

MAC-layer Concurrent Beamforming Protocol for Indoor Millimeter Wave Networks

Jian Qiao, Xuemin (Sherman) Shen, *Fellow, IEEE*,
Jon W. Mark, *Life Fellow, IEEE*, Yejun He, *Senior Member, IEEE*

Abstract—In this paper, we study concurrent beamforming issue for achieving high capacity in indoor millimeter wave networks. The general concurrent beamforming issue is first formulated as an optimization problem to maximize the sum rates of concurrent transmissions considering the mutual interferences. To reduce the complexity of beamforming and total setup time, concurrent beamforming is decomposed into multiple single-link beamforming and an iterative searching algorithm is proposed to quickly achieve the sub-optimal 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—Millimeter wave communications, concurrent transmissions, beamforming, setup time, medium access control.

I. INTRODUCTION

Millimeter-wave (mmWave) band communication, 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 communication is its capability to achieve multi-Gbps rate to support bandwidth-intensive multimedia applications. However, mmWave communication suffers high propagation loss due to its high frequency band. In order to compensate for the tremendous propagation loss and reduce shadowing effect, high-gain directional antenna array is favored to improve the system efficiency and transmission range, especially for non-line-of-sight (NLOS) channels [8]. Since the dimensions and necessary spacing of 60 GHz antennas are in the order of millimeters [9], multiple antennas can be integrated into portable devices.

Manuscript received Dec. 6, 2013; revised Feb. 28, 2014; accepted March 28, 2014. This research has been 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.

Copyright ©2013 IEEE. Personal use of this material is permitted. However, permission to use this material for any other purposes must be obtained from the IEEE by sending a request to pubs-permissions@ieee.org.

Jian Qiao, Xuemin (Sherman) Shen, and Jon W. Mark are with the Broadband Communications Research (BBCR) Group, Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, Canada, N2L 3G1, (email: {jqiao, xshen, jwmark}@bbcr.uwaterloo.ca).

Yejun He is with the College of Information Engineering, Shenzhen University, Shenzhen, China, 518060 (email: heyejun@126.com)

Digital Object Identifier 10.1109/TVT.2014.xxxxxx.

Beamforming determines a beam toward a certain direction formed by multiple antennas to maximize the transmission rate. The antenna gains of the transmitter (TX) and the receiver (RX) have significant impact on the transmission data rates. Thus beamforming protocol is required to select the best transmission and reception beams, according to the selection metric [10], [11], e.g., signal-to-noise ratio (SNR). Because of 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 interferences 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 interferences 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 interferences 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 60 GHz band has several challenges: (1) 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; (2) the concurrent links make beamforming even more difficult, because the mutual interferences are unknown until the best transmission and reception beam patterns for all the concurrent links are finalized; and (3) no complete 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 pre-defined beam steering vectors (i.e., codebook) without the necessity of AOD/AOA or CSI estimation. The 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

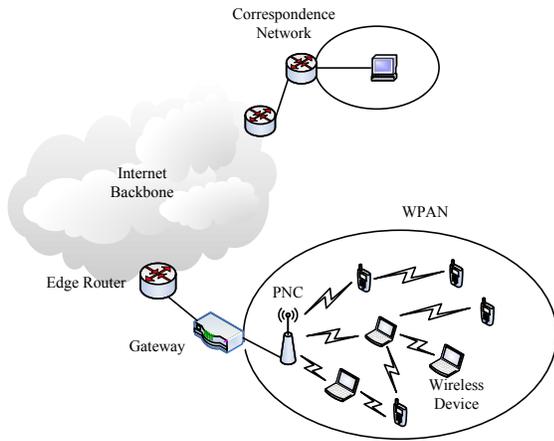


Fig. 1: Indoor mmWave Network Architecture

beamforming and propose an iterative searching algorithm to quickly achieve the sub-optimal 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 the paper is organized as follows. In Section II, related works are presented. The network topology, timing structure, and 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 60 GHz band have been actively studied in [10], [11], [15], [16], [18]–[20] and specified in standards, including IEEE802.15.3c (TG3c) [21] for WPANs, 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 was formulated in [17] and an automatic alignment mechanism was provided to adaptively track the transmitter location and steers 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 millimeter-wave signals by means of a maximum directivity beamformer 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 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).

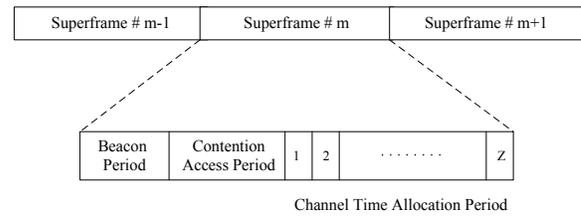


Fig. 2: Superframe-based Timing Structure

Recently, another type of beamforming protocols realized on MAC layer is proposed in [10], [11], [14], [19], [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 set-up time and to mitigate the high path loss of 60GHz WPAN systems. In [11], multi-level heuristic searching algorithm 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 pre-specified 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.

To the best of our knowledge, the previous works on beamforming protocols for indoor mmWave networks are designed for one pair of transmitter and receiver (i.e., 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, especially for the densely populated networks. It is necessary to jointly consider the beamforming for all the transmission links operating simultaneously, in order to mitigate the mutual interferences 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 (D2D) 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, in order to achieve best system performance.

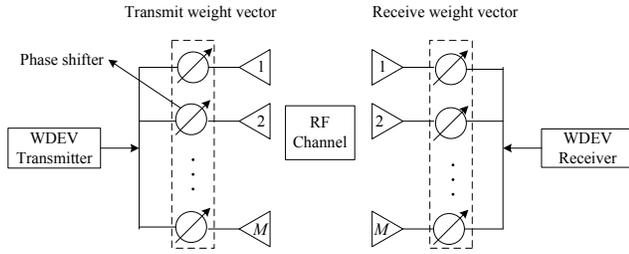


Fig. 3: Beamforming Structure Model

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 messages 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 TDMA slot granted by PNC for multiple 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. 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 Giga-samples per second at baseband. To reduce the overhead and energy consumption, the beamforming is operated in radio frequency (RF) band, including only a single RF chain. At the transmitter, the signal after baseband processing is up-converted to the RF band. The RF signal is phase-shifted by applying the transmit weight vector and is transmitted via the MIMO 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 down-converted for baseband processing.

IV. CONCURRENT BEAMFORMING PROBLEM

In this section, 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 communication

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:

$$\mathbf{W} = |w_{(m,u)}| = |j^{\lfloor \frac{m \times \text{mod}((u+N/2), N)}{N/4} \rfloor}| \quad (1)$$

where N is also the total number of beam patterns, $m \in \{0, 1, 2, \dots, M-1\}$, $u \in \{0, 1, 2, \dots, N-1\}$, and $j = \sqrt{-1}$. The above 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 DFT-based codebook design [23]. With the same notations in (1), the DFT-based codebook can be given by the following matrix:

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

where $m = 1, 2, \dots, M$ and $u = 1, 2, \dots, N$. The weight vectors in DFT-based codebook are composed of complex numbers which 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 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 interferences. 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:

- $B_T = [n_t^1, n_t^2, \dots, n_t^L, \dots, n_t^L]$ is the set of beam patterns selected for the L links for data transmission;
- $B_R = [n_r^1, n_r^2, \dots, n_r^L, \dots, n_r^L]$ 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

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

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), $n_t^k, n_r^l \in \{1, 2, \dots, N\}$ with $k, l = 1, 2, \dots, L$.

To maximize the sum rates, we formulate the concurrent beamforming problem as an optimization problem (P):

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

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

$$n_t^l, n_r^l, n_t^k \in \mathcal{Z}^+ \quad (6)$$

where \mathcal{Z}^+ is the set for all positive integers. This optimization problem is a non-linear 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 proved that the Knapsack problem is NP-complete [24]. Concurrent beamforming is even more difficult than the Knapsack problem because the profits of items (rate) is not determined until the active beam patterns of other links are determined. As a result, the concurrent beamforming problem can not 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; 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.

C. Iterative Searching Algorithm

In conventional codebook-based beamforming protocol with exhaustive search for single link, the transmitter sends the training sequence with one of its beam patterns, while the receiver attempts to listen to it with different beam patterns. The above 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 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 w.r.t. the number of concurrent links.

Algorithm 1 Iterative Searching Algorithm for Beamforming

BEGIN:

1: L links are scheduled to be active in a time slot of CTAP.

2: Initialize the beam sets $B_T = \vec{0}$ and $B_R = \vec{0}$

3: **repeat**

4: **for** link $l = 1$ to L (l is link number index) **do**

5: **if** $n_t^l = 0$ and $n_r^l = 0$ **then**

6: set n_t^l and n_r^l according to

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

7: **else**

8: set n_t^l and n_r^l according to

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

9: **end if**

10: **end for**

11: **until** $B_T = \{n_t^l\}$ and $B_R = \{n_r^l\}$ converges

END;

To obtain the best transmission beam set B_T^* and reception beam set B_R^* , 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 sub-optimal solutions. There are many efficient beamforming protocols (e.g., multi-stage scheme [10] and multi-level 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 $B_T = \vec{0}$ and $B_R = \vec{0}$. In the initial searching round, the beamforming procedure of the first link is conducted with the beamforming protocol for single communication pair, then $B_T[1]$ and $B_R[1]$ are updated with the selected beam patterns. For the following l^{th} ($1 < l \leq L$) link, the beamforming is conducted with the single-link beamforming protocol considering the interferences generated from the concurrent links whose beamforming has been determined. The single-link 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 pair of transmission/reception beam 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 above procedure, another iterative searching round is re-conducted considering the interferences 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 \vec{B}_T and \vec{B}_R is better than the beam sets B_T and B_R of the previous round in terms of the total throughput.

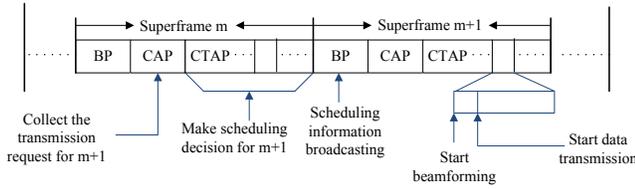


Fig. 4: Procedure for Scheduling and Beamforming

The above process is repeated until the beam set 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 can not 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 can not ensure the global optimality of the solution.

V. BEAMFORMING PROTOCOL

In this section, 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 m^{th} superframe. Then the scheduling decision is made by PNC for the $(m+1)^{th}$ CTAP before the $(m+1)^{th}$ beacon period, 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 CTAP period, the proposed concurrent beamforming protocol should work distributively. Each time slot of CTAP consists of beamforming period and data transmission period. Thus, the total setup time of concurrent beamforming has 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, inter-link notification, iterative searching convergency, and acknowledgement.

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 single link cannot be applied directly due to the following challenges:

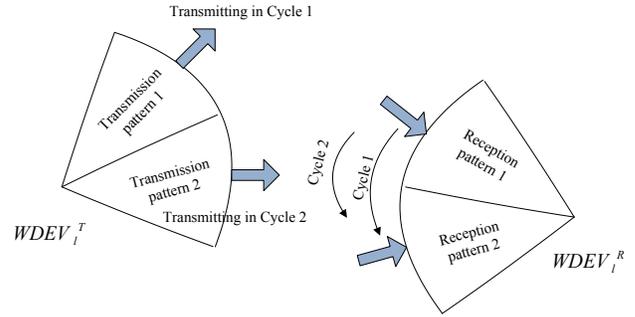


Fig. 5: An Example for Single Link Beamforming

- 1) The interferences from other concurrent links have 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 pre-determined even if the time is synchronized.
- 3) The beam selection metric, i.e., sum rates, is not measurable and each link can not know them by itself.

In BP of the m^{th} 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 pre-assigned 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 interferences 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 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

Header	NoC	NoF	Beam Selection Identification
--------	-----	-----	-------------------------------

Fig. 6: Format of Each Notification Packet

of other links.

B. Inter-link Notification

Following the Single Link Beamforming phase, Inter-link Notification phase is required to move to next single link beamforming. As indicated in Section V-A, although each link receives the beamforming sequence information during the Beacon period, link $(l + 1)$ needs the trigger information to start beamforming right after the completion of link l 's beamforming. The 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: header, number of current link (*NoC*), number of following link (*NoF*), 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 convergency phase as to be described in Section V-C. A short inter-phase spacing (SIPS) 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 high data rate for mmWave networks supporting bandwidth intensive applications. The notification packet, SINR values, and other management information do not require 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 towards each other according to the topology information, to deliver signaling and management information among WDEVs.

C. Iterative Searching Convergency

With Single Link Beamforming phase and Inter-link Notification phase, beamforming can be conducted link by link to achieve the transmission/reception beam set. To realize the iterative searching algorithm distributively, two main issues need to be considered:

- A Convergency 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 convergency condition can achieve better solution with more rounds of iterative searching. A loose

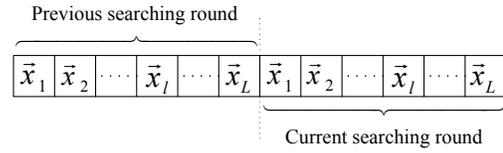


Fig. 7: Format of Beam Selection Identification in Notification Packet

convergency condition can quickly find the approximate solution.

- Since beamforming is conducted link by link without the control of PNC, the convergency condition information should be delivered to WDEVs in a distributive manner.

For concurrent beamforming, the general convergency condition is 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 n^{th} round are the same as those obtained in the $(n - 1)^{th}$ round for all $l \in \{1, 2, \dots, L\}$. The above ideal convergency condition can cause a large number of searching rounds and much longer setup time due to the following reasons: 1) 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. 2) At system-level beamforming, the new beam pair of one link can lead to the beam pattern re-selection of many other links and more searching rounds because of the mutual interferences. The concurrent beamforming procedure is kind of chain reaction inspired by the the transmission beam re-selection since the transmission beams generate interferences to other links. To significantly shorten the total setup time, a sum rate threshold Th_{rate} in percentages is used to determine the beam pattern re-selection. For example, after conducting single link beamforming for link l , if the new achieved sum rates are within $[1, (1 + Th_{rate}))$ of the sum rates of previous round, the beam patterns of link l remain the same.

As shown in Fig. 6, Beam Selection Identification Field of the notification packet is used to notify the convergency information among WDEVs. A vector $\vec{x}_l = [n_t^l, n_r^l]$ is saved in each sub-field of the beam selection identification field to record 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 \vec{x}_l ($l = 1, 2, \dots, L, \dots, L$) 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 are converged.

D. Acknowledgement

After a link completes its beamforming for the current searching round, it either waits for the trigger information to start the beamforming for next searching round, or it will stop beamforming after receiving the convergency message and use the selected transmission/reception beam patterns for data transmission. After the receiver of the L^{th} link receives the notification packet and compare the beam selection results of the current and previous searching round, it will broadcast

a 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 pseudo codes 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:
1: Each link  $l$  can generate a notification packet
2: for Each iterative searching round  $n$  do
3:   for Link  $l = 1$  to  $L$  ( $l$  is link number index) do
4:     Link  $l$  receives a notification packet
5:     if The  $NoF = l$  in the notification packet then
6:       Link  $l$  starts beamforming;
7:       Update  $NoC = l$ ;
8:       Update  $NoF = l + 1$ ;
9:       Record the beam selection result  $\vec{x}_l = [n_t^l, n_r^l]$ ;
10:      if  $l \neq L$  then
11:        Link  $l$  sends out updated notification packet;
12:      else
13:        The beam selection results of  $n^{th}$  round and  $(n+1)^{th}$ 
        round are compared;
14:        if  $B_T^n = B_T^{n+1}$  and  $B_R^n = B_R^{n+1}$  then
15:          Go to END;
16:        else
17:          Update  $n = n + 1$ ;
18:          Link  $L$  sends out message to trigger new round
          beamforming;
19:        end if
20:      end if
21:    else
22:      Link  $l$  disregards the notification packet
23:    end if
24:  end for
25: 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.

To simplified the analysis, the following assumptions are made: a) there is no link blockage between WDEVs and the line-of-sight transmission is always available; b) the channel status does not change during the concurrent beamforming period, thus the beam re-selection of a link can only result from the beam re-selections of other interferers; c) the beam re-selection of a link in the n^{th} searching round is due to the transmission beam re-selections in the $(n - 1)^{th}$ round; d) each receiver is randomly located in the area, thus the received power (or interferences) at each receiver is independent. Let X_n be the number of re-selections on transmission beams among L concurrent links in the n^{th} searching round ($X_n \in \{0, 1, 2, \dots, L\}$). X_n is a discrete-time Markov chain

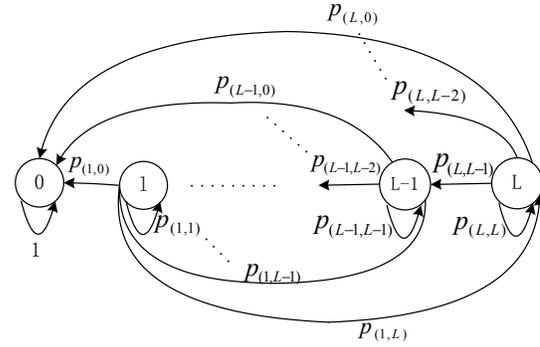


Fig. 8: Markov Chain for X_n

with transition probability $p_{i,j}$ illustrated in Fig. 8. The state transition ends when $X_n = 0$ even if there are some re-selections on reception beams in the n^{th} 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

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

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

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

where $\Delta\alpha$ is the beamwidth. 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 in order to communicate with each other. To keep link connectivity after the beam re-selection, only the adjacent beam of the current active beam can be the re-selection candidate based on flat-top antenna model. A receiver can obtain the transmission power from its transmitter after transmission beam re-selection if the receiver locates within 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 interferences to other receivers.

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

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

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

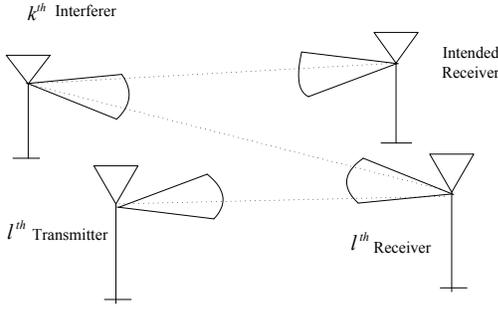


Fig. 9: Geometry of Directional Interference

WDEV_k^T is evaluated as:

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

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

$$SINR = \frac{P_T G_{max}^2 \frac{\lambda^2}{16\pi^2 d_l^2} e^{-\xi d_l}}{WN_0 + \sum_{k \neq l} P_T G_{max}^2 f_{k,l} \frac{\lambda^2}{16\pi^2 d_k^2} e^{-\xi d_k}} \quad (11)$$

From (11), to improve the rate of link l , the interferences need to be reduced since the transmission beam re-selection does not change the received power if they are still within each other's beam. Three probabilities are defined:

- 1) The probability that WDEV₁ is located within WDEV₂'s beam is $Q_1 = \frac{\Delta\alpha}{2\pi}$;
- 2) The probability that WDEV₁ is still located within WDEV₂'s beam after WDEV₂'s beam re-selection is $Q_2 = \frac{(\Delta\alpha - \frac{2\pi}{N})}{2\pi} = \frac{\Delta\alpha}{2\pi} - \frac{1}{N}$;
- 3) The probability that WDEV₁ moves out of (into) WDEV₂'s beam after WDEV₂'s beam re-selection is $Q_3 = \frac{\Delta\alpha - (\Delta\alpha - \frac{2\pi}{N})}{2\pi} = \frac{1}{N}$.

In the following, two events are defined: event B is that the transmission beam re-selection on link l can improve the sum rates according to the above sufficient condition, given there are i interferences with transmission beam re-selections in previous searching round while event C is the beam re-selection on the receiver WDEV_l^R. Therefore, we have

$$P(B) = P(B, C) + P(B, \bar{C}). \quad (12)$$

First, we consider the case that only the transmission beam is re-selected 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

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

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

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

Thus, the probability that the total interferences at WDEV_l^R

are reduced with g interferers moving into or move out of WDEV_l^R's beam is

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

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

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

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

$$P_2 = \sum_{h=1}^i \sum_{g=1}^h P_h P_g P_1 \quad (17)$$

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

$$P(B, \bar{C}) = Q_2 (1 - Q_1)^{L-1} P_2 \quad (18)$$

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 re-selected. The probability $(1 - Q_1)^{L-1}$ is to make sure the transmitter does not generate interferences to other $(L - 1)$ receivers after transmission beam re-selection.

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

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

Thus the state transition probability is

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

We can obtain the n-step transition probability matrix as

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

The probability that the system enters state $X_n = 0$ from initial state $X_1 = L$ without traversing any state $X_q = 0$

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 ($\mu = 13.4, \sigma = 2.0$)

($1 < q < n$) is

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

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

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

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

$$T_{pro} = \mu_n L N^2 \quad (24)$$

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

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

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

With $\rho = 30m$, $L = 10$, $\Delta\alpha = 1.5 \frac{2\pi}{N}$, $\gamma = 2$, $\xi = 0$, 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

In this section, 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 isolated sequential beamforming (ISB) protocol. The ESCB protocol finds the best transmission/reception beam sets for all the concurrent links by exhaustive search while the ISB protocol sequentially obtains the transmission/reception beam for each link without consideration of mutual interferences.

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 $30m \times$

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

$30m$ 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

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

where γ is the path loss exponent. $A = 45.5$ and $\gamma = 1.4$ are set for NLOS environment. To reflect the shadowing effect, the human blockage model defined in 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. The decay time t_{decay} and the 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 Table II and Table III, respectively.

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 ESCB protocol, especially for larger number of concurrent links. For example, with 12 concurrent links, the proposed beamforming protocol can reduce 85% 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 Sec.V-B, the communication overheads are minor in comparison with the

TABLE III: MAC related parameters

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

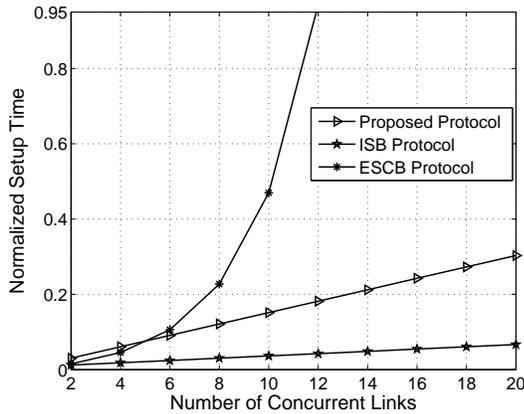


Fig. 10: Normalized Total Setup Time

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, especially in the scenarios with more concurrent links. The ISB protocol conducts beamforming without the consideration of mutual interferences. When the number of concurrent links in the network is small, the mutual interferences have 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 ISB protocol because of the severe mutual interferences. Additionally, it is demonstrated by Fig. 10 and Fig. 11, that the proposed beamforming protocol can save significant total setup time with reasonable system throughput reduction compared with ESCB protocol.

The system throughput of the ISB protocol greatly relies on

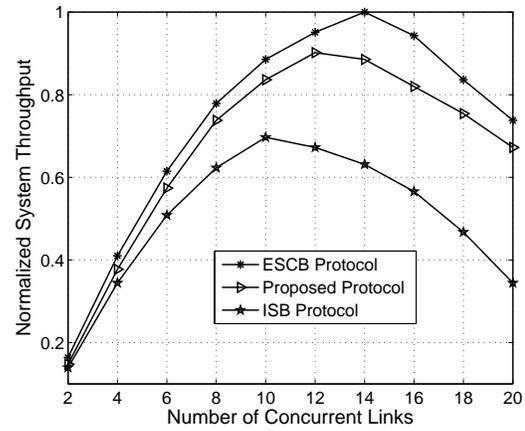


Fig. 11: Normalized System Throughput

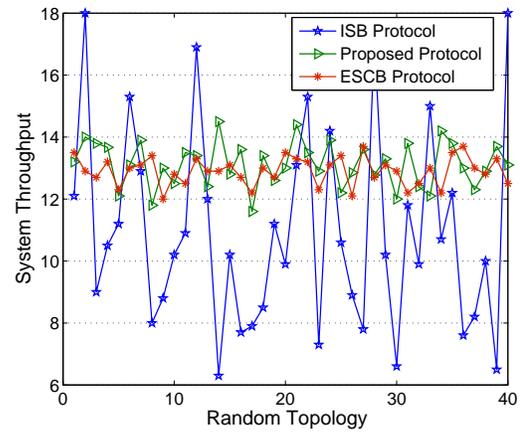


Fig. 12: Network Throughput Variation with Different Topologies

the geographic distribution of the transmitters and receivers. The geographic distribution determines the mutual interferences (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 while 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 can not provide. The proposed concurrent beamforming protocol determines the beam selection for each link taking into account the interferences and 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 while one link conducts beamforming, in order to consider the interferences. This method introduces extra energy consumption compared with ISB protocol. However, the ESCB protocol consumes much more energy because

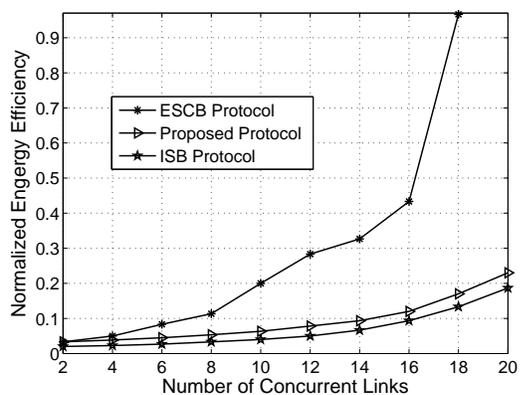


Fig. 13: Energy Efficiency of the Three Protocols

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 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 sub-optimal 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 PHY-layer designs and different antenna configurations for indoor mmWave networks. It should also be useful for other mmWave networks, such as mmWave 5G cellular networks and mmWave based wireless backhaul.

REFERENCES

[1] J. Qiao, L. X. Cai, X. Shen, and J. W. Mark, "Enabling Multi-hop Concurrent Transmissions in 60 GHz Wireless Personal Area Networks," *IEEE Trans. on Wireless Commun.*, vol. 10, no. 11, pp. 3824-3833, Nov. 2011

[2] L. X. Cai, L. Cai, X. Shen, and J. W. Mark, "REX: A Randomized EXclusive Region Based Scheduling Scheme for mmWave WPANs with Directional Antenna," *IEEE Trans. Wireless Commun.*, vol. 9, no. 1, pp. 113-121, Jan. 2010.

[3] L. X. Cai, L. Cai, X. Shen, and J. W. Mark, "Resource Management and QoS Provisioning for IPTV over mmWave-based WPANs with Directional Antenna," *ACM Mobile Networks and Applications (MONET)*, vol. 14, no. 2, pp. 210-219, 2009.

[4] J. Qiao, L. X. Cai, X. Shen, and J. W. Mark, "STDMA-based Scheduling Algorithm for Concurrent Transmissions in Directional Millimeter Wave Networks," in *Proc. IEEE ICC*, pp. 5221-5225, June 2012.

[5] A. Maltsev, R. Maslennidov, A. Sevastyanov, A. Khoryaev, and A. Lomayev, "Experimental Investigations of 60 GHz WLAN Systems in Office Environment," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 8, pp. 1488-1499, Oct. 2009.

[6] J. Qiao, B. Cao, X. Zhang, X. Shen, and J. W. Mark, "Efficient Concurrent Transmission Scheduling for Cooperative Millimeter Wave Systems," in *Proc. IEEE GLOBECOM*, pp. 4187-4192, Dec. 2012.

[7] R. Mudumbai, S. Singh, and U. Madhow, "Medium Access Control for 60 GHz Outdoor Mesh Networks with Highly Directional Links," in *Proc. IEEE INFOCOM*, pp. 2871-2875, April 2009.

[8] S. Geng, J. Kivinen, X. Zhao, and P. Vainikainen, "Millimeter-Wave Propagation Channel Characterization for Short-Range Wireless Communications," *IEEE Trans. Veh. Technol.*, vol. 58, no.1, pp. 3-13, Jan. 2009

[9] F. Gutierrez, S. Agarwal, K. Parrish, and T. S. Rappaport, "On-Chip Integrated Antenna Structures in CMOS for 60 GHz WPAN Systems," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 8, pp. 1367-1378, Oct. 2009.

[10] 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," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 8, pp. 1390-1399, Oct. 2009.

[11] H. H. Lee, and Y. C. Ko, "Low Complexity Codebook-Based Beamforming for MIMO-OFDM Systems in Millimeter-Wave WPAN," *IEEE Trans. on Wireless Commun.*, vol. 10, no. 11, pp. 3607-3612, Nov. 2011.

[12] R. Nelson and L. Kleinrock, "Spatial-TDMA: A Collision-free Multihop Channel Access Protocol," *IEEE Trans. Commun.*, vol. 33, no. 9, pp. 934-944, Sept. 1985.

[13] C. Sum, Z. Lan, R. Funada, J. Wang, T. Baykas, M.A. Rahman, and H. Harada, "Virtual Time-Slot Allocation Scheme for Throughput Enhancement in a Millimeter-Wave Multi-Gbps WPAN System," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 8, pp. 1379-1389, Oct. 2009

[14] B. Li, Z. Zhou, W. Zou, X. Sun, and G. Du, "On the Efficient Beamforming Training for 60 GHz Wireless Personal Area Networks," *IEEE Trans. on Wireless Commun.*, vol. 12, no. 2, pp. 504-515, Feb. 2013.

[15] M. S. Choi, G. Grosskopf, D. Rohde, B. Kuhlow, G. Przyrembel, and H. Ehlers, "Experiments on DOA-Estimation and Beamforming for 60 GHz Smart Antennas," in *Proc. IEEE VTC-Spring*, pp.1041-1045, April 2003.

[16] G. Grosskopf, R. Eggemann, and H. Ehlers, "Maximum Directivity Beam-former at 60 GHz with Optical Feeder," *IEEE Trans. on Antennas and Propagation*, vol. 51, no 11, pp. 3040-3046, Nov. 2003.

[17] N. Celik, M. F. Iskander, R. Emrick, S. J. Franson, and J. Holmes, "Implementation and Experimental Verification of a Smart Antenna System Operating at 60 GHz Band," *IEEE Trans. on Antenna and Propagation*, vol. 56, no. 9, pp. 2790-2800, Sept. 2008.

[18] X. An, C. Sum, R. V. Prasad, J. Wang, Z. Lan, J. Wang, R. Hekmat, H. Harada, and I. Niemegeers, "Beam Switching Support to Resolve Link-Blockage Problem in 60 GHz WPANs," in *Proc. IEEE PIMRC*, pp.390-394, Sept. 2009.

[19] S. Hur, T. Kim, D. J. Love, J. V. Krogmeier, T. A. Thomas, and A. Ghosh, "Multilevel Millimeter Wave Beamforming for Wireless Backhaul," in *Proc. IEEE GLOBECOM Workshops*, pp.253-257, Dec. 2012.

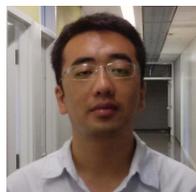
[20] L. Zhou, and Y. Ohashi, "Efficient Codebook-Based MIMO Beamforming for Millimeter-Wave WLANs," in *Proc. IEEE PIMRC*, pp.1885-1889, Sept. 2012.

[21] IEEE Std 802.15.3c-2009, *Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs) Amendment 2: Millimeterwave-based Alternative Physical Layer Extension*, IEEE Computer Society, Oct. 2009.

[22] IEEE P802.11ad, *Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band*, IEEE Computer Society, Jul. 2011

[23] L. Wan, X. Zhong, Y. Zheng, and S. Mei, "Adaptive Codebook for Limited Feedback MIMO System," in *Proc. WOCN*, pp.1-5, Apr. 2009.

- [24] D. Pisinger, "Where are the hard knapsack problems?" *Computers and Operations Research*, pp. 2271–2284, 2005.
- [25] F. Winkler, E. Fischer, E. Grass, and P. Langendörfer, "An Indoor Localization System Based on DTDOA for Different Wireless LAN Systems," in *Proc. WPNC*, pp. 117-122, June, 2006
- [26] A. Maltsev, "Channel Models for 60 GHz WLAN Systems", IEEE 802.11-09-0344-07ad, March 2010.

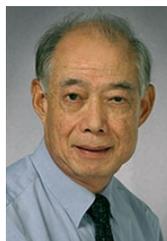


Jian Qiao is currently working toward his PhD degree at the Department of Electrical and Computer Engineering, University of Waterloo, Canada. He received B.E. degree in Beijing University of Posts and Telecommunications, China in 2006 and the MSc degree in Electrical and Computer Engineering from University of Waterloo, Canada in 2010. His research interests include millimeter wave WPANs, medium access control, resource management, and millimeter wave 5G cellular networks.



Xuemin (Sherman) Shen (IEEE M'97-SM'02-F'09) received the B.Sc.(1982) degree from Dalian Maritime University (China) and the M.Sc. (1987) and Ph.D. degrees (1990) from Rutgers University, New Jersey (USA), all in electrical engineering. He is a Professor and University Research Chair, Department of Electrical and Computer Engineering, University of Waterloo, Canada. He was the Associate Chair for Graduate Studies from 2004 to 2008.

Dr. Shen's research focuses on resource management in interconnected wireless/wired networks, wireless network security, social networks, smart grid, and vehicular ad hoc and sensor networks. Dr. Shen served as the Technical Program Committee Chair/Co-Chair for IEEE Infocom'14, IEEE VTC'10 Fall, the Symposia Chair for IEEE ICC'10, the Tutorial Chair for IEEE VTC'11 Spring and IEEE ICC'08, the Technical Program Committee Chair for IEEE Globecom'07, the General Co-Chair for Chinacom'07 and QShine'06, the Chair for IEEE Communications Society Technical Committee on Wireless Communications, and P2P Communications and Networking. He also serves/served as the Editor-in-Chief for IEEE Network, Peer-to-Peer Networking and Application, and IET Communications; a Founding Area Editor for IEEE Transactions on Wireless Communications; an Associate Editor for IEEE Transactions on Vehicular Technology, Computer Networks, and ACM/Wireless Networks, etc.; and the Guest Editor for IEEE JSAC, IEEE Wireless Communications, IEEE Communications Magazine, and ACM Mobile Networks and Applications, etc. Dr. Shen received the Excellent Graduate Supervision Award in 2006, and the Outstanding Performance Award in 2004, 2007 and 2010 from the University of Waterloo, the Premier's Research Excellence Award (PREA) in 2003 from the Province of Ontario, Canada, and the Distinguished Performance Award in 2002 and 2007 from the Faculty of Engineering, University of Waterloo. Dr. Shen is a registered Professional Engineer of Ontario, Canada, an IEEE Fellow, an Engineering Institute of Canada Fellow, a Canadian Academy of Engineering Fellow, and a Distinguished Lecturer of IEEE Vehicular Technology Society and Communications Society.



Jon W. Mark (M'62-SM'80-F'88-LF'03) received the Ph.D. degree in electrical engineering from McMaster University in 1970. In September 1970 he joined the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, where he is currently a Distinguished Professor Emeritus. He served as the Department Chairman during the period July 1984-June 1990. In 1996 he established the Center for Wireless Communications (CWC) at the University of Waterloo and is currently

serving as its founding Director. Dr. Mark had been on sabbatical leave at the following places: IBM Thomas J. Watson Research Center, Yorktown Heights, NY, as a Visiting Research Scientist (1976-77); AT&T Bell Laboratories, Murray Hill, NJ, as a Resident Consultant (1982-83); Laboratoire MASI, Universit Pierre et Marie Curie, Paris France, as an Invited Professor (1990-91); and Department of Electrical Engineering, National University of Singapore, as a Visiting Professor (1994-95). He has previously worked in the areas of adaptive equalization, image and video coding, spread spectrum communications, computer communication networks, ATM switch design and traffic management. His current research interests are in broadband wireless communications, resource and mobility management, and cross domain interworking.

Prof. Mark is a Life Fellow of IEEE and a Fellow of the Canadian Academy of Engineering. He is the recipient of the 2000 Canadian Award for Telecommunications Research and the 2000 Award of Merit of the Education Foundation of the Federation of Chinese Canadian Professionals. He was an editor of IEEE Transactions on Communications (1983-1990), a member of the Inter-Society Steering Committee of the IEEE/ACM Transactions on Networking (1992-2003), a member of the IEEE Communications Society Awards Committee (1995-1998), an editor of Wireless Networks (1993-2004), and an associate editor of Telecommunication Systems (1994-2004).



Yejun He (IEEE SM'09) received his Ph.D. degree in Information and Communication Engineering from Huazhong University of Science and Technology (HUST) in 2005, M.S. degree in Communication and Information System from Wuhan University of Technology (WHUT) in 2002 respectively, and his B.S. degree from Huazhong University of Science and Technology in 1994. From Sept. 2005 to March 2006, he was a Research Associate with the Department of Electronic and Information Engineering,

The Hong Kong Polytechnic University. From April 2006 to March 2007, he was a Research Associate with the Department of Electronic Engineering, Faculty of Engineering, The Chinese University of Hong Kong. Dr. He has been a Professor of Information and Communication Engineering at Shenzhen University, China since 2011. From July 2012 to August 2012, he was a Visiting Professor with Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, Canada. From Oct. 2013 to Oct. 2014, he is an Advanced Visiting Scholar (a Visiting Professor) with School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA. His Research Interests include Channel Coding and Modulation; MIMO-OFDM wireless communication; Space-time processing; Smart antennas and so on. He has been a Senior Member of IEEE since 2009. He is also serving/served as reviewer/Technical Program Committee member/Session Chair for various journals and conferences, including IEEE Transactions on Vehicular Technology, IEEE Transactions on Communications, IEEE Communications Letters, International Journal of Communication Systems, Wireless Communications and Mobile Computing, Wireless Personal Communication, KSII Transactions on Internet and Information Systems, IEEE VTC, IEEE PIMRC, IEEE WCNC, IEEE WCSP and so on. He is the Principal Investigator in more than 10 current or finished research projects including NSFC and so on. He translated three English books into Chinese and authored or co-authored more than 70 research papers as well as applied for 12 patents since 2002. He has been Associate Editor of Security and Communication Networks since 2012.