance guarantee; and the channel time allocation period (CTAP) composed of z channel time slots for bandwidth-intensive and delay-sensitive applications, respectively. Each time slot in CTAP is a time-division multiple access (TDMA) slot granted by PNC for multiple

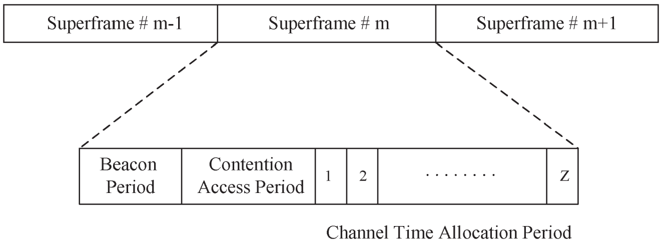

Fig. 2. Superframe-based timing structure.

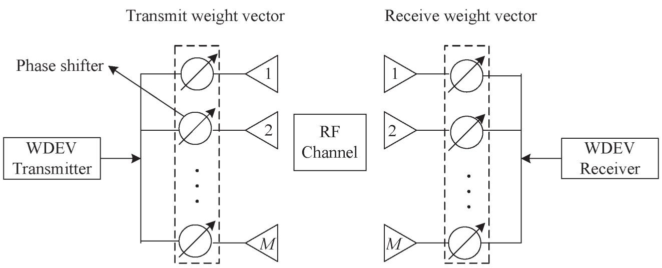

Fig. 3. Beamforming structure model.

communication links. The beamforming operation is processed for all the active links at the beginning of each TDMA time slot.

B. Beamforming Model

We consider a system with L multiple concurrent communication links. An asymmetric channel is considered since the channels of both communication directions may not be reciprocal. Fig. 3 shows the beamforming model for link l between transmitter WDEV_l^T and receiver WDEV_l^R, i.e., aiming to obtain the best transmission beam pattern for WDEV_l^T and the best reception beam pattern for WDEV_l^R. Multiple digital-to-analog converters (DACs) or analog-to-digital converters (ADCs) consume high power because the multiple DACs and ADCs operate at several gigasamples per second at the baseband. To reduce the overhead and energy consumption, the beamforming is operated in the RF band, including only a single RF chain. At the transmitter, the signal after baseband processing is upconverted to the RF band. The RF signal is phase-shifted by applying the transmit weight vector and is transmitted via the multiple-input–multiple-output channel. At the receiver, the received RF signal is phase-shifted by the receive weight vector and combined in the RF domain. Then, the combined signal is downconverted for baseband processing.

IV. Concurrent Beamforming Problem

Here, we first describe the codebook design adopted in this paper and then formulate the concurrent beamforming problem as an optimization problem, which is solved by the proposed iterative searching algorithm.

A. Codebook Design

The beamforming training with exact phase shift and amplitude adjustment results in large training data and high overheads. Consequently, in both the standards [21], [22] and recent papers [10], [11], [19], 60-GHz band communications prefers the codebook-based beamforming by giving each antenna a phase shift without amplitude adjustment. A codebook is a matrix, in which each column (a weight vector) indicates a phase shift for each antenna element and forms a specific beam pattern. For M antennas with N weight vectors $(N \geq M)$, the codebook used in IEEE 802.15.3c WPANs is given by the following matrix:

$$\mathbf{W} = \left|w_{(m,\,u)}\right| = \left| j^{\left\lfloor \frac{m\times \bmod\ ((u+N/2),\, N)}{N/4} \right\rfloor} \right| \tag{1}$$

where N is also the total number of beam patterns, $m \in \{0, 1, 2, \ldots, M-1\}$, $u \in \{0, 1, 2, \ldots, N-1\}$, and $j = \sqrt{-1}$. The given codebook can result in losing beam gain in some directions [10] if N or M is larger than 4. The reason is that the optimal beam pattern may not be achieved with a limited number of phase shifts for each antenna elements.

To achieve uniform antenna gain in different directions, we use discrete Fourier transform (DFT)-based codebook design [23]. With the same notations in (1), the DFT-based codebook can be given by the following matrix:

$$\mathbf{W} = \left|w_{(m,\,u)}\right| = \left| e^{-j2\pi(m-1)(u-1)/N} \right| \tag{2}$$

where $m = 1, 2, \ldots, M$, and $u = 1, 2, \ldots, N$. The weight vectors in the DFT-based codebook are composed of complex numbers that assign the unit amplitude and specific phase shift for each antenna element without losing beam gain in the designed directions.

B. Concurrent Beamforming Formulation

Conventionally, beamforming is to search the best transmission/reception beam pattern for each communication link to optimize a cost function, such as the signal-to-interference-plus-noise ratio (SINR). With concurrent links, the SINR of each link depends on both the beam selection of this link and the beam selection of other concurrent links because of the possible mutual interference. The directional antenna radiates much greater power in certain directions for increased performance on transmission/reception while reducing interference from unwanted sources. Each transmitter WDEV_k^T in link k can generate interference to the receiver WDEV_l^R in link l if they are active simultaneously. The amount of interference depends on the antenna gains of the transmission and reception directions. Since the ultimate goal of beamforming is to transmit more data in the network, we use the sum data rate as the cost function to select the best transmission and reception beam patterns for the concurrent links, instead of the data rate for each link. Given a set of L concurrent links in each time slot, the following sets are defined.

- $B_T = [n_t^1, n_t^2, \ldots, n_t^l, \ldots, n_t^L]$ is the set of beam patterns selected for the L links for data transmission.
- $B_R = [n_r^1, n_r^2, \ldots, n_r^l, \ldots, n_r^L]$ is the set of corresponding reception beam patterns for the L links.

By applying the Shannon capacity formula, the transmission rate of link l can be estimated as

$$\begin{aligned} R_l &= \eta W \cdot \log_2(1 + \mathrm{SINR}_l) \\ &= \eta W \cdot \log_2 \left(1 + \frac{P\left(n_t^l,\, n_r^l\right)}{WN_0 + \sum_{k \neq l} P\left(n_t^k,\, n_r^l\right)} \right) \end{aligned} \tag{3}$$

where W is the system bandwidth, $\eta \in (0, 1)$ is the coefficient describing the efficiency of the transceiver design, and N_0 the one-side power spectral density of white Gaussian noise. $P(n_t^k,\, n_r^l)$ denotes the received power at the WDEV_l^R from WDEV_k^T. n_t^k and n_r^l are the selected beam patterns for WDEV_k^T and WDEV_l^R, respectively. In (3), $n_t^k,\, n_r^l \in \{1, 2, \ldots, N\}$ with $k,\, l = 1, 2, \ldots, L$.

To maximize the sum rates, we formulate the concurrent beamforming problem as an optimization problem P, i.e.,

$$\max \quad \sum_{l=1}^{L} \eta W \cdot \log_2 \left(1 + \frac{P\left(n_t^l,\, n_r^l\right)}{WN_0 + \sum_{k \neq l} P\left(n_t^k, n_r^l\right)} \right) \tag{4}$$

$$\text{s.t.} \quad 1 \leq n_t^l,\, n_r^l,\, n_t^k \leq N \tag{5}$$

$$n_t^l,\, n_r^l,\, n_t^k \in \mathcal{Z}^+ \tag{6}$$

where $\mathcal{Z}^+$ is the set for all positive integers. This optimization problem is a nonlinear integer programming problem. The concurrent beamforming problem is similar to Knapsack problem [24] in the case that items (antenna patterns) can be put into the knapsack (active in the channel). The objective is to maximize the total profit (sum rates) with the total weight (interference) constraints. It is proven that the Knapsack problem is NP-complete [24]. Concurrent beamforming is even more difficult than the Knapsack problem because the profits of items (rate) are not determined until the active beam patterns of other links are determined. As a result, the concurrent beamforming problem cannot be solved by applying existing approximation algorithms for Knapsack problems. There are two main challenges to solve the optimization problem on concurrent beamforming: 1) It is NP-hard without polynomial time solution; and 2) the received power $P(n_t^k,\, n_r^l)$ is dependent on both the transmission/reception beam patterns and the 60-GHz indoor channel status. To obtain the best transmission and reception beam pattern, the channel status has to be available. However, it is almost impractical to obtain the updated channel status for indoor environment due to the moving people and obstacles [8]. Therefore, in this paper, we propose a MAC-layer beamforming protocol independent of the channel status.

Algorithm 1 Iterative Searching Algorithm for Beamforming

BEGIN:
L links are scheduled to be active in a time slot of CTAP.
Initialize the beam sets $B_T = \overrightarrow{0}$ and $B_R = \overrightarrow{0}$
repeat
  for link $l = 1$ to L (l is link number index) **do**
    if $n_t^l = 0$ and $n_r^l = 0$ **then**
      set n_t^l and n_r^l according to

$$\arg\max_{n_t^l, n_r^l \in \{1,\ldots,N\}} \sum_{\beta=1}^{l} \eta W \cdot \log_2 \left(1 + \frac{P\left(n_t^\beta, n_r^\beta\right)}{WN_0 + \sum_{k<\beta} P\left(n_t^k, n_r^\beta\right)} \right)$$

    else
      set n_t^l and n_r^l according to

$$\arg\max_{n_t^l,\, n_r^l \in \{1,\ldots,N\}} \sum_{\beta=1}^{L} \eta W \cdot \log_2 \left(1 + \frac{P\left(n_t^\beta,\, n_r^\beta\right)}{WN_0 + \sum_{k\neq\beta} P\left(n_t^k,\, n_r^\beta\right)} \right)$$

    end if
  end for
until $B_T = \{n_t^l\}$ and $B_R = \{n_r^l\}$ converges
END;

C. Iterative Searching Algorithm

In the conventional codebook-based beamforming protocol with exhaustive search for a single link, the transmitter sends the training sequence with one of its beam patterns, whereas the receiver attempts to listen to it with different beam patterns. This process is repeated until all the beam patterns have been tried by the transmitter. Then, the best transmission/reception beam pattern can be found by detecting the best SINR at the receiver. The total number of transmission attempts is $N_r \times N_t$ for each link if N_t and N_r denote the number of beam patterns at the transmitter and the receiver, respectively. For L concurrent transmission links with mutual interference, there should be $(N_r \times N_t)^L$ total transmission attempts to select the best set of transmission/reception beam patterns. The exhaustive search method is not feasible since the computation and communication loads grow exponentially with respect to the number of concurrent links.

To obtain the best transmission beam set B_T^* and reception beam set B_R^*, the concurrent beamforming problem is decomposed and conducted link by link to reduce the complexity and setup time, instead of optimizing beam selection for all the L links simultaneously. The decomposed method can solve the problem in an iterative manner and achieve suboptimal solutions. There are many efficient beamforming protocols (e.g., a multistage scheme [10] and a multilevel scheme [11]) to attain the best transmission/reception beam patterns for single-link beamforming. Hence, it is assumed that the efficient beam pattern selection protocol for single communication pair is available, and the proposed iterative searching algorithm is to find the beam sets B_T^* and B_R^* for L concurrent links.

The beam sets B_R and B_T are initialized as $B_T = \overrightarrow{0}$ and $B_R = \overrightarrow{0}$. In the initial searching round, the beamforming procedure of the first link is conducted with the beamforming protocol for a single communication pair; then, $B_T[1]$ and $B_R[1]$ are updated with the selected beam patterns. For the following lth ($1 < l \leq L$) link, the beamforming is conducted with the single-link beamforming protocol considering the interference generated from the concurrent links whose beamforming has been determined. The single-link beamforming

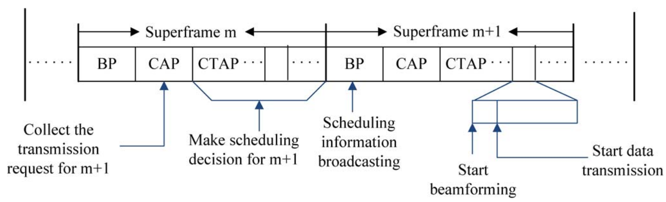

Fig. 4. Procedure for scheduling and beamforming.

of link l conducted in concurrent beamforming uses the sum rates as the selection metric rather than the SINR of link l. By trying different pairs of transmission/reception beams in link l, the beam pair resulting maximum sum rates is selected. Then, $B_T[l]$ and $B_R[l]$ are updated. After the transmission and reception beam patterns for all the L links are determined based on the given procedure, another iterative searching round is reconducted considering the interference from the other $L-1$ links since there is a predetermined beam pattern for the other $L-1$ links. In each iterative searching round, the obtained beam sets $\widetilde{B}_T$ and $\widetilde{B}_R$ are better than the beam sets B_T and B_R of the previous round in terms of the total throughput.

The given process is repeated until the beam sets B_T and B_R converge (i.e., no change of B_T and B_R will result in higher sum rates of all the L links). In other words, for a specific searching round, if the beam patterns of all the links are not updated, the beam sets B_T and B_R can be determined to converge. The step-by-step description of the proposed iterative searching algorithm is shown in Algorithm 1.

Remarks: The iterative searching algorithm ensures that we cannot find a better transmission/reception beam set by conducting beamforming link by link. However, it is possible to attain a better solution by conducting beamforming for two or more links simultaneously. Therefore, the proposed iterative searching algorithm only obtains a locally optimal solution for concurrent beamforming and cannot ensure the global optimality of the solution.

V. Beamforming Protocol

Here, we present a comprehensive beamforming protocol to realize the proposed iterative searching algorithm among WDEVs. As shown in Fig. 4, the PNC receives a number of transmission requests in the CAP period of the mth superframe. Then, the scheduling decision is made by PNC for the $(m+1)$th CTAP before the $(m+1)$th BP, during which the PNC broadcasts the scheduling information to all the WDEVs in the network. The scheduling information indicates the active links in each time slot. The sequence of these active links to conduct beamforming is randomly assigned in this paper. Since the PNC cannot control the WDEVs during the CTAP period, the proposed concurrent beamforming protocol should work distributively. Each time slot of CTAP consists of the beamforming period and the data transmission period. Thus, the total setup time of concurrent beamforming has a significant impact on the resource utilization efficiency. To shorten the total setup time, a concurrent beamforming protocol based on the proposed iterative searching algorithm is presented with four phases, namely, single-link beamforming (see Fig. 5), interlink notification, iterative searching convergence, and acknowledgement.

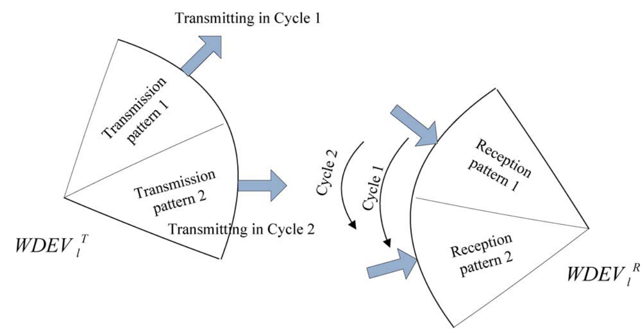

Fig. 5. Example for single-link beamforming.

The proposed concurrent beamforming protocol is based on the detection of SINR at the receivers. Thus, it can be applied to many mmWave networks to conduct concurrent beamforming without knowledge of channel gain and location information of the WDEVs.

A. Single-Link Beamforming

In the proposed iterative searching algorithm, concurrent beamforming is conducted link by link to reduce the complexity. The existing beamforming protocols for a single link cannot be applied directly due to the following challenges.

1) The interference from other concurrent links has to be known to determine the best transmission and reception beam patterns for each link. However, other concurrent links cannot conduct beamforming at the same time as the targeted link.
2) In a distributive manner, it is difficult for a link to know the start/end beamforming time of adjacent links to conduct beamforming sequentially. Since the beamforming duration for each link is quite different, the start time of beamforming for each link cannot be predetermined even if the time is synchronized.
3) The beam selection metric, i.e., sum rates, is not measurable, and each link cannot know them by itself.

In the BP of the mth superframe, the PNC broadcasts the scheduling information to WDEVs to indicate the links to be active in each time slot and the sequence (from 1 to L) for all the active links to conduct beamforming. According to the preassigned sequence, each link (e.g., link l) starts beamforming by allowing the transmitter (WDEV_l^T) to send the training sequence with every beam pattern to the receiver (WDEV_l^R). The transmission beam pattern generates interference to the receivers of other concurrent links. The SINR values of other concurrent links can be detected at the corresponding receivers by trying each transmission beam pattern of the transmitter WDEV_l^T. Then, the detected SINR values are sent to the receiver WDEV_l^R. For each transmission beam pattern, the receiver WDEV_l^R switches its beam pattern one by one and records the corresponding received SINR of link l. After traversing every beam pair, WDEV_l^R knows the SINR values of all the links corresponding to each beam pair. WDEV_l^R determines the best beam pair (n_t^l and n_r^l) in terms of sum rates by adding the transmission rates of all the concurrent links together. Each transmission rate can be estimated by (3). The

Header	NoC	NoF	Beam Selection Identification

Fig. 6. Format of each notification packet.

training at WDEV_l^R includes N_t cycles, and each cycle includes N_r attempts. The training sequence is a long preamble composed of a synchronization sequence and a channel estimation sequence specified in IEEE802.15.3b, generated from Golay code with 32 repetitions of length 128 bits [21].

After determining the best beam pair, WDEV_l^R transmits the feedback information to WDEV_l^T to indicate WDEV_l^T's best transmission beam pattern since WDEV_l^T does not yet know its optimal transmit direction corresponding to WDEV_l^R. Upon the completion of the feedback, the WDEV_l^T activates the selected beam pattern as the interference for beamforming of other links.

B. Interlink Notification

Following the single-link beamforming phase, the interlink notification phase is required to move to the next single-link beamforming. As indicated in Section V-A, although each link receives the beamforming sequence information during the BP, link $(l+1)$ needs the trigger information to start beamforming right after the completion of link l's beamforming. Transmitter WDEV_l^T activates its optimal beam pattern for SINR considerations of the following links; meanwhile, it sends out a notification packet with four fields: the header, the number of current link (NoC), the number of following link (NoF), and beam selection identification, as shown in Fig. 6.

The information in the header, NoC, and NoF fields is necessary for other nodes to decide if they should start beamforming currently. After the nodes receive the notification packet, the two nodes forming link $(l+1)$ conduct the single-link beamforming triggered by the sequence number $(l+1)$ in the NoF field. The beam selection identification field is used for iterative searching convergence phase, as will be described in Section V-C. A short interphase spacing time is added for WDEVs to set up beamforming before the single-link beamforming phase starts.

Concurrent beamforming is to find the best transmission directions and reception directions to achieve a high data rate for mmWave networks supporting bandwidth-intensive applications. The notification packet, SINR values, and other management information do not require a high transmission rate. It can be supported even with the NLOS transmissions. Thus, it is not necessary to use optimal beam pairs to deliver such information considering the fact that it takes longer time to obtain the optimal beam pairs between WDEVs. With the localization service provided by the mmWave indoor system [25], the PNC can obtain the approximate network topology information and broadcast it to WDEVs during CAP. WDEVs can activate the corresponding beam pattern toward each other according to the topology information to deliver signaling and management information among WDEVs.

C. Iterative Searching Convergence

With the single-link beamforming and the interlink notification phases, beamforming can be conducted link by link

Previous searching round

$\vec{x}_1$	$\vec{x}_2$	$\cdots$	$\vec{x}_l$	$\cdots$	$\vec{x}_L$	$\vec{x}_1$	$\vec{x}_2$	$\cdots$	$\vec{x}_l$	$\cdots$	$\vec{x}_L$

Current searching round

Fig. 7. Format of beam selection identification in a notification packet.

to achieve the transmission/reception beam set. To realize the iterative searching algorithm distributively, two main issues need to be considered.

- A convergence condition is required to indicate the end of the searching algorithm while determining the accuracy of the obtained solution and the total beamforming time. A strict convergence condition can achieve better solution with more rounds of iterative searching. A loose convergence condition can quickly find the approximate solution.
- Since beamforming is conducted link by link without the control of PNC, the convergence condition information should be delivered to WDEVs in a distributive manner.

For concurrent beamforming, the general convergence condition is when the iterative searching keeps going until B_T and B_R reach a steady state. Specifically, B_T and B_R converge if n_t^l and n_r^l determined in the nth round are the same as those obtained in the $(n-1)$th round for all $l \in \{1, 2, \ldots, L\}$. The given ideal convergence condition can cause a large number of searching rounds and much longer setup time due to the following reasons. First, a new beam pattern pair (n_t^l and n_r^l) for link l may be found to achieve minor improvement on the sum rates, which brings communication and computation overheads to reduce the system throughput. Second, at system-level beamforming, the new beam pair of one link can lead to the beam pattern reselection of many other links and more searching rounds because of the mutual interference. The concurrent beamforming procedure is a kind of chain reaction inspired by the transmission beam reselection since the transmission beams generate interference to other links. To significantly shorten the total setup time, a sum rate threshold $\mathrm{Th}_{\mathrm{rate}}$ in percentages is used to determine the beam pattern reselection. For example, after conducting single-link beamforming for link l, if the new achieved sum rates are within $[1, (1+\mathrm{Th}_{\mathrm{rate}}))$ of the sum rates of previous round, the beam patterns of link l remain the same.

As shown in Fig. 6, the beam selection identification field of the notification packet is used to notify the convergence information among WDEVs. A vector $\overrightarrow{x}_l = [n_t^l, n_r^l]$ is saved in each subfield of the beam selection identification field to record the beam selection result of link l. The format of the beam selection identification field is shown in Fig. 7. It records the beam selection results of both the current and the previous searching round for all the L links. If all the $\overrightarrow{x}_l$ $(l = 1, 2, \ldots, l, \ldots, L)$ of the current round are the same as those of the previous round, it can be concluded that the beam sets B_T and B_R have converged.

D. Acknowledgement

After a link completes its beamforming for the current searching round, it will either wait for the trigger information to start the beamforming for the next searching round or stop beamforming after receiving the convergence message and use the selected transmission/reception beam patterns for data transmission. After the receiver of the Lth link receives the notification packet and compare the beam selection results of the current and previous searching round, it will broadcast an acknowledgement (ACK) message to all the WDEVs to indicate the completion of beamforming if the comparison shows that both rounds have the same beam selection results.

The notification packets delivered among WDEVs control the whole process of concurrent beamforming. The following pseudocodes, as shown in Algorithm 2, describe the procedure of concurrent beamforming with details on the notification packet transmissions and the corresponding actions done by the WDEVs.

Algorithm 2 Procedure for Concurrent Beamforming

```
BEGIN:
Each link l can generate a notification packet
for Each iterative searching round n do
    for Link l = 1 to L (l is link number index) do
        Link l receives a notification packet
        if The NoF = l in the notification packet then
            Link l starts beamforming;
            Update NoC = l;
            Update NoF = l + 1;
            Record the beam selection result x_l = [n_t^l, n_r^l];
            if l ≠ L then
                Link l sends out updated notification packet;
            else
                The beam selection results of nth round and
                (n + 1)th round are compared;
                if B_T^n = B_T^{n+1} and B_R^n = B_R^{n+1} then
                    Go to END;
                else
                    Update n = n + 1;
                    Link L sends out message to trigger new
                    round beamforming;
                end if
            end if
        else
            Link l disregards the notification packet
        end if
    end for
end for
END;
```

VI. Performance Analysis

The computational complexity significantly affects the network performance, such as total setup time, transmission efficiency, and energy consumption. Although the proposed iterative searching algorithm reduces the exponential searching space to linear searching space, theoretical analysis is required to show the exact complexity of the proposed algorithm.

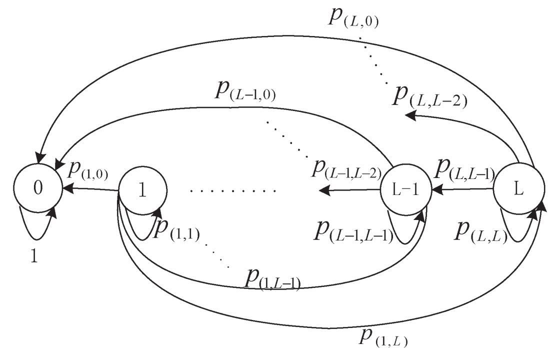

Fig. 8. Markov chain for X_n.

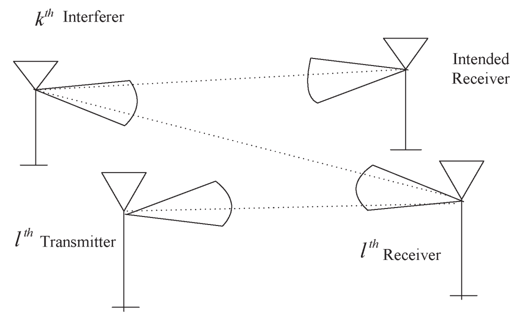

Fig. 9. Geometry of directional interference.

To simplify the analysis, the following assumptions are made. First, there is no link blockage between WDEVs, and the line-of-sight transmission is always available. Second, the channel status does not change during the concurrent beamforming period; thus, the beam reselection of a link can only result from the beam reselections of other interferers. Third, the beam reselection of a link in the nth searching round is due to the transmission beam reselections in the $(n-1)$th round. Fourth, each receiver is randomly located in the area; thus, the received power (or interference) at each receiver is independent. Let X_n be the number of reselections on transmission beams among L concurrent links in the nth searching round $(X_n \in \{0, 1, 2, \ldots, L\})$. X_n is a discrete-time Markov chain with transition probability $p_{i,j}$ shown in Fig. 8. The state transition ends when $X_n = 0$ even if there are some reselections on reception beams in the nth searching round since the receivers are not interferers.

There are L transmitters and L receivers randomly distributed in the area A. Consider the transmitter WDEV_l^T, receiver WDEV_l^R, and interferer WDEV_k^T shown in Fig. 9. The directional antenna model is described as

$$g(\alpha) = \frac{G(\alpha)}{G_{\max}} \quad \text{where} \quad G_{\max} = \max_{\alpha} G(\alpha) \tag{7}$$

where α is the horizontal angle in different directions. To make the analysis trackable, the flat-top antenna model is adopted. Specifically

$$g(\alpha) = \begin{cases} 1, & |\le| \le \frac{\Delta\alpha}{2} \\ 0, & \text{otherwise} \end{cases} \tag{8}$$

where $\Delta\alpha$ is the beamwidth. The directional antenna radiates power to all the directions while having focus on specific directions. To reflect this feature, we have $\Delta\alpha > \frac{2\pi}{N}$, where N is the number of beam patterns for each WDEV. The transmitter and the receiver should be within each other's beam to communicate with each other. To keep link connectivity after the beam reselection, only the adjacent beam of the current active beam can be the reselection candidate based on the flat-top antenna model. A receiver can obtain the transmission power from its transmitter after transmission beam reselection if the receiver locates within the overlap area of the two beams. A sufficient condition to select a new transmission beam for link l to improve the sum rates is that the new beam selection can improve the rate of link l while it does not generate interference to other receivers.

By standard Friis transmission equation, the received power at WDEV_l^R is

$$P_R^l = P_T G_{\max}^2 \frac{\lambda^2}{16\pi^2 d_l^\gamma} e^{-\xi d_l} \tag{9}$$

where d_l is the transmission distance, ξ is the attenuation factor due to absorption in the medium, and γ is the path-loss exponent. Similarly, the interference power from interferer WDEV_k^T is evaluated as

$$P_{\text{interf}}^k = P_T G_{\max}^2 f_{k,l} \frac{\lambda^2}{16\pi^2 d_k^\gamma} e^{-\xi d_k} \tag{10}$$

where $f_{k,l} = 1$ if WDEV_k^T and WDEV_l^R are within each other's beam; otherwise, $f_{k,l} = 0$. The SINR of link l is

$$\text{SINR} = \frac{P_T G_{\max}^2 \frac{\lambda^2}{16\pi^2 d_l^\gamma} e^{-\xi d_l}}{W N_0 + \sum_{k \neq l} P_T G_{\max}^2 f_{k,l} \frac{\lambda^2}{16\pi^2 d_k^\gamma} e^{-\xi d_k}}. \tag{11}$$

From (11), to improve the rate of link l, the interference needs to be reduced since the transmission beam reselection does not change the received power if they are still within each other's beam. Three probabilities are defined.

1) The probability that WDEV_1 is located within WDEV_2's beam is $Q_1 = (\Delta\alpha/2\pi)$.
2) The probability that WDEV_1 is still located within WDEV_2's beam after WDEV_2's beam reselection is $Q_2 = (\Delta\alpha - (2\pi/N)/2\pi = (\Delta\alpha/2\pi) - (1/N)$.
3) The probability that WDEV_1 moves out of (into) WDEV_2's beam after WDEV_2's beam reselection is $Q_3 = (\Delta\alpha - (\Delta\alpha - (2\pi/N))/2\pi = (1/N)$.

In the following, two events are defined. Event B is that the transmission beam reselection on link l can improve the sum rates according to the above sufficient condition, given that there is i interference with transmission beam reselections in the previous searching round, whereas event C is the beam reselection on the receiver WDEV_l^R. Therefore, we have

$$P(B) = P(B, C) + P(B, \overline{C}). \tag{12}$$

First, we consider the case that only the transmission beam is reselected at the transmitter WDEV_l^T to improve the sum rates. The probability that there are h interferers located within the WDEV_l^R's beam among the i interferers is

$$P_h = \binom{i}{h} Q_1^h (1 - Q_1)^{i-h} \triangleq F(i, h, Q_1). \tag{13}$$

The probability that there are g interferers whose beams move into or move out of WDEV_l^R's beam by their transmission beam reselections among the h interferers is

$$P_g = \binom{h}{g} (2Q_3)^g (1 - 2Q_3)^{h-g}. \tag{14}$$

Thus, the probability that the total interference at WDEV_l^R is reduced with g interferers moving into or moving out of WDEV_l^R's beam is

$$\begin{aligned} P_1 &= P\left(\sum_{z=1}^{g} X_z P_T G_{\max}^2 \frac{\lambda^2}{16\pi^2 d_z^\gamma} e^{-\xi d_z} < 0\right) \\ &= P\left(\sum_{z=1}^{g} X_z \frac{e^{-\xi d_z}}{d_z^\gamma} < 0\right) \end{aligned} \tag{15}$$

where $X_z (z = 1, 2, \ldots, g)$ are independent and identically distributed (i.i.d.) random variables with $P(X_z = 1) = P(X_z = -1) = 1/2$ since the receiver has the same probability to move into or to move out of the interferer's beam by reselecting the interferer's transmission beam. All the WDEVs are randomly located in the whole area; thus, all d_z are i.i.d. with the same probability density function $f(d)$. Let $\vec{X} = \{X_1, X_2, \ldots, X_g\}$, $\vec{D} = \{d_1, d_2, \ldots, d_g\}$, and $W(\vec{X}, \vec{D}) = \sum_{z=1}^{g} X_z (e^{-\xi d_z}/d_z^\gamma)$; then, we have

$$\begin{aligned} P_1 &= \sum_{a=1}^{2^g} P(\vec{X} = \vec{X}_a) P\left(W(\vec{X}_a, \vec{D}) < 0 | \vec{X} = \vec{X}_a\right) \\ &= \frac{1}{2^g} \sum_{a=1}^{2^g} \int \cdots \int_{W(\vec{X}_a, \vec{D}) < 0} \left(\prod_{z=1}^{g} f(d_z)\right) d\vec{D}. \end{aligned} \tag{16}$$

Because $P(X_z = 1) = P(X_z = -1) = 1/2$, all the $P(\vec{X} = \vec{X}_a$, $a = 1, \ldots, 2^g)$, have the same probability of $1/2^g$. The probability that i beam reselections of the transmitters can result in the reduction of the total interference at WDEV_l^R is

$$P_2 = \sum_{h=1}^{i} \sum_{g=1}^{h} P_h P_g P_1. \tag{17}$$

According to the sufficient condition to improve sum rates, we have

$$P(B, \overline{C}) = Q_2 (1 - Q_1)^{L-1} P_2. \tag{18}$$

The probability Q_2 in (18) is to let the receiver locate within the overlap area of the adjacent transmission beams such that it can still obtain the power after the transmission beam is reselected. The probability $(1 - Q_1)^{L-1}$ is to make sure the transmitter does not generate interference to other $(L - 1)$ receivers after transmission beam reselection.

Similarly, we can obtain the probability $P(B, C)$ as

$$P(B,C)=\frac{1}{2}Q_2^2(1-Q_1)^{L-1}\sum_{h=1}^{i}\sum_{g=1}^{h}F(i,h,2Q_3)F(h,g,Q_3)P_1. \tag{19}$$

Thus, the state transition probability is

$$p_{i,j}=\begin{cases}\binom{L}{j}P(B)^j\left(1-P(B)\right)^{L-j}, & (1\le i,j\le L)\\ 0, & (i=0 \text{ and } j\neq 0)\\ 1, & (i=j=0).\end{cases} \tag{20}$$

We can obtain the n-step transition probability matrix as

$$\mathbb{P}^{(n)}=(\mathbb{P})^n=\left|p_{i,j}^{(n)}\right|_{(L+1)\times(L+1)}. \tag{21}$$

The probability that the system enters state $X_n=0$ from initial state $X_1=L$ without traversing any state $X_q=0$ $(1<q<n)$ is

$$\hat{p}_{L,0}^{(n)}=\sum_{y=1}^{L}p_{L,y}^{(n-1)}p_{y,0}. \tag{22}$$

The average number of iteration searching rounds from the initial state to the converged beam sets is

$$\mu_n=\sum_{n=1}^{\infty}n\times\hat{p}_{L,0}^{(n)}=\sum_{n=1}^{\infty}\sum_{y=1}^{L}np_{L,y}^{(n-1)}p_{y,0}. \tag{23}$$

The searching space of the proposed algorithm, which is denoted T_{pro}, is given as

$$T_{\text{pro}}=\mu_n LN^2 \tag{24}$$

compared with the original searching space with the exhaustive search method (denoted T_{org}) $T_{\text{org}}=N^{2L}$.

Given a $\rho\times\rho$ square area A, $f(d)$ is

$$f(d)=\begin{cases}2\frac{d}{\rho^2}\left(\frac{d^2}{\rho^2}-4\frac{d}{\rho}+\pi\right), & (0<d\le\rho)\\ 2\frac{d}{\rho^2}\left(4\sqrt{\frac{d^2}{\rho^2}-1}-\left(\frac{d^2}{\rho^2}+2-\pi\right)\right. & \\ \qquad\left.-4\arctan\left(\frac{d^2}{\rho^2}-1\right)\right), & (\rho<d\le\sqrt{2}\rho).\end{cases} \tag{25}$$

With $\rho=30$ m, $L=10$, $\Delta\alpha=1.5(2\pi/N)$, $\gamma=2$, $\xi=0$, and $N=8$, the average number of iteration searching rounds can be obtained as 15.3. The searching space can be reduced more than 99%. μ_n provides the average number of iterative searching rounds. For specific cases, the number of searching rounds n depends on the initial search point, the converged point, the convergent rate, and the convergent threshold Th_{rate}.

VII. Performance Evaluation

Here, simulation results are provided to demonstrate the performance of the proposed concurrent beamforming protocol, compared with another two beamforming protocols, namely, exhaustive searching concurrent beamforming (ESCB) protocol and the isolated sequential beamforming (ISB) protocol. The ESCB protocol finds the best transmission/reception beam sets for all the concurrent links by exhaustive search, whereas the ISB protocol sequentially obtains the transmission/reception beam for each link without consideration of mutual interference.

We simulate a typical mmWave indoor environment (e.g., large office space) where the PNC is placed in the center of the room and all WDEVs are randomly distributed in a 30 m × 30 m region. The source and destination nodes of each link are randomly selected. The channel model defined in 802.11ad TG [26] is adopted for simulations. The path-loss model for conference room environment [26] is given as

$$\text{PL[dB]}=A+20\log_{10}(f)+10\gamma\log_{10}(d) \tag{26}$$

where γ is the path-loss exponent. $A=45.5$ and $\gamma=1.4$ are set for the NLOS environment. To reflect the shadowing effect, the human blockage model defined in the 802.11ad channel model document [26] is adopted. Four parameters are used to describe the shadow effect. The duration t_D characterizes the time between the last zero crossing before and the first zero crossing after the shadowing event. Decay time t_{decay} and rising time t_{rise} define the time duration between the zero crossings of the signal level and a given threshold of 10 dB in each case. The mean attenuation A_{mean} describes the average attenuation. The shadowing effect model is composed of a series of periods: a linearly decaying period, a period of constant signal level, and a linearly increasing period. The probability distributions of the four parameters are described in Table I. The transmission rate of each link is estimated by (3). The propagation related and MAC-layer related simulation parameters are shown in Tables II and III, respectively.

TABLE I
Parameters of Shadowing Effect

Parameters	Distribution
$t_D[s]$	Weibull ($\lambda=0.59, k=6.32$)
$t_{decay}[s]$	Weibull ($\lambda=0.044, k=2.07$)
$t_{rise}[s]$	Weibull ($\lambda=0.045, k=1.76$)
$A_{mean}[dB]$	Gaussian ($\mu=13.4, \sigma=2.0$)

TABLE II
Propagation-Related Parameters

Parameters	Value
Central frequency (f)	60 GHz
System bandwidth (W)	1.728 GHz
Transmission power (P_T)	0.1mW
Background noise (N_0)	-134dBm/MHz
Path loss exponent for LOS (n_{LOS})	2.0
Path loss exponent for NLOS (n_{NLOS})	1.4
Reference distance (d_{ref})	1.0 m
Path loss at d_{ref} (PL_0)	68.0 dB
Minimum Rx sensitivity level	-59.3 dBm
Shadow Margin	5.0 dB

TABLE III
MAC-RELATED PARAMETERS

Parameters	Value
Superframe period	$65535\mu s$
Beacon period	$55\ \mu s$
Random access period	$120\ \mu s$
Number of slots in transmission period	817
Slot time	$80\ \mu s$
Training sequence	$3.259\ \mu s$
SIFS time (T_{SIFS})	$2.5\ \mu s$
Notification packet size	2 Kbytes
ACK period T_{ACK}	$7.212\ \mu s$
Convergency threshold Th_{rate}	0.05
Number of beams N	16

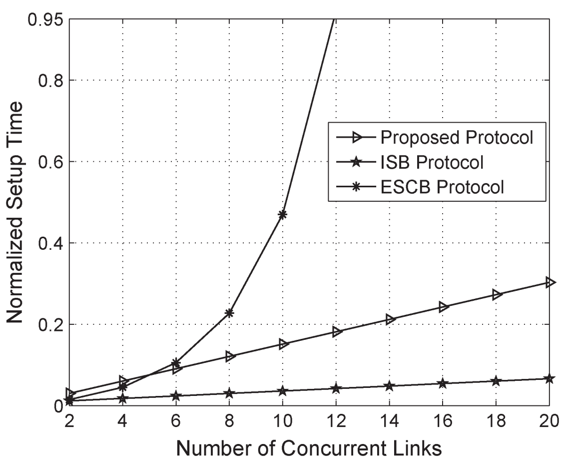

Fig. 10. Normalized total setup time.

A. Total Setup Time

Fig. 10 shows the normalized average setup time to conduct concurrent beamforming with respect to the number of concurrent links. For fair comparison, the time to conduct single-link beamforming is the same for all the three beamforming protocols. The proposed concurrent beamforming protocol significantly reduces the total setup time compared with the ESCB protocol, particularly for a larger number of concurrent links. For example, with 12 concurrent links, the proposed beamforming protocol can reduce 85% of the setup time. The total setup time accounts for both the searching time and the time for signaling and management information transmission. Although the proposed concurrent beamforming introduces more communication overheads as described in Section V-B, the communication overheads are minor in comparison with the total time it saves since it reduces the exponential searching complexity to linear searching complexity.

B. Network Throughput

Fig. 11 shows the normalized system throughput of the three beamforming protocols. The proposed beamforming protocol can achieve much better system throughput than the ISB protocol, particularly in the scenarios with more concurrent links. The ISB protocol conducts beamforming without consideration

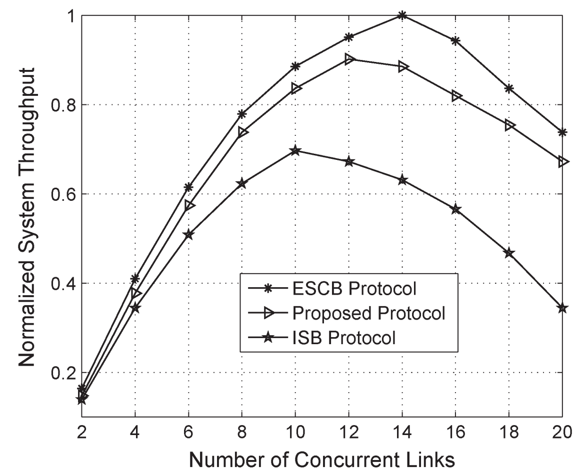

Fig. 11. Normalized system throughput.

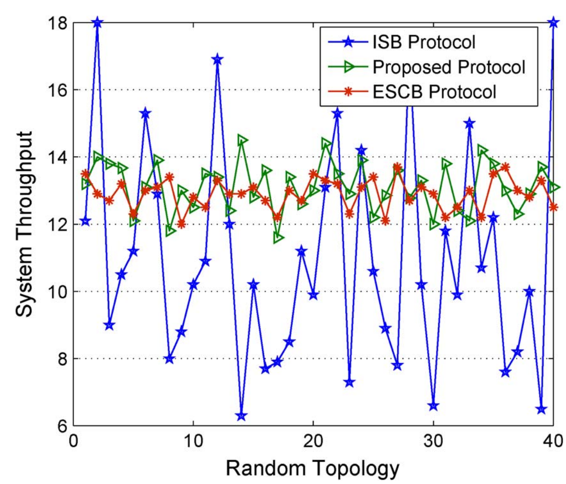

Fig. 12. Network throughput variation with different topologies.

for mutual interference. When the number of concurrent links in the network is small, the mutual interference has a minor impact on the system throughput due to directional transmission and high propagation loss over relatively large transmission distance. For dense networks, the system throughput would be reduced significantly by the ISB protocol because of the severe mutual interference. Additionally, it is shown in Figs. 10 and 11 that the proposed beamforming protocol can save significant total setup time with reasonable system throughput reduction compared with the ESCB protocol.

The system throughput of the ISB protocol greatly relies on the geographic distribution of the transmitters and receivers. The geographic distribution determines the mutual interference (not considered in the ISB protocol), and so do the transmission rate and the system throughput. Fig. 12 shows the system throughputs of the three protocols for 15 concurrent links with 40 random topologies. It is shown that the network throughput of ISB varies much with different topologies, whereas the proposed protocol can achieve more stable system throughput. The multimedia applications operating in mmWave networks require stable or even guaranteed throughput, which the ISB protocol cannot provide. The proposed concurrent beamforming protocol determines the beam selection for each link taking

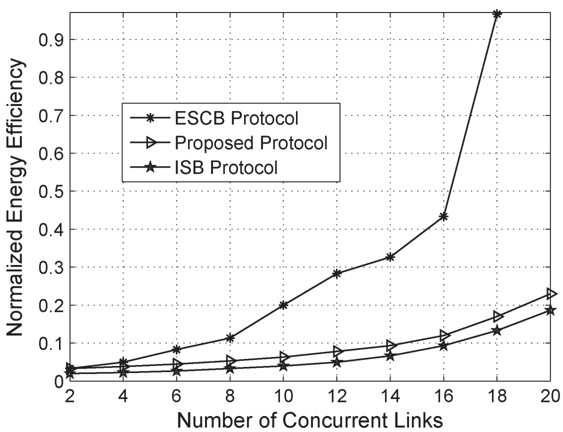

Fig. 13. Energy efficiency of the three protocols.

into account the interference; thus, it can achieve more stable system throughput.

C. Energy Consumption

As indicated in the Section V-A, all the interferers (transmitter of other concurrent links) need to be active with the proposed protocol, whereas one link conducts beamforming, to consider the interference. This method introduces extra energy consumption compared with the ISB protocol. However, the ESCB protocol consumes much more energy because all the transmitters remain active for the whole beamforming procedure and the ESCB protocol spends much more time to obtain the beamforming results. For fair comparison, we use the total energy consumption (for the transmission of both TSs and communication overheads) divided by achieved system throughput, to show the energy efficiency. As shown in Fig. 13, the proposed concurrent beamforming protocol achieves better energy efficiency than the ESCB protocol.

VIII. Conclusion

In this paper, we have proposed a MAC-layer comprehensive beamforming protocol including four phases based on the proposed iterative searching algorithm to setup multiple directional concurrent transmissions. The proposed iterative searching algorithm can provide a suboptimal solution on network throughput to find transmission/reception beam patterns. The theoretical analysis shows the complexity to conduct beamforming can be reduced from exponential searching space to linear searching space. The simulation results have demonstrated significant performance improvements on total setup time and transmission efficiency for dense indoor mmWave networks. The proposed concurrent beamforming protocol has the flexibility to support multiple physical-layer designs and different antenna configurations for indoor mmWave networks. It should also be useful for other mmWave networks, such as mmWave fifth-generation cellular networks and mmWave-based wireless backhaul.

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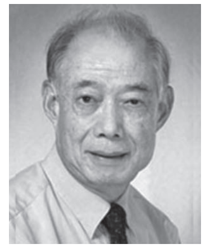

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