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

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***Abstract*—In this paper, we propose a feasible beamforming (BF) scheme realized in media access control (MAC) layer following the guidelines of the IEEE 802.15.3c criteria for millimeter-wave 60GHz wireless personal area networks (60GHz WPANs). The proposed BF targets to minimize the BF set-up time and mitigates the high path loss of 60GHz WPAN systems. It is based on designed multi-resolution codebooks, which generate three kinds of patterns of different half power beam widths (HPBWs): quasi-omni pattern, sector and beam. These three kinds of patterns are employed in the three stages of the BF protocol, namely device-to-device (DEV-to-DEV) linking, sector-level searching and beam-level searching. All the three stages can be completed within one superframe, which minimizes the potential interference to other systems during BF set-up period. In this paper, we show some example codebooks and provide the details of BF procedure. Simulation results show that the setup time of the proposed BF protocol is as small as 2% when compared to the exhaustive searching protocol. The proposed BF is a complete design, it re-uses commands specified in IEEE 802.15.3c, completely compliant to the standard; It has thus been adopted by IEEE 802.15.3c as an optional functionality to realize Giga-bit-per-second (Gbps) communication in WPAN Systems.**

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

I. Introduction

Millimeter-wave band communication recently gains more and more attention due to its capability to wirelessly 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. This trend has motivated the mobilization of standardization efforts internationally. Wireless personal area networks (WPANs) is one of the scandalized systems in the unlicensed millimeter-wave band extending from 57GHz to 66 GHz [1], [2]. The standardization process for WPANs by IEEE 802.15 Task Group 3c (TG3c) is recently near-to-completion, and the designed system with the ability of providing mandatory data rate of 1.6 Gbps and an optional mode with data rate up to 3 Gbps. It is currently becoming a good reuse candidate by IEEE 802.11 Task Group ad (TGad) [3].

The ultimate purpose of WPAN systems is to deliver throughput in the order of multi-Gbps over a reasonable range. To fulfill this mission, system designers have come up with various ways not only to increase the system efficiency but also to improve the transmission range since transmission range of 60GHz frequency band is much limited due to high path loss, reflection loss and other degradation during radio propagation. So use of several highly directive antennas has been naturally proposed to overcome the high propagation losses [4].

While directional antennas suffer from poor flexibility in that they can not be easily tuned towards different directions where the potential transmitter/receiver is located [5]. Directional transmission based on antenna array beamforming (BF) thus emerges as an attractive solution, featuring high BF gain and electronically steerability. Due to the extremely short wavelength, the integration of multiple antennas into portable 60 GHz devices is probably achieved as the dimensions and necessary spacing of 60 GHz antennas are on the order of millimeters [6]. With the availability of multiple antennas at both transmitter and receiver, the multiple-input multiple-output (MIMO) techniques based on spatial multiplexing or space time coding is naturally one potential candidate [7]. The problem is, however, that MIMO techniques require multiple RF chains, increasing cost consumption when considering the millimeter-wave paradigm. Additionally improving the link budget is the main aim in 60GHz WPANs instead of improving the spatial efficiency, traditional smart antenna BF is therefore more favored over MIMO systems [5].

There are few contributions existing in the literature of millimeter wave BF. In [8], the paper reported a BF scheme achieved by a Silica-based beam former before optoelectronic conversion. However since the antenna weights were calculated by the pseudo-inverse of the coefficient matrix, the calculation load exponentially increases with respect to the number of antenna elements. To provide an automatic alignment mechanism, the more general BF problem was formulated in [9] without far-field assumption. Although the work was the first to show the performance of a smart-antenna system which adaptively tracks the transmitter location and steers the beam to maximize the receiver power, the antenna array is steered mechanically based on the estimated angle of departure (AOD) / angle of arrival (AOA). In general the BF attempts in 60Ghz millimeter wave system outline two limitations: (1) There is no a complete protocol to setup a beamformed communication link. (2) Measuring signal's

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AOD or AOA, or acquisition of the entire channel state information (CSI) matrices for weight vector calculation is of high calculation load and incurs high overhead.

To fill these avoids, we have proposed a complete MAC layer BF protocol following the guidelines of the IEEE 802.15.3c criteria for millimeter-wave 60-GHz WPANs without necessary of AOD/AOA or CSI estimation. In short, the contributions of this paper are two-fold as follows: (1) Proposing a complete BF protocol to find the best beam pair for data streaming (2) Detailing all frame structures used in the protocol.

II. System Model

A. Network Topology

A network in a WPAN system is commonly known as a piconet shown in Figure 1. A piconet consists of several independent devices (DEVs), one of which (such the laptop in Figure 1) is selected as the piconet coordinator (PNC) that schedules peer-to-peer communications between DEVs. The remaining DEVs will establish DEV-to-DEV communication links (such as the link between DVD player and TV monitor), hereon referred to as links. Each link consists of a transmitting DEV and a receiving 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 beamformed link may be set up between two DEVs. This paper is just focusing on how to set up this beamformed link.

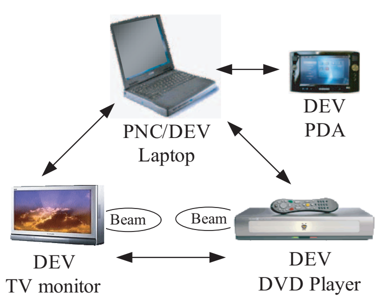

Fig. 1. Typical example of a WPAN piconet architecture

B. Piconet Timing

Timing in WPAN piconet is based on “superframe”, illustrated in Figure 2. The superframe is composed of three parts: (1) The beacon, used to set the time allocations and to communicate management information for the piconet. (2) The contention access period (CAP), used to communicate commands and/or asynchronous data if it is present in the superframe. (3) The 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 2 DEVs in the allocated CTA.

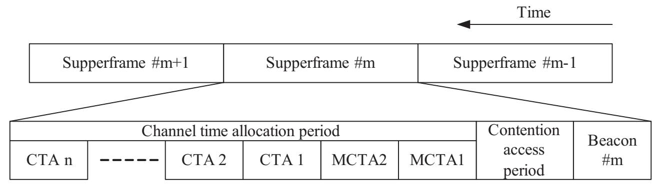

Fig. 2. Superframe structure in WPAN piconet

C. BF Model

The BF model of asymmetric antenna system (AAS), defined as that a device uses different beam patterns for transmission and reception, is illustrated in Figure 3. The AAS is considered here because the channels of forward and reverse links may not be reciprocal due to the obstacles' different locations. In this figure, Device 1 (DEV1) has M_t transmit

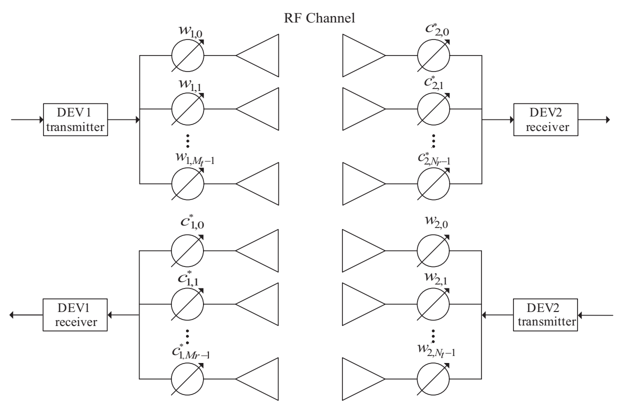

Fig. 3. BF Model

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 split, and emitted to the free space after filtering by the transmit weight vector. At the receiver, the received RF signal is weighted by the receiver weight vector, then down-converted into base band for baseband processing. The same operation is conducted for the reverse link from DEV2 to DEV1. The objective of BF is to select the optimal transmit and receive antenna weight vectors (patterns) to optimize a cost function which measures the link quality according to a selected criterion. In this paper, effect signal to noise and interference ratio (SNIR) 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 or direction. In order to simplify the phase shifter and minimize the power consumption of 60GHz RF electrical components, the codebooks for the BF protocol are designed for a phased antenna array implementing only specific 4 phase shifts per elements (0^o 90^o 180^o 270^o) without amplitude adjustment.

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The codebooks are the basis of BF operation. Figure 4 shows the example codebook of 8 patterns generated by 4 antenna elements with antenna spacing of $\lambda/2$. All these patterns can be specified by the following matrix:

$$\begin{aligned} \text{ID} &= \begin{matrix} 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{matrix} \\ \mathbf{W} &= \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ -1 & -j & -j & -j & 1 & j & j & j \\ 1 & j & -1 & -j & 1 & j & -1 & -j \\ -1 & 1 & j & -1 & 1 & -1 & -j & 1 \end{bmatrix}. \end{aligned} \quad (1)$$

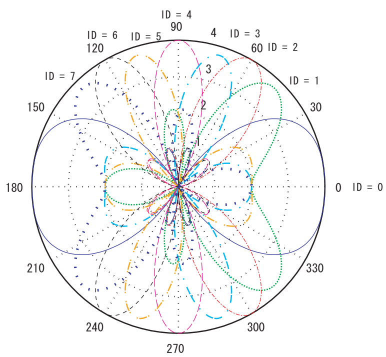

Fig. 4. Codebook of 4 antenna elements separated by $\lambda/2$ (8 patterns)

TABLE I
CODEBOOK WITH 4 ELEMENTS SEPARATED BY $\lambda/2$ (8 PATTERNS)

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

Table I shows the parameters of each pattern, where θ_{max} is maximum gain direction, half power beam width (HPBW) is the 3dB bandwidth and D_{max} is maximum antenna array directivity. Each beam pattern in Figure 3 is identified by a given pattern ID, listed in the first column of Table I. The pattern ID is also corresponding to the column of weight matrix. The pattern ID will be used in the BF protocol to indicate the best beam pattern. For more information of the complete codebook design, please refer to [10].

IV. BF Protocol

We assume that all devices capable of the proposed BF shall support 3 kinds of beam patterns created by codebooks: quasi-omni pattern, sector and beam. Quasi-omni pattern is the lowest resolution pattern specified in the codebooks, referring to an antenna pattern that covers a very broad region of interest space around DEVs. Sector is the second level resolution pattern and is used to refer to a direction of an array pattern that covers an area of multiple consecutive or non-consecutive beams. Different sectors can overlap. Beam is a highest resolution pattern specified in the codebooks.

The BF is processed in the assigned CTA. It starts from starting point of first allocated CTA. The BF is composed of 3 stages: DEV-to-DEV linking, sector searching stage and beam searching stage. Through these 3 stages, the final objective of BF is to find the best transmission and reception beam pair for both forward and reverse links.

A. DEV-to-DEV linking

After association process completes between PNC and DEVs, all DEVs direct its best quasi-omni pattern (in the sense of largest SINR) to PNC. So DEV-to-DEV linking is required. After DEV-to-DEV linking any two DEVs which intent to communicate to each other are able to find each other by finding their own best quasi-omni pattern for command transmission.

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 $Q^{(2,t)}$, $Q^{(2,r)}$ quasi-omni patterns for transmission and reception, respectively.

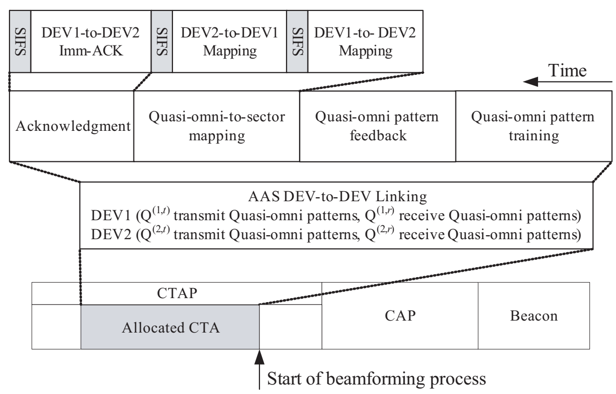

Fig. 5. DEV-to-DEV linking in allocated CTA

As shown in Figure 5, at the starting point of the incoming allocated CTA, both DEV1 and DEV2 start BF process from DEV-to-DEV linking simultaneously. The DEV-to-DEV linking is composed of 4 sub-stages: quasi-omni training, quasi-omni feedback, quasi-omni-to-sector mapping and acknowledgement. During training period, the receiver tries to receive the training sequences from transmitter, and decide best transmit and receive quasi-omni patterns according to the estimated SINR. The decision is then feedback in the quasi-omni feedback period. After feedback period, the best transmit and receive quasi-omni pattern for both forward and reverse link are decided. So this new information about the selected patterns is exchanged in quasi-omni-to-sector mapping substage for the preparation of next training step. The stage then ends with an acknowledgement (ACK).

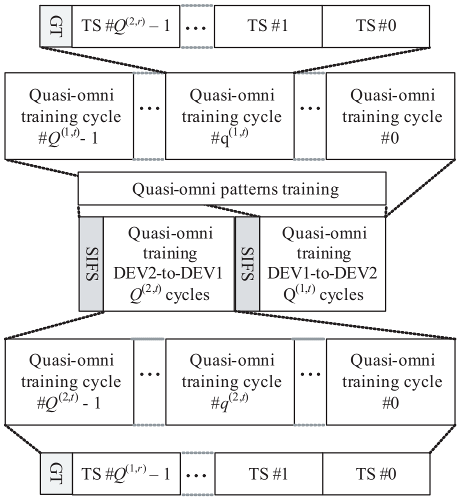

Fig. 6. Quasi-omni training period

1) Quasi-Omni Training Stage: Figure 6 shows the structure of quasi-omni training. It is divided into two parts: quasi-omni training from DEV1 to DEV2 and from DEV2 to DEV1. Each training period ends with a short inter-frame spacing (SIFS), the time for DEVs to switch between transmit and receive mode. During each training period, training sequences (TS) are sent between DEVs. The long preamble consisting a synchronization sequence and a channel estimation sequence specified in IEEE802.15.3c is used as the 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 $Q^{(1,t)}$ 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). During each cycle, DEV2 shall attempt to receive at least any one of TSs. DEV2 switches its quasi-omni pattern one by one, and wait 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 training from DEV2 to DEV1 takes place where DEV2 transmit TSs over $Q^{(2,t)}$ cycles as shown in Figure 5. 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.

2) Quasi-Omni Feedback Stage: Following quasi-omni training stage is the feedback stage shown in Figure 7. It is composed of two parts: DEV1-to-DEV2 feedback and DEV2-

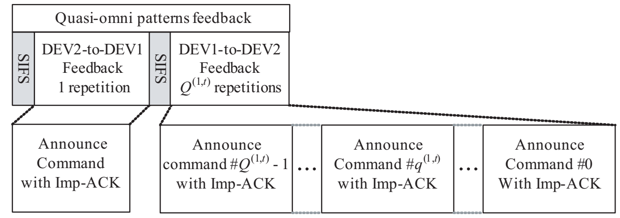

Fig. 7. Quasi-omni feedback period

to-DEV1 feedback. Both of them end with SIFS. DEV1 shall transmit its best quasi-omni pattern ID and corresponding link signal to SINR, estimated by using the received TSs. Those 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 quasi-omni transmit patterns. This is required since DEV1 does not yet know its optimal transmit direction. DEV2 switches to its optimal quasi-omni receive pattern, and attempts to receive at least one transmit sent on DEV1's optimal transmit direction. In return, DEV2 shall transmit its feedback by sending an Announce command with Imp-ACK requested. Since DEV2 has already known its best transmission pattern, multiple repetitions are not necessary anymore. Instead an Announce command shall be sent on DEV2's optimal quasi-omni transmit pattern, and DEV1 shall listen on its optimal quasi-omni receive pattern. The feedback informs DEV1 of its optimal transmit direction and corresponding link's SINR. Upon completion of the feedback stage, both DEV1 and DEV2 know their optimal transmit and receive quasi-omni patterns. These shall be used for any further frame exchanges.

3) Quasi-Omni Mapping 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 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 which completes the DEV-to-DEV linking stage. The mapping stage also appears in sector-level searching stage to indicate the number of beams inside the selected best sectors, the information would be useful in the following beam level searching stage. However the mapping stage is an optional stage for beam level searching stage, depending on whether the following optional

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

[2]The Imp-ACK is specified in IEEE 802.15.3b, which is one 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.

tracking stage is employed.

B. Sector-level and beam-level Searching Stages

After DEV-to-DEV linking stage, DEVs are able to find each other by finding the optimal transmit and receive quasi-omni patterns, ready for command transmission. Then the BF goes to the sector level and beam level searching stages. The operation procedure and frame structure are the same to the DEV-to-DEV linking, that is, including 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: in the sector-level searching, the objective is to find the best sector pair inside the selected quasi-omni patterns while in the beam-level searching, the objective is to find the best beam pair inside the selected sectors. The reason why we have 2 searching levels is because we try to find the optimal beam pairs with as short as possible searching time. Another difference is that feedback stages of both directions have only one repetition feedback as illustrated in Figure 8. The reason is very clear that, at the sector level searching stage, both DEV1 and DEV2 know what are optimal transmit and receive quasi-omni patterns from DEV-to-DEV linking stage, the found optimal quasi-omni pattern can be used for all command transmission. Accordingly, at the beam level searching stage, selected sector pair in sector level searching stage can be used for command transmissions in order to benefit from the possible gain improvement.

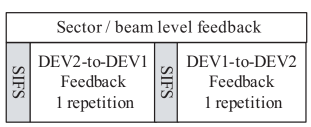

Fig. 8. Structure of Sector level or beam level feedback

TABLE II
MAC RELATED SIMULATION PARAMETERS

Superframe period	$65535\mu s$
Command transmission rate	50.6Mbps
PHY preamble (long)	$3.259\mu s$
Channel estimation sequence (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)	$2.372\mu s$
SIFS	$2.5\mu s$
ACK	$7.212\mu s$
Guard time	$0.0625\mu s$
Backoff	$30\mu s$
Payload size	2k bytes
Payload transmission rate	1.619Gbps
Payload ACK policy	No-ACK or Imm-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	1 for AWGN; 64 for CM2.3
Power amplifier model	SiGe, OBO=3dB
Phase noise model	PSD(0)=-93dB/Hz @ 1MHz, f_z=1MHz, F_D=100MHz
Pulse Shaping Filter and Receiver Filter	Root-raised cosine Filter (Roll-off factor = 0.25)

V. Numerical results

In this part, we follow the guidelines of the IEEE 802.15.3c criteria to estimate set-up time and bit error rate (BER) performance for proposed BF mechanism. The MAC simulations with simulation period of 20ms are conducted in Qualnet between two 3-meter-apart DEVs. All commands and training sequences are transmitted with the physical layer signal access point (PHY-SAP) data rate of 50.6Mbps while the payload is transmitted with PHY-SAP data rate of 1.619Gbps. The MAC related simulation parameters are listed in Table II and the PHY related simulation parameters are in Table III.

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 sector. Furthermore we assume that every 4 sectors is able to cover the same area of one quasi-omni pattern, that is, totaly we have 4 quasi-omni patterns. Figure 9 shows the setup time of this example 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 is not 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) = $619.782\mu s$. As the channel becomes worse, i.e., the PER increases from 0 to 0.5, the BF setup time naturally increases 13.2% up to $701.585\mu s$ due to the command retransmission after a waiting time. However If we use the exhaustive searching scheme, which tries all beam pair combinations and finally find the best pair for transmission and reception, the set-up time is around $31.57ms$ even PER = 0, (64 beams for both transmitter and receiver of DEV1 and DEV2, resulting in 4096 combinations for forward and backward training). The figure also shows the BF set-up time for symmetric antenna system (SAS), where we assume that the channel is 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 $385.932\mu s$ when PER = 0, up to $440.4675\mu s$ in the case of PER = 0.5, still much less than the exhausted search of $15.79ms$. In general, the proposed scheme significantly reduced the set-up time, as small as 2% when compared to the exhaustive searching protocol. It

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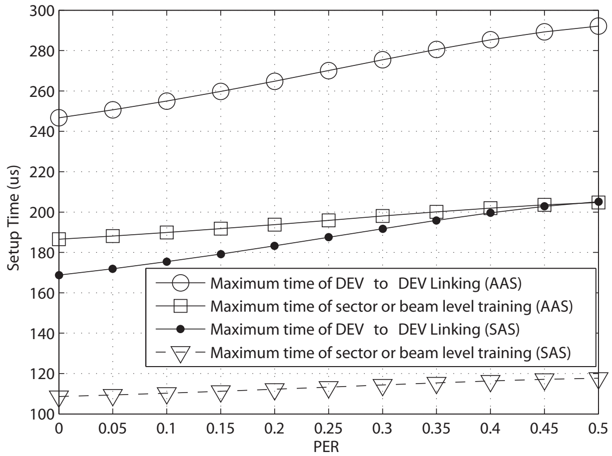

Fig. 9. BF setup time

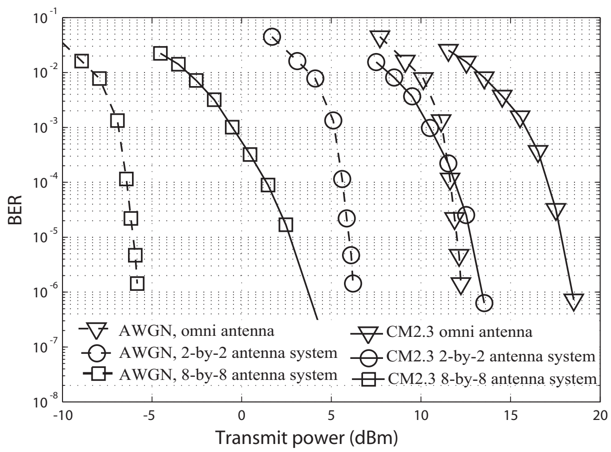

Fig. 10. BER performance

therefore efficiently minimizes the potential interference to other systems during BF set-up period, and makes the BF scheme more feasible for 60 GHz WPANs. Furthermore since beamformed communication link may be lost due to channel variation, the BF operation may repeat, so a short BF re-setup is more meaningful.

B. BER performance

In this part, BER performance of beamformed link will be evaluated. The recommended mandatary proposal with the data rate up to 1.619 Gbps at the PHY-SAP is selected for performance comparison. We assume that the signals are ideally synchronized. The transmission power is decided to guarantee the transmission range is around 10 meters.

Figure 10 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.

VI. CONCLUSION

The paper presented a MAC layer BF protocol following the guidelines of the IEEE 802.15.3c criteria for 60 GHz WPANs. The proposed BF protocol is based on designed codebooks generated with 4 kinds of phase shift without amplitude adjustment. Such a codebook design can significantly reduce the power consumption of BF antenna array. Based on the designed codebooks, the paper clarified the frame structure and specified the BF protocol. The designed protocol was compliment with IEEE 802.15.3c and reused almost all commands specified in IEEE standard. Numerical results show that the proposed BF protocol significantly reduces the BF set-up time from $31.57ms$ of exhausted searching scheme to only $619.782\mu s$, as small as 2% when compared to the exhaustive searching protocol. It is significantly reduce the protectional interference to other systems. The proposal BF protocol is a feasible and complete design, it has adopted by IEEE 802.15.3c as an optional functionality for WPAN systems.

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