Beam Codebook Based Beamforming Protocol for Multi-Gbps Millimeter-Wave WPAN Systems

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***Abstract*—In order to realize high speed, long range, reliable transmission in millimeter-wave 60GHz wireless personal area networks (60GHz WPANs), we propose a beamforming (BF) protocol realized in media access control (MAC) layer on top of multiple physical layer (PHY) designs. The proposed BF protocol targets to minimize the BF set-up time and to mitigate the high path loss of 60GHz WPAN systems. It consists of 3 stages, namely the device (DEV) to DEV linking, sector-level searching and beam-level searching. The division of the stages facilitates significant reduction in setup time as compared to BF protocols with exhaustive searching mechanisms. The proposed BF protocol employs discrete phase-shifters, which significantly simplifies the structure of DEVs as compared to the conventional BF with phase-and-amplitude adjustment, at the expense of a gain degradation of less than 1dB. The proposed BF protocol is a complete design and PHY-independent, it is applicable to different antenna configurations. Simulation results show that the setup time of the proposed BF protocol is as small as 2% when compared to the exhaustive searching protocol. Furthermore, based on the codebooks with four phases per element, around 15.1dB gain is achieved by using eight antenna elements at both transmitter and receiver, thereby enabling 1.6Gbps-data-streaming over a range of three meters. Due to the flexibility in supporting multiple PHY layer designs, the proposed protocol has been adopted by the IEEE 802.15.3c as an optional functionality to realize Gbps communication systems**

***Index Terms*—beam codebook, beamforming, MAC, protocol, 60 GHz, millimeter-wave, multi-Gbps, WPAN**

I. Introduction

MILLIMETER-WAVE band communication recently gained more and more attention for the development of short-range high-speed wireless networks. The advantage of this technology lies on its capability to support multi-Gbps throughput. With these attractive characteristics, millimeter-wave technology is suitable for consumer-electronics (CE) oriented applications such as high definition video streaming and high speed file exchange for portable devices. Wireless personal area networks (WPANs), which are used to convey high rate information over relatively short distances among relatively few participants with low-cost implementation, is one of the standardized systems in 60GHz band [1], [2].

The ultimate purpose of the 60GHz WPAN systems is to deliver MAC throughputs in the order of multi-Gbps over a reasonable range. To accomplish this, system designers have to increase the system efficiency and improve the transmission range, especially in non-line-of-sight (NLOS) channels [5]. In order to compensate the high propagation loss in 60GHz channels and reduce the effects of shadowing, the use of antenna array has been proposed. The integration of multiple antennas into portable devices can be achieved since the dimensions and necessary spacing of 60GHz antennas are in the order of millimeters [6]. Since multiple antennas are available at both transmitter and receiver, the multiple-input multiple-output (MIMO) techniques based on spatial multiplexing or space time coding should be considered [7], [8]. The MIMO techniques have been widely adopted by 2.4 or 5 GHz radio, such as IEEE 802.11n [9], IEEE 802.16e [10] and 3GPP LTE [11],[12]. The disadvantage of MIMO techniques is the requirement of multiple RF chains, which significantly increase the complexity and cost of the devices (DEVs). Additionally, improving transmission range is a main concern in 60GHz WPANs instead of improving the spatial efficiency. Therefore, directional transmission based on antenna array beamforming (BF) with high gain and electronic steerability is favored over MIMO systems [13], [14], [15].

Currently, there are very few contributions in literature related to BF in 60 GHz. In [16], a BF scheme is achieved by a Silica-based beamformer before optoelectronic conversion. The antenna weights are calculated by the pseudo-inverse of the channel matrix; the calculation load exponentially increases with respect to the number of antenna elements. A general BF problem was formulated in [17] to provide an automatic alignment mechanism. Although the performance of a smart-antenna system, which adaptively tracks the transmitter location and steers the beam to maximize the receiver power is shown, the antenna array has to be steered mechanically based on the estimated angle of departure (AOD) / angle of arrival (AOA); this estimation is complex and time consuming. In general the BF attempts in 60GHz millimeter wave systems have three limitations: (1) BF is conducted based on a specified antenna structure; (2) the measuring signal's AOD or AOA, or acquisition of the entire channel state information (CSI) matrices for weight vector calculation is of high calculation load and introduces large overhead; (3) no complete MAC protocol to setup a directional communication link is available.

In this paper, we propose a complete MAC layer BF protocol without the necessity of AOD/AOA or CSI estimation. The proposed BF protocol has the following features: (1) It

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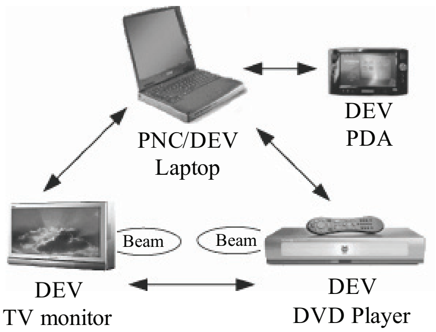


Fig. 1. Typical example of a WPAN piconet architecture

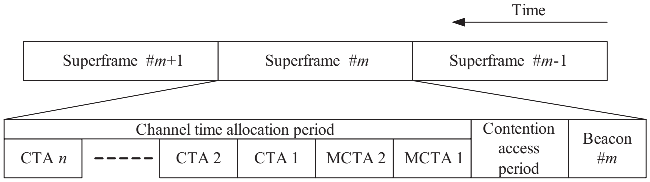


Fig. 2. Superframe structure in WPAN piconet

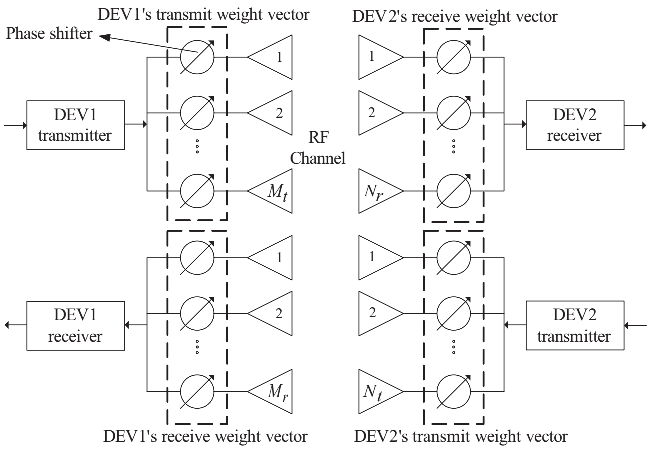


Fig. 3. BF model

consists of three stages, namely, the device (DEV) to DEV linking, sector-level searching, and beam-level searching. The division of the stages facilitates significant reduction in setup time as compared to the BF protocols with the exhaustive searching mechanisms; (2) it employs only discrete phase-shifts, which simplifies the DEVs' structure when compared to conventional BF with phase-and-amplitude adjustment, at the expense of a degradation of less than 1dB; (3) the BF protocol is designed to be PHY-independent and is applicable to different antenna configurations; (4) the proposed BF protocol is a complete MAC procedure, it efficiently sets up a directional communication link based on codebooks.

The rest of the paper is organized as follows. In Section II, background information related to WPAN network topology, piconet timing and BF model is provided. In Section III, BF codebooks are presented since the BF protocol is based on codebooks. In Section IV, the proposed BF protocol is explained in detail. In Section V, the BF set-up time and system performance with BF are evaluated. Conclusions are stated in Section VI.

II. System Model

A. Network Topology

A network in a WPAN system is commonly known as a piconet, as shown in Figure 1. A piconet consists of several independent DEVs, one of which (such as the laptop in Figure 1) is selected as the piconet coordinator (PNC) that schedules peer-to-peer communications between DEVs. The remaining DEVs establish DEV-to-DEV communication links, hereon referred to as links. Each link consists of a transmit DEV and a receive DEV. The PNC provides the basic timing and manages the shared wireless resource for the DEVs in the piconet. To improve the transmission quality, a directional link may be set up between two DEVs (such as the link between a DVD player and a TV monitor). This paper focuses on how to set up directional links.

B. Piconent Timing

In this work, timing in WPAN piconet is based on superframe [19], illustrated in Figure 2. The superframe is composed of three parts: (1) A beacon, to set the time allocations and to communicate management information for the piconet; (2) a contention access period (CAP), to transmit commands and/or asynchronous data if it is present in the superframe; (3) a channel time allocation period (CTAP), composed of channel time allocations (CTAs), including management CTAs (MCTAs). Each CTA is a TDMA slot granted by PNC for certain DEVs. The BF operation is processed between two DEVs in the allocated CTA.

C. BF Model

The BF model of asymmetric antenna system (AAS) is illustrated in Figure 3. A general AAS model is considered in the paper due to the following two reasons: (1) Different antenna configuration, for example the different subsets of all antenna elements may be used for transmission or reception to generate different sizes of beam patterns; (2) the channels of both communication directions may not be reciprocal due to the different locations of obstacles. For example, in NLOS channels, if the obstacles are close to the transmitter but far away from the receiver, different paths may arrive at two ends of communications links.

In Figure 3, Device 1 (DEV1) has M_t transmit antennas and M_r receive antennas while Device 2 (DEV2) has N_t transmit antennas and N_r receive antennas. For the link from DEV1 to DEV2, the signal after baseband processing is up-converted into radio frequency (RF) band. The RF band signal is emitted to the free space after the phase shifting according to the transmit weight vector. At the receiver, the received RF signal is phase-shifted by the receiver weight vector and then down-converted into base band. The same operation would be conducted for the reverse link from DEV2 to DEV1. The objective of the proposed BF is to find the optimal transmit and receive antenna weight vector through MAC operation in order to optimize a cost function that measures the link quality metric. In this paper, signal to interference plus noise ratio (SINR) is selected as the metric.

III. Beam Codebooks

A codebook is a matrix where each column specifies a BF weight vector. Each column also specifies a pattern. The

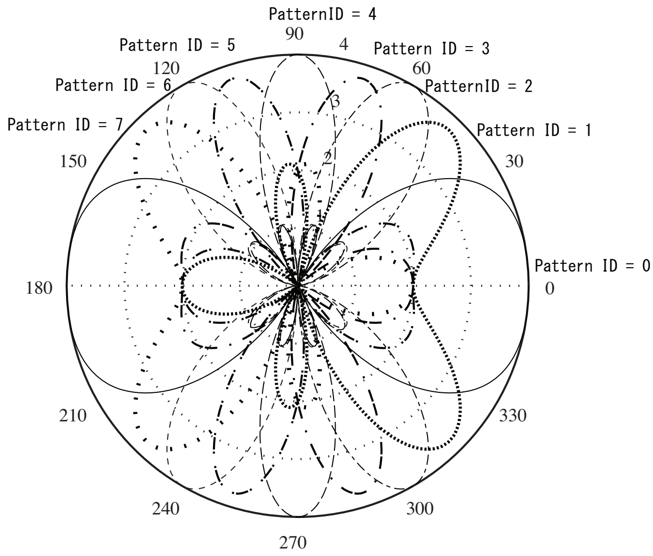


Fig. 4. An example codebook of 4 antenna elements separated by $\lambda/2$ (8 patterns)

codebooks are the basis of the proposed BF. In order to simplify the phase shifter and minimize the power consumption of the 60GHz RF electrical components, the codebooks recommended for the proposed BF protocol are designed for a phased antenna array implementing only specific four phase shifts per element (0^o 90^o 180^o 270^o) without amplitude adjustment. Figure 4 shows the example codebook of eight patterns generated by four dipole antenna elements with antenna spacing of $\lambda/2$. All patterns in Figure 4 can be specified by the following matrix

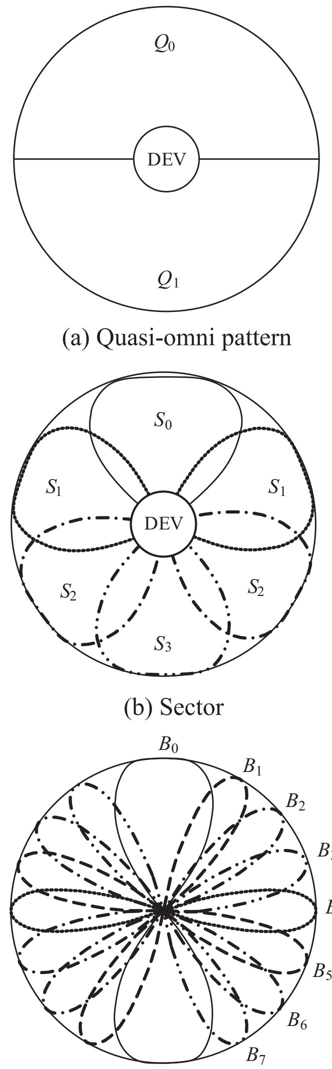
$$\begin{array}{rcc} \text{Pattern ID} & = & \begin{array}{cccccccc} 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{array} \\ \mathbf{W} & = & \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ -1 & -j & -j & -j & 1 & j & j & j \\ 1 & j & -1 & -j & 1 & j & -1 & -j \\ -1 & 1 & j & -1 & 1 & -1 & -j & 1 \end{bmatrix} \end{array}$$

The parameters of each pattern inside the example codebook are shown in Table I, where θ_{max} is the maximum gain direction, half power beam width (HPBW) is the 3dB bandwidth and D_{max} is the maximum antenna array directivity. In Figure 4, some beams can not reach the maximum gain (10*log(4)=6.02dBi); this is because an optimal BF weight vector for some directions can not be created by using only the limited number of four phase shifts per element. However the gain loss at the maximum gain direction is only 0.54dB, which is within the acceptable range of 1 dB. Each beam in Figure 4 is identified by a given pattern ID, listed in the first column of Table I. The pattern ID also corresponds to the column of weight matrix, which will be used in the BF protocol to indicate the best beam. For more information of the complete codebook design, please refer to [18].

IV. Beamforming Protocol

Assume that all devices capable of the proposed BF shall support three kinds of beam patterns, as shown in Figure 5: quasi-omni pattern, sector, and beam. All these patterns are created by codebooks. Quasi-omni pattern is the lowest resolution pattern specified in the codebooks. It is used to refer to an antenna pattern that covers a broad region of interest space around DEVs (not necessarily spans over the whole 360^o). Sector is the second level resolution pattern and is used to refer to a direction of an array pattern that covers a relatively broad area of consecutive or non-consecutive beams. Different sectors can overlap. Beam is a highest resolution pattern specified in the codebooks.

To shorten the BF setup time, the BF process is divided into three stages based on the above mentioned three kinds of



(a) Quasi-omni pattern

(b) Sector

(c) Beam

Fig. 5. Category of beam patterns

TABLE I
Example codebook of 4 elements separated by $\lambda/2$ (8 patterns)

Pattern ID	θ_{max}	HPBW	D_{max}
0	0^o	79^o	6.02dBi
1	46^o	31^o	5.48dBi
2	60^o	26^o	6.02dBi
3	72^o	26^o	5.48dBi
4	90^o	26^o	6.02dBi
5	108^o	26^o	5.48dBi
6	120^o	26^o	6.02dBi
7	134^o	31^o	5.48dBi

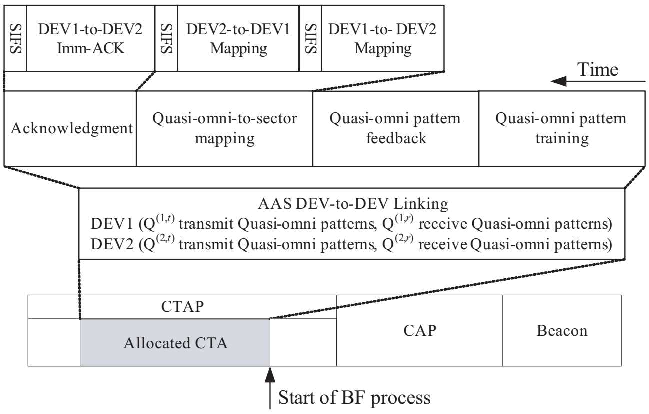


Fig. 6. DEV-DEV linking in the allocated CTA

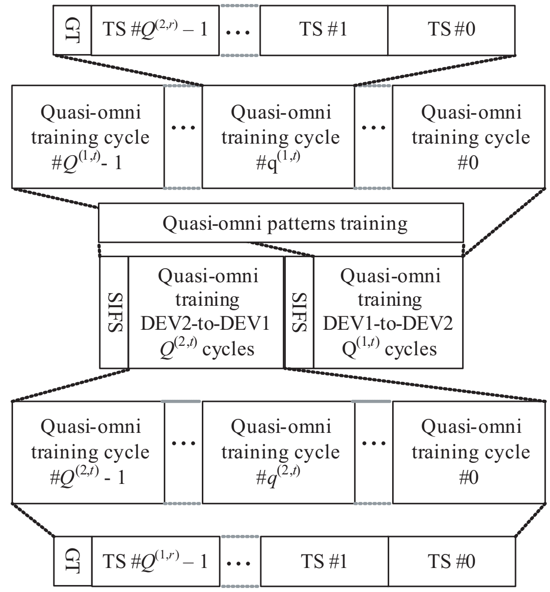


Fig. 7. Quasi-omni pattern training period

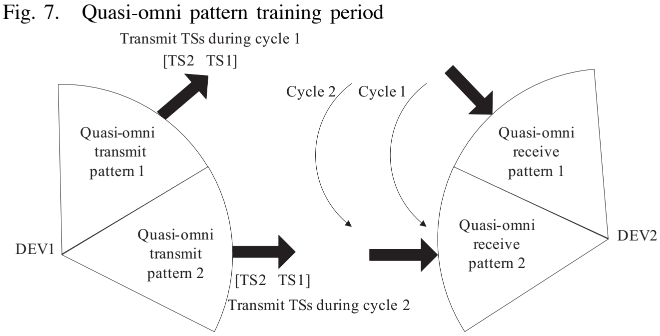


Fig. 8. An example of quasi-omni pattern training from DEV1 to DEV2

patterns: DEV-to-DEV linking, sector-level searching, beam-level searching and an optional beam-tracking stage. Through these stages, the proposed BF will find the best transmit and receive beam pair.

A. DEV-to-DEV Linking

After association process has been completed between PNC and DEVs, all DEVs direct their own best quasi-omni pattern (in the sense of largest SINR) to PNC, and are ready for DEV-to-DEV linking. During DEV-to-DEV linking a pair of DEVs select the best quasi-omni patterns for command transmission over the directional link between them.

Consider two devices, i.e. DEV1 and DEV2, which are capable of BF. DEV1 has $Q^{(1,t)}$ transmit-quasi-omni patterns and $Q^{(1,r)}$ receive-quasi-omni patterns; accordingly, DEV2 has $Q^{(2,t)}$ and $Q^{(2,r)}$ quasi-omni patterns for transmission and reception, respectively.

The BF is processed during the allocated CTA, as shown in Figure 6. At the start of the allocated CTA, both DEV1 and DEV2 start BF process at DEV-to-DEV linking simultaneously. The DEV-to-DEV linking is composed of four substages: quasi-omni pattern training, quasi-omni pattern feedback, quasi-omni-to-sector mapping and acknowledgement. During the training period, the receiver tries to receive the training sequences (TSs), and decides the best transmit and receive quasi-omni patterns according to the estimated SINR. The decision is then fed back in the quasi-omni pattern feedback. After that, the best transmit and receive quasi-omni patterns are known at both DEVs. Then the information about the selected patterns is exchanged in quasi-omni-to-sector mapping substage for the preparation of the following BF stages. The stage ends with an acknowledgement (ACK).

1) Quasi-Omni Pattern Training Stage: Figure 7 shows the structure of quasi-omni pattern training. It is further divided into two parts: the training from DEV1 to DEV2 and the training from DEV2 to DEV1. Each training period ends with a short inter-frame spacing (SIFS), the time for DEVs to switch from transmit to receive mode and vice versa. During each training period, TSs will be sent between DEVs. The long preamble consisting of a synchronization sequence and a channel estimation sequence specified in IEEE802.15.3b is used as TSs, which are created from Golay code with 32 repetitions of length 128 bits [3]. The training from DEV1 to DEV2 consists of $Q^{(1,t)}$ cycles; the $Q^{(1,t)}$ cycles shall be sent from each of the $Q^{(1,t)}$ transmit-quasi-omni patterns of DEV1. During each cycle, DEV1 shall send $Q^{(2,r)}$ repetitions of TSs in the same direction. $Q^{(2,r)}$ repetitions shall be received by each of $Q^{(2,r)}$ receive-quasi-omni patterns of DEV2. Each cycle except the last one shall end with a guard time (GT), the time for transmitter to switch from one pattern to the other. During each cycle, DEV2 shall attempt to receive at least one of TSs. DEV2 switches its quasi-omni pattern one by one, and waits in each quasi-omni direction for T_s period, where T_s is the time period of a TS. At the completion of full $Q^{(1,t)}$ cycles, DEV2 will have had an opportunity to receive a TS using each combination of DEV1's $Q^{(1,t)}$ quasi-omni transmit patterns and DEV2's $Q^{(2,r)}$ quasi-omni receive patterns. Based on this information, DEV2 selects the best quasi-omni pattern pair, i.e. DEV1's optimal transmit-quasi-omni pattern and DEV2's optimal receive-quasi-omni pattern. Following the training from DEV1 to DEV2, a similar quasi-omni pattern training from DEV2 to DEV1 takes place where DEV2 transmits TSs over $Q^{(2,t)}$ cycles as shown in Figure 7. At the completion of the cycles, DEV1 selects the best quasi-omni pattern pair, i.e., DEV2's optimal transmit-quasi-omni pattern and DEV1's optimal receive-quasi-omni pattern.

Figure 8 shows an example of quasi-omni pattern training from DEV1 to DEV2 when $Q^{(1,t)}$=$Q^{(2,r)}$=2. In this example, after the completion of DEV1-to-DEV2 training, DEV2's

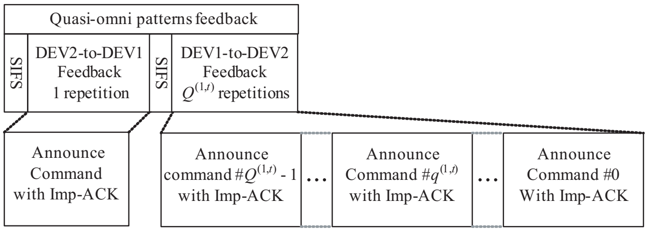


Fig. 9. Quasi-omni pattern feedback period

receive-quasi-omni pattern 2 may at least receive TS2 from DEV1's transmit-quasi-omni pattern 2 during cycle 2. If this link is with the highest SINR, then DEV2 knows that DEV1's transmit-quasi-omni pattern 2 and DEV2's receive-quasi-omni pattern 2 are the best pattern pair. This information will be fed back during the quasi-omni pattern feedback. quasi-omni pattern training from DEV2 to DEV1 is conducted in the same way.

2) Quasi-Omni Pattern Feedback Stage: Following the quasi-omni pattern training stage is the feedback stage shown in Figure 9. It is composed of two parts: DEV1-to-DEV2 feedback and DEV2-to-DEV1 feedback. Both of them end with SIFS. DEV1 shall transmit its best quasi-omni pattern ID and corresponding link SINR, which is estimated by using the received TSs. This information is sent by an Announce command [1] with implied acknowledgement (Imp-ACK) requested [2]. The Announce command shall be sent $Q^{(1,t)}$ times in the $Q^{(1,t)}$ different transmit-quasi-omni patterns. This is required since DEV1 does not yet know its optimal transmit direction. DEV2 switches to its optimal receive-quasi-omni pattern, and attempts to receive at least one transmit sent along DEV1's optimal transmit direction. In return, DEV2 shall transmit its feedback by sending an Announce command with Imp-ACK requested. Since DEV2 already knows its best transmit pattern, multiple repetitions are not necessary. Instead an Announce command shall be sent on DEV2's optimal transmit-quasi-omni pattern, and DEV1 shall listen on its optimal receive-quasi-omni pattern. The feedback informs DEV1 of its optimal transmit direction and corresponding link's SINR. Upon the completion of the feedback stage, both DEV1 and DEV2 know their optimal transmit and receive quasi-omni patterns. These shall be used for further frame exchanges.

Figure 10 shows an example of quasi-omni pattern feedback from DEV2 to DEV1 When $Q^{(2,t)} = Q^{(1,r)} = 2$. At this stage, DEV2, as a transmitter, knows DEV1's best transmit pattern and its best receive pattern trough DEV1-to-DEV2 training; however DEV2 still does not know its best transmit pattern. So DEV2 has to transmit the feedback information from each of its transmit pattern 1 and 2. While DEV1, as a receiver in this stage, has known DEV2's best transmit pattern and its best receive pattern though DEV2-to-DEV1 training. So DEV1 just needs to wait at the best receive pattern 2 during quasi-omni pattern feedback from DEV2 to DEV1.

[1]Announce command is a command frame specified in IEEE 802.15.3; this command allows DEVs to send unrequested information to one or more DEVs in CTA

[2]The Imp-ACK is specified in IEEE 802.15.3b; this is a method that allows a CTA to be used for bi-directional data transfer. With Imp-ACK, the response frame instead of normal ACK is implied when the target DEV sends any frame, in response to a frame that has an ACK policy of Imp-ACK.

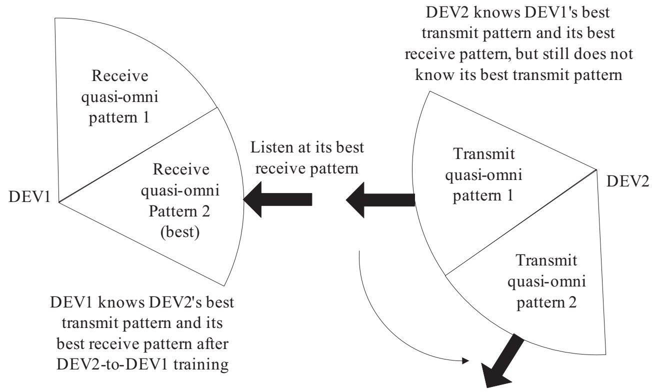


Fig. 10. An example of quasi-omni pattern feedback from DEV2 to DEV1

3) Quasi-Omni Mapping Stage and Acknowledgement Stage: Following the feedback stage is the mapping stage also shown in Figure 6. In this stage, DEV1 shall transmit quasi-omni-to-sector-mapping information through an Announce command with immediate acknowledge (Imm-ACK) requested [3]. The mapping information indicates the number of sectors to be trained in the sector-level training, namely, the number of transmit sectors and the number of receive sectors in the selected quasi-omni patterns for both transmitter and receiver respectively. DEV2 shall reply by sending back its own quasi-omni-to-sector mapping in an Announce command with Imm-ACK requested. DEV1 shall reply with an Imm-ACK, thereby completing the DEV-to-DEV linking stage. All commands shall be transmitted through the optimal transmit and receive quasi-omni pattern pair found in the previous two stages. The mapping stage also appears in sector-level searching stage to indicate the number of beams inside the selected best sectors, and the information would be used in the following beam-level searching stage. However the mapping stage is an optional stage for beam-level searching stage, depending on whether the optional beam tracking stage is employed or not.

B. Sector-Level and Beam-Level Searching

After DEV-to-DEV linking, the devices are able to find each other by finding the optimal transmit and receive quasi-omni patterns, and are ready for command transmission. Then, the BF goes to the sector-level and beam-level searching. The operation procedure and frame structure are the same as the DEV-to-DEV linking; it also includes four sub-stages: training, feedback, mapping, and acknowledgement. One of the differences is that the searching area changes according to the information indicated in each mapping stage: The sector-level searching is to find the best sector pair inside the optimal quasi-omni patterns while the beam-level searching is to find the best beam pair inside the optimal sectors. The reason for having two searching levels is to find the optimal beam pairs with the shortest possible searching time. Another difference is that the feedback stages of both directions have only one repetition of feedback, as illustrated in Figure 11. The reason is very clear, at the sector-level searching stage, both DEV1 and DEV2 know what optimal transmit and receive quasi-omni patterns are from DEV-to-DEV linking, these optimal quasi-omni patterns can be used for all command transmissions. Accordingly, at the beam-level searching stage, the selected

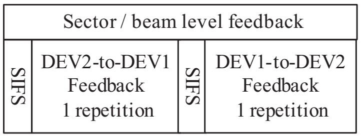


Fig. 11. Structure of the sector-level or the beam-level feedback

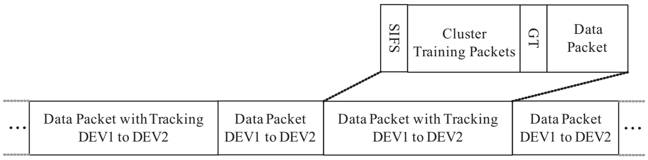


Fig. 12. Data packets with tracking

sector pair in the sector-level searching stage is recommended to be used for command transmissions in order to benefit from the possible gain improvement.

C. Optional Beam Tracking Stage

Beam tracking stage is an optional stage, that is used to track the changes in the transmit and receive weight vector due to channel variation over time. With the help of the beam tracking stage, the BF does not have to re-conduct immediately even if the optimal beam pair is lost. Instead, a backup beam pair found during tracking may be used to continue the already started data streaming. In the beam tracking stage, the beam selected in the searching stage is taken as the center beam. The center beam and its adjacent beams in the codebook, are further grouped; this beam group is referred to as a cluster. During tracking, the whole cluster is tracked periodically and is adjusted dynamically to achieve optimal link quality.

Beam tracking is conducted during data streaming in the allocated CTA. If the beam tracking stage is employed, the tracking period shall be specified in the mapping sub-stage of the beam-level searching stage. Figure 12 shows an example of the data streaming from DEV1 to DEV2. Once every tracking period, a group of TSs shall be sent at the end of data packets from each beam combinations of DEV1's transmit cluster and DEV2's receive cluster. After completing the transmission of TSs, a SINR table is set up where the links' SINRs of different beam combinations are recorded. The SINR table is updated after each tracking.

If both DEV1 and DEV2 support beam-tracking, beam switching, the operation to switch the beam to the better backup beam, will then be triggered by the tracking results which show SINRs of beams in the cluster at DEV2 (for tracking from DEV1 to DEV2). If DEV2 does not have results indicating that a change in transmit beam is desirable, DEV2 shall respond with an Imm-ACK and tracking continues. Otherwise, DEV2 shall respond with a feedback of the results in an Announce command with ACK policy set to Imm-ACK, indicating the index of DEV1's largest-SINR beam. The feedback command shall be sent through the quasi-omni pattern pair that covers the original transmit beam since even if the beam is blocked, the quasi-omni pattern may still be usable. Upon receiving the results, DEV1 shall acknowledge them with an Imm-ACK using the optimal quasi-omni pattern pair. The data exchange shall be continued using the new transmit beam from the start of the next data frame. If the

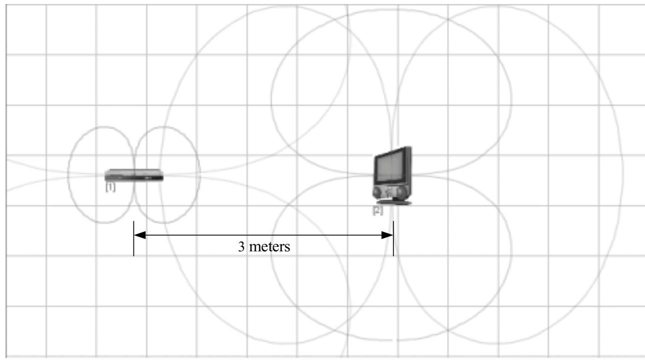


Fig. 13. Simulation scenario

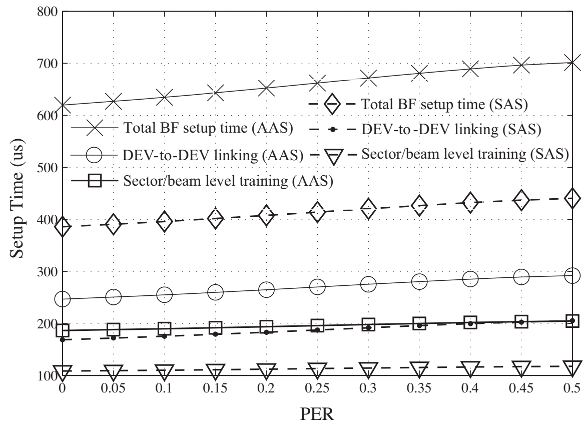


Fig. 14. Beamforming setup time

results indicate that DEV2 should use a new receive beam and DEV1 should still use the same transmit beam, DEV2 shall switch as soon as possible. If DEV2 cannot find any beam to continue the data streaming, DEV2 declares"BF failed"; After a waiting time, if DEV1 does not receive any feedback from DEV2, DEV1 declares "BF failed". Then, BF is conducted again to re-set the communication link.

V. Simulation results

In this part, we follow the guidelines of IEEE 802.15.3c criteria to estimate set-up time, gain loss due to codebook limitations, bit error rate (BER) performance and MAC throughput for the proposed BF mechanism. The MAC simulations with a simulation period of 20ms are conducted in Qualnet between two 3-meter-apart DEVs, as shown in Figure 13. The announce commands, feedback commands, and training sequences are all transmitted over common mode with the physical layer signal access point (PHY-SAP) data rate as 50.6Mbps, while the payload is transmitted in the mandatory mode with the PHY-SAP data rate as 1.619Gbps. The PHY simulations are conducted in Matlab, where the NLOS residential case (CM2.3) is from 60GHz WPAN channel model of IEEE 802.15.3c [20]. The channel model is abstracted from the experimental data, and is modeled based on the Saleh-Valenzuela model [21]. This is one of the typical environments defined in the usage models for uncompressed video streaming and file transferring [22] in 60GHz WPAN systems. Tables II, III and IV list the MAC related, PHY related, and propagation related simulation parameters.

TABLE II
MAC RELATED SIMULATION PARAMETERS

Maximum Superframe period	$65535\mu s$
Command transmission rate	50.6Mbps
PHY preamble (long)	$3.259\mu s$
Channel estimation sequence (long) (CES)	$0.593\mu s$
Beacon (100 octets)	$15.81\mu s$
Training sequence (T_s)	$3.259\mu s$
PHY header (10 octets)	$1.581\mu s$
MAC header (15 octets)	$2.372\mu s$
Feedback IE as payload	$0.632\mu s$
Mapping IE as payload	$0.751\mu s$
Association request IE as payload	$2.607\mu s$
Association response IE as payload	$3.277\mu s$
SIFS (T_{SIFS})	$2.5\mu s$
ACK (T_{ACK})	$7.212\mu s$
Guard time (T_{GT})	$0.0625\mu s$
Backoff ($T_{backoff}$)	$30\mu s$
Payload size	2Kbytes
Payload transmission rate	1.619Gbps
Payload ACK policy	No-ACK

TABLE III
PHY RELATED SIMULATION PARAMETERS

Channel mode	AWGN / CM2.3
Symbol (chip) rate	1728Msps
Modulation	$\pi/2$-BPSK
Channel code	RS(255,239)
FFT length	256
CP length	0 for AWGN; 64 for CM2.3
Equalization	None for AWGN; Frequency domain equalizer for CM2.3
Power amplifier model	SiGe, OBO=3dB
Phase noise model	PSD(0)=-93dBc/Hz @ 1MHz, f_z=1MHz, F_D=100MHz
Pulse Shaping Filter and Receiver Filter	Root-raised cosine Filter (Roll-off factor = 0.25)

A. BF Setup Time

In this part, we assume that DEV1 as well as DEV2 have 64 beams for both transmission and reception. The 64 beams are separated into 16 sectors with 4 beams in each sectors. Furthermore we assume that a quasi-omni pattern is able to cover 4 sectors, that is, totally we have 4 quasi-omni patterns. Figure 14 shows the average setup time with respect to the packet error rate (PER). The setup time is calculated from the arrival of the first allocated CTA. For AAS, it is shown that if there are no transmission errors, the total setup time is around $246.706\mu s$ (DEV-to-DEV linking) + $2 * 186.538\mu s$ (sector and beam-level searching [3]) = $619.8\mu s$. As the channel becomes worse, i.e. the PER increases from 0 to 0.5, the BF setup time naturally increases by 13.2%, up to $701.6\mu s$ due to the command retransmissions after a waiting time. However, if we use the exhaustive search, which tries all beam pair combinations and finally finds the best pair for transmit and receive, the set-up time is around $31.57ms$ even if PER = 0. The reason is that exhaustive search has to try $64 \times 64 = 4096$ combinations for one direction search, however the proposed BF only has to try 4×4 (DEV-to-DEV linking) + $4 \times 4 \times 2$ (sector and beam searching) = 48 combinations, which is two-digits less than the combinations from exhaustive search. The figure also shows the BF set-up time for symmetric antenna system (SAS), where the antenna configurations for transmission and reception are assumed to be the same, and the uplink and dowlink channels are reciprocal. In the case of SAS, since the optimal transmit beam pair is just the optimal receive beam pair, only one direction training is necessary. It is shown that the set-up time is around $386.0\mu s$ when PER = 0, and up to $440.5\mu s$ in the case of PER = 0.5, these values are still much less than the exhaustive search of $15.79ms$. In general, the proposed scheme significantly reduces the set-up time, which is 98% shorter than the exhaustive search, and much shorter than the maximum superframe duration. Therefore it can easily fit within one superframe, thereby efficiently minimizing the potential interference to other systems during BF set-up, and making the BF scheme more feasible for 60GHz WPANs. Furthermore, since the directional communication link may be lost due to channel variation, the BF operation may repeat; hence, a short BF setup time is important.

[3]The set-up time for sector-level and beam-level searching are taken as the same; however they may be slightly different due to the length of mapping information.

TABLE IV
PROPAGATION RELATED PARAMETERS

Center Frequency	60GHz
Bandwidth	1.728GHz
Average noise power per bit	-81.9dBm
Rx noise figure	10dBm
Average noise power per bit	-71.9dBm
Implementation loss	1.5dB
Propagation loss index	2dB for AWGN; 2.5dB for CM2.3
Path loss at 1m	68.0dB
Minimum Rx sensitivity level	-59.3dBm
Shadow Margin	5.0dB
Range	3.0 m

B. Gain Loss due to Codebook Limitations

The proposed BF is a codebook-based scheme. In order to simplify the phase shifter and minimize the power consumption of RF elements, the codebooks are recommended to be generated with four phases per element (0^o, 90^o, 180^o, 270^o) similar to the example codebook shown in Section III. Due to the limitation of codebook design, the full array gain can be achieved at some directions such as 0^o, 60^o, 90^o, 120^o of the example codebook mentioned in Section III. However at some other directions there would be some gain loss, such as at 33^o of the example codebook, where the direction is just along the intersection of two beams, or at 46^o, in which direction the designed beam can not achieve the full array gain. The simulation results shown in Figure 15 are achievable gains of optimal BF with phase and amplitude adjustment and the worst-case of directional link gains of the codebook-based BF.

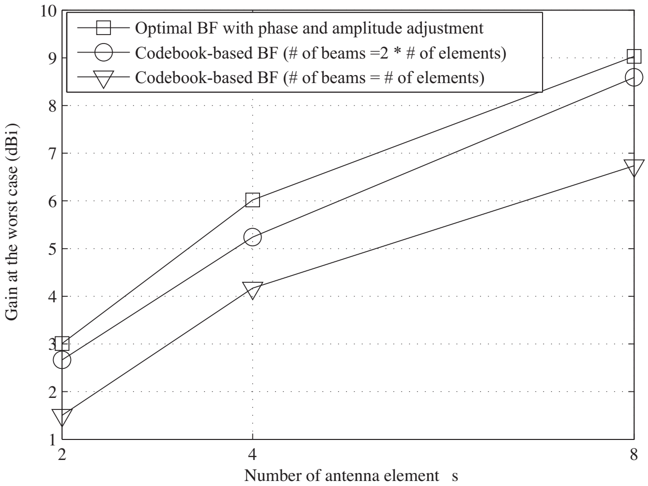


Fig. 15. Gain loss due to codebook limitations

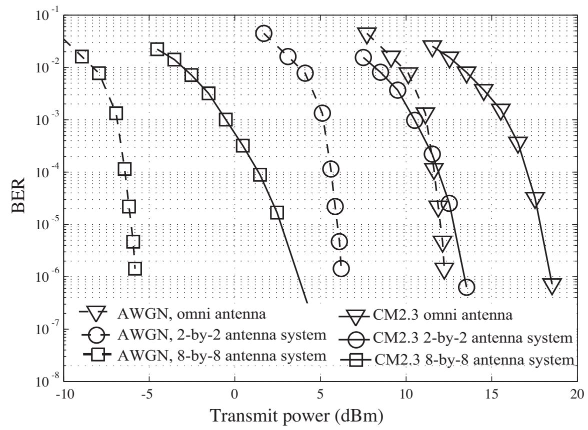


Fig. 16. BER performance

For the optimal BF with adjustable phase and amplitude, the beam can direct to any direction with full array gain. For the proposed codebook-based BF, the performance significantly depends on the codebooks: if the number of beams is equal to the number of antenna elements, there is a large gain loss at the worst case of directional links, however if the number of beams is twice of the number of antenna elements, the gain losses are less than 1dB compared to the optimal BF.

C. BER Performance

In this part, BER performance of beamformed links is evaluated. The mandatory data rate of 1.619Gbps at the PHY-SAP (by IEEE 802.15.3c) is selected for performance comparison. We assume that the signals are synchronized. The transmit power is determined based on a transmission range of 3 meters, a typical distance for video transmissions.

Figure 16 shows the BER performance of the omni and directional links. In the figure, the performance of omni-antenna, 2-by-2 antenna system, i.e., 2 transmit and 2 receive antennas, and 8-by-8 antenna systems is given for both AWGN (LOS) and CM2.3 (NLOS) channels. It is shown that in the AWGN channels, the antenna gain can be fully obtained, that is, 6dB gain and 18dB gain can be achieved by 2 by 2 and 8 by 8 antenna system, respectively. In the CM2.3 channel, 5.1dB gain and 15.1dB gain can be obtained by the 2-by-2 and 8-by-8 antenna systems, respectively. Although some of the energy is lost due to narrow transmit and receiver beams, BF provides significant gains in NLOS channels. In countries where transmit power is limited to 10dBm, our results indicate that data rates over 1.6Gbps is possible by using 8-by-8 BF over a range of 3 meters in the CM2.3 channel.

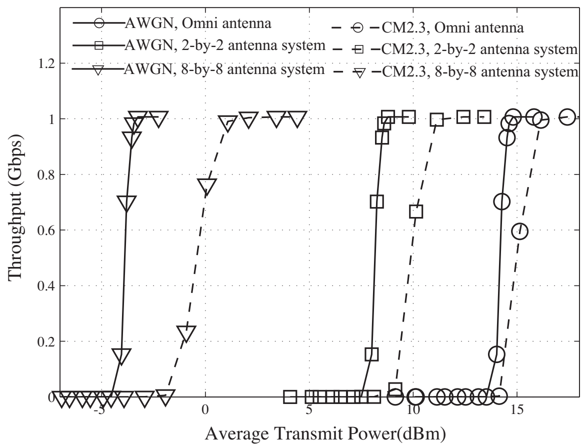


Fig. 17. MAC throughput

D. MAC Throughput

Figure 17 shows the MAC throughput over a mandatory PHY rate of 1.619Gbps with No-ACK policy. It is shown that, for a 10dBm transmit power limit, a 1Gbps MAC throughput can by achieved by the 2-by-2 antenna system in AWGN and by the 8-by-8 antenna system in the CM2.3 channel.

VI. Conclusion

In this paper, we proposed a complete BF protocol based on discrete phase shift codebooks in order to realize Gbps communication in millimeter-wave 60GHz WPANs. The proposed BF is applicable to different antenna configurations. Its setup time is sufficiently short, as little as 2% as compared to the setup time of exhaustive searching protocol; it is therefore easily to fit within one superframe, thereby generating minimum interference to other systems during the setup period. In the implementation example based on the codebooks with only four phases per element, around 15.1dB gain can be achieved by using eight antenna elements at both transmitter and receiver, thereby making possible 1.6Gbps-data-streaming over a range of 3 meters in NLOS channels. The proposed BF protocol has the flexibility of supporting multiple PHY layer designs; thus, it has been adopted by the IEEE 802.15.3c as an optional functionality to realize Gbps communication systems.

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