Beamforming Codebook Design and Performance Evaluation for 60GHz Wideband WPANs

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***Abstract*—The paper proposes a codebook design to support beamforming mechanism in a wide band millimeter-wave 60GHz wireless personal area networks (60GHz WPANs) in a realistic millimeter-wave environment. The codebooks are designed symmetrically in order to mitigate the possible beam shift due to the large differences of wave lengthes at different sub-bands of a wide band communication system. In order to provide a high data rate and high performance with minimum power consumption in 60GHz systems, the codebooks are generated with 90 degree phase resolution without amplitude adjustment. The codebooks are designed for different numbers of antenna elements, supporting a multitude of antenna configurations. The paper provides codebook design mechanism, some example codebooks and some analysis on antenna gain loss due to phase shift errors of phase shifters. Simulation results shows that: (1) To keep the gain loss at the intersections of any two patterns inside the codebook lower than 1dB, the number of patterns inside the codebook shall be at least 2 times of the number of antenna elements used for pattern generation; (2) The designed codebooks are robust to phase shift errors: the gain loss is lower than 1dB with only 10% outage probability when standard deviation of phase shift errors at phase shifters is 0.5 [28.6 degree]. The proposed codebooks are a feasible design, they are the key basis of the beamforming protocol in 60GHz WPANs (IEEE 802.15.3c).**

Due to the ever increasing market demands for ultra high rate indoor wireless applications such as uncompressed high-definition video streaming [1], the millimeter-wave 60 GHz band with the feature of high path loss is of a special interest for the development of high data rate short distance communications [2]. Wireless personal area networks (WPANs), defined as networks used to convey high rate information over relatively short distances among relatively few participants with low-cost implementation, become feasible due to the available spectrum at 57-64 GHz in US and at 59-66 GHz in Japan [3], [4]. Standardization process for WPANs is started by IEEE 802.15 WPAN Millimeter Wave Alternative PHY Task Group 3c in March 2005. The designed system has an ability of providing mandatory data rate of 1.5Gbps and an optional mode with data rate up to 3 Gbps [5], [6].

However the design of WPANs at 60GHz frequency band is facing challenges. One of the major challenges is the limited link budget due to high path loss, reflection loss and other degradation during radio transmission. Although the high loss is sometimes a good-to-have feature to reduce the interference between adjacent piconets, the transmitted energy is too quickly absorbed at the 60GHz band, it makes the link budget poor in many cases and even worse in non-line-of-sight (NLOS) scenario due to few amount of wave paths. All above reasons make us pay much more attention on beamforming techniques [10].

Several works have been published for physical layer millimeter wave beamforming based on estimated channel state information (CSI), such as [11], that is, to find an optimal beamforming weight vector for transmitter and receiver. Although physical layer solution is a natural way and may provide an optimal performance, acquisition of the entire CSI matrices is time costly and incurs high overhead. Furthermore to generate the weight matrices with exact phase shifts and exact amplitudes is also hard for WPANs compliant devices (DEVs) because of high power consumption of radio frequency (RF) band electrical elements. Optimal physical layer beamforming may therefore become infeasible for rapid-process required 60GHz systems.

In order to reduce complexity and overhead, the more feasible codebook based beamforming mechanism gained more and more attention in many standardized systems, such as IEEE 802.16e [7] and 3GPP LTE [8],[9]. However the codebooks in [7] and [9] are designed for baseband signal processing, that is, pre-code or post-code matrix for multiple-input multiple-output (MIMO) systems. The problem is that MIMO techniques require multiple RF chains, which are expensive and power consuming when considering the millimeter-wave paradigm. Furthermore improving link budget is the main target in 60GHz WPANs instead of improving the spatial efficiency, the traditional smart antenna beamforming would be favored over the coding or multiplicity [10]. This is why the 60GHz beamforming prefers a codebook-based media access control (MAC) layer solution.

However, designing codebook in wide band 60GHz WPANs is also a challenge. One of big differences of the codebook design in 60GHz WPANs systems from other standardized systems is that the bandwidth spans over 9GHz. The problem is that, the codebook is always designed under the assumption that antenna spacing is the fixed times of wavelength, such as a half of the wavelength. However, as the center frequency changes over the wide bandwidth, the wavelength may also change a lot; This may result in all patterns inside the code-

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book rotating from the expected direction. So if the codebook is not perfectly designed, it is highly possible that the best beam pair we find through MAC solution may not be good enough for data streaming.

As a possible solution to above problems, the paper proposes a codebook design to support the beamforming protocol in 60GHz WPANs. The designed codebooks have the following features:

(1) The codebooks are designed for a phased antenna array, each column of a codebook matrix specifies the phase shift of each antenna element, and a practical beam can be generated with the phases specified in each column of the codebook.

(2) The codebooks are generated with a 90-degree phase resolution without amplitude adjustment in order to minimize power consumption of 60GHz RF band electrical devices.

(3) The codebooks are designed symmetrically spanning the 360 degrees around devices in order to minimize the gain loss due to the possible beam shift at different frequency band.

(4) The codebooks support a multitude of antenna configurations such as single antenna element, sectored antennas, switched antennas, and 1-dimensional (1-D) and 2-dimensional (2-D) beamforming antenna arrays. It is also available for different numbers of antenna elements.

(5) The columns of the codebook are orthogonal to each other, so that multiple beams can be generated simultaneously without large interference to each other. These beams can also be synthesized to create a wider beam.

The designed codebooks are feasible for 60GHz WPANs, and they are the strong basis of the beamforming protocol defined in WPANs of IEEE 802.15.3c.

I. System Model

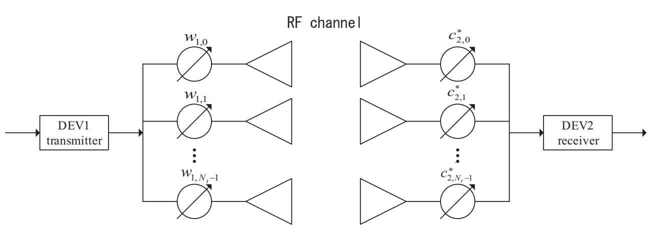

Fig. 1. System Model

The beamforming system model is illustrated in Figure 1 where DEV1 has N_t transmit antennas while DEV2 has N_r receive antennas. At the transmitter, the data stream after baseband signal processing, is up-converted to the RF band. The phase of RF signal is then shifted by transmit weight vector and transmitted into free space from different antenna elements. At the receiver, the received signals are weighted by receive weight vector, and then combined together, down-converted for baseband processing.

The objective of beamforming is to select the optimal transmit and receive weight vectors to optimize a cost function which measures the link quality according to a selected criterion. This criterion can be, for example, effect SNR, capacity, etc. To optimized them, (1) For a complex beamforming antenna array, defined as antenna array capable of configuration for beamforming, the weights can be adjusted in both phase and amplitude; (2) For a phased antenna array implementing specific phase shifts, the weights are restricted to those specific phase shifts; (3) Sectored and switched antennas where one antenna is active at a time, is the special case of beamforming antenna array, the weights are identity matrix, the beamforming therefore degenerated into antenna selection. To simplify the beamforming electrical components, the paper is mainly focusing on case (2).

II. Beamforming Procedure

A complete MAC layer beamforming protocol is specified in [5] based on the proposed codebook. During beamforming, the best beam pair, or in other words, the best transmit and receive weight vectors, are selected from known codebooks. We will briefly introduce this beamforming design in this section in order to give a general image of how to use these codebooks.

We assume that all devices capable of beamforming shall support 3 kinds of beam patterns: quasi-omni pattern, sector and beam. Quasi-omni pattern is the lowest resolution pattern specified in the codebooks. it is used to refer 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 a relatively broad area of multiple beams. A sector can cover a set of consecutive or non-consecutive beams. Different sectors can overlap. Beam is a highest resolution pattern specified in the codebooks. The final objective of beamforming is to find the best beam pair for data streaming. Note that sector is just a group of beams, it is not directly specified by codebooks

Before beamforming, directional association shall be done. To support directional association with a beamforming antenna array, directional beacons are required. Piconet controller (PNC) shall cover target area by sending each directional beacon with a different transmit quasi-omni pattern.

The beamforming protocol is composed of 2 stages: DEV-to-DEV linking and beam-searching. DEV-to-DEV linking stage is required because DEVs may not communicate to each other after association since the best quasi-omni patterns for command exchange directs to the PNC. After DEV-to-DEV linking any two devices with the intention of communications are able to find each other by finding the best quasi-omni pattern pair for command transmission and reception.

After association stage for PNC-to-DEV communications or DEV-to-DEV linking stage for DEV-to-DEV communications, the beamforming steps into the search stages. Beamforming search stage consists of 2 levels: sector level searching and beam level searching. Sector level searching is to find the best sector pair for transmission and reception, while beam level searching is to furthermore find the best beam pair in the selected sectors.

III. Beam Codebooks

A codebook is a matrix where each column specifies the beamforming weight vector. Each column also specifies a pattern or direction. The set of columns spans the entire space, which is 360 degrees around a DEV. To support the beamforming, a 1-D or 2-D phased antenna is selected. The codebooks are generated symmetrically, in other words, the codebooks are generated so that the total beam patterns in the codebook may create a near-circle pattern, that is, to keep the gain loss at the intersections of any two adjacent patterns as low as possible. By doing so, even the beams are rotated due to the changes of wavelength at some frequency band, we may not lose much antenna gain even in the worst condition. To minimize the high power consumption in 60GHz RF band electrical devices, the codebooks are generated with only 4 phase shifts (0 90 180 270 degrees) without amplitude adjustment since, as we known, the simpler the phase shifters are, the less power loss they may have.

A. 1-D and 2-D Antenna Array

The power gain of an antenna array = power gain of a single antenna $\times|\text{array factor}|^2$. Beam codebooks considered in this paper are the design of array factor, they are specified by the number of antenna elements M, and the desired number of beams K.

The array factor of the 1-D uniform-spaced antenna array, generated by the kth weight vector of the codebook, can be represented as

$$A_k(\theta) = \sum_{m=0}^{M} w_{m,k} e^{j2\pi n(d/\lambda)\cos\theta}, \tag{1}$$

where $w_{m,k}$, $0 \le m \le M-1$ and $0 \le k \le K-1$, is mth element of kth weight vector in the codebook, d is the antenna spacing and λ is the wave length. If the antenna elements are located along y-axis, then θ is the polar angle with respect to x-axis.

The antenna array directivity is defined as

$$D_k = \frac{\max_\theta |A_k(\theta)|^2}{\mathbf{w}_k^H \mathbf{\Omega} \mathbf{w}_k}, \tag{2}$$

where $(\ )^H$ denotes operation of transpose and complex conjugate, $\mathbf{w}_k = [w_0 w_1 \ldots w_{M-1}]^T$, $(\ )^T$ is the transpose operation, $\mathbf{\Omega}$ is defined with each entry $\Omega_{n,m}$ specified as

$$\begin{aligned} \Omega_{n,m} &= \frac{\sin 2\pi(\frac{d}{\lambda})(n-m)}{2\pi(\frac{d}{\lambda})(n-m)}, \\ n,m &= 0,\ldots,M-1 \end{aligned} \tag{3}$$

Similarly, the array factor of 2-D antenna array would be

$$\begin{aligned} A_{k,l}(\theta,\phi) &= \sum_{m=0}^{M_x-1}\sum_{n=0}^{M_y-1} w_{m,n,k,l} e^{j2\pi m(\frac{d_x}{\lambda})\sin\theta\cos\phi + j2\pi n(\frac{d_y}{\lambda})\cos\theta} \\ &= A_{x,k}(\theta,\phi) A_{y,l}(\theta,\phi), \end{aligned} \tag{4}$$

where

$$\begin{aligned} A_{x,k}(\theta,\phi) &= w_{x,m,k} e^{j2\pi m(d_x/\lambda)\sin\theta\cos\phi}, \\ A_{y,l}(\theta,\phi) &= w_{y,n,l} e^{j2\pi n(d_y/\lambda)\cos\theta}, \end{aligned} \tag{5}$$

are array factors along x-axis and y-axis respectively if the antenna elements are located in the x-y plane. θ is the polar angle with respect to x-axis, and ϕ is the azimuth angle with respect to z-axis. d_x and d_y are antenna spacing along x-axis and y-axis respectively. M_x and M_y are the extended parameters from M, which mean that the number of antenna elements along x-axis and y-axis, respectively. Accordingly, K_x and K_y are extended from K, indicating the number of patterns generated by antenna elements along x-axis and y-axis respectively. $w_{m,n,k,l} = w_{x,m,k} w_{y,n,l}$, where $0 \le m \le M_x - 1$, $0 \le n \le M_y - 1$ and $0 \le k \le K_x - 1$, $0 \le l \le K_y - 1$. Equation 4 means that a 2-D codebook of linear planar antenna array can be obtained from 2 corresponding 1-D codebooks along x-axis and y-axis. Therefore, only 1-D codebook needs to be defined.

B. Codebook Design for Phased Antenna Array

In this section, we will specify the codebook design for 1-D arrays with uniform spacing of $\lambda/2$.

As for a 1-D phased antenna array, when $K \le M$, the beam vectors are given by column vectors of the following matrix:

$$\begin{aligned} &W(m,k) = j^{\text{floor}\{\frac{m\times \mod (k+(K/2),K)}{K/4}\}}, \\ &m = 0,\ldots,M-1; k = 0,\ldots,K-1. \end{aligned} \tag{6}$$

where the function floor() returns the biggest integer smaller than or equal to its argument. $M = \mod(X,Y)$ is defined as $M - nY$ where n is the nearest integer less than or equal to X/Y.

For the special case where $K = M/2$, the beam vectors are given by the column vectors of the following matrix:

$$W(m,k) = \begin{cases} (-j)^{\mod(m,K)}, \\ m = 0,\ldots,M-1 \text{ and } k = 0; \\ j^{\text{floor}\{\frac{m\times \mod (k+(K/2),K)}{K/4}\}}, \\ m = 0,\ldots,M-1 \text{ and } k = 1,\ldots,K-1 \end{cases} \tag{7}$$

IV. Example Codebooks and Performance Evaluation

This section presents some example codebooks with antenna spacing of half wavelength, the codebooks are generated based on the designing mechanism in last section, and we will also find some rules for the codebook design through these examples. Codebooks are specified in a matrix, where each column is a weight vector corresponding to one beam pattern. The beam patterns will be drawn in figures with linear coordinate. All details of a codebook will be shown in a table, where θ_{max} is maximum gain direction, half power beam width (HPBW) is the 3dB bandwidth and D_{max} is maximum antenna array directivity.

The performance of codebooks is evaluated in the sense of maximum antenna gain loss at the intersections of any two patterns of a codebook. The antenna gain loss at the maximum gain direction due to phase shift errors are also evaluated. Antenna gain loss at the maximum gain direction is defined as gain degradation at the direction of maximum gain, calculated by comparing gain difference between two cases: with/without phase shift errors. The phase shift errors are modeled as Gaussian distribution with 0 mean and standard deviation (Std) following either of two cases: (1) Phase shift errors are independent of absolute phase shift. And the phase shift errors of phase shifters are independent of each other, they follow the same distribution with the same standard deviation. (2) Phase shift errors depend on absolute phases, they follow the same distribution but with standard deviation proportional to the absolute phase shift. The Case (2) is considered here due to the measured data in [12].

A. Codebook A: 2 patterns created by 2 antenna elements

The following matrix creates 2 patterns shown in Figure 2. The parameters of each pattern are shown in Table I.

$$\mathbf{W}_A = \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix} \tag{8}$$

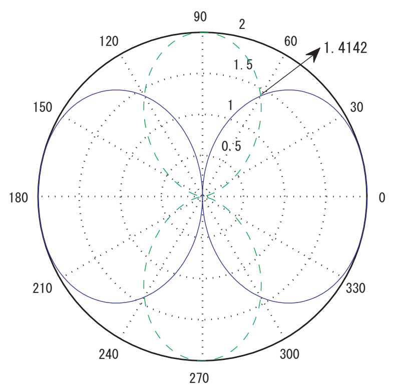

Fig. 2. Codebook of 2 patterns generated by 2 elements

TABLE I
CODEBOOK OF 2 PATTERNS GENERATED BY 2 ELEMENTS

Codebook Column Index	θ_{max}	HPBW	D_{max}
0	0^o	120^o	3.01dBi
1	90^o	60^o	3.01dBi

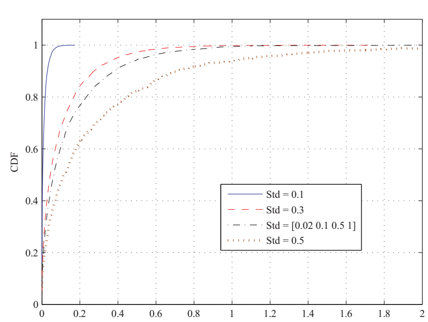

Fig. 3. Gain loss due to phase shift errors (2 patterns generated by 2 elements)

In this codebook, target area of 360 degrees is covered by only 2 beam patterns. The maximum array gain by using 2 antenna elements is $10\log(2) = 3.01$dBi shown in Figure 2. The maximum gain loss at the intersections of these two beams is around $3.01-10\log(1.4142) = 1.505$dB. If this codebook is adopted at both transmitter and receiver, we may lose 3.01dB gain in the worst condition

Figure 3 shows the gain loss due to the phase shift errors of phase shifters at the maximum gain direction. Although the two beams have different 3dB bandwidth, the robust performance to the phase shift errors are almost the same. As the Std increases from 0.1 to 0.5, the performance degrades. There is also a vector $[0.02\ 0.1\ 0.5\ 1]$ indicating that Stds of phase shift errors are 0.02, 0.1, 0.5 and 1 for phase 0^o, 90^o, 180^o and 270^o, respectively. In this example, the average Std of phase shifters is around 0.4, the performance of its gain loss due to phase shift errors is in between the performance of Std = 0.3 and Std = 0.5. It further means that although the phase shift errors depend on absolute phases, the average Std of phase shift errors can also be used to estimate the performance degradation due to the phase errors.

B. Codebook B: 4 patterns created by 2 antenna elements

By using 2 beam patterns to cover the target area of 360 degrees, the maximum gain loss at the intersections of two beam patterns is around 1.505dB. To reduce the gain loss at the intersections, we created 4 beam patterns with only 2 antenna elements defined by the following matrix. The beam patterns are shown in Figure 4 and the parameters of each pattern are shown in Table II.

$$\mathbf{W}_B = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & -j & 1 & j \end{bmatrix} \tag{9}$$

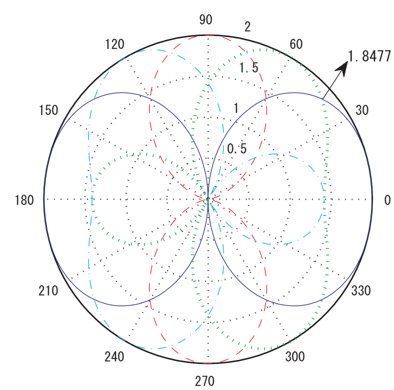

Fig. 4. Codebook of 4 patterns generated by 2 elements

Figure 4 shows that the maximum gain loss at the intersections could be minimized by adding two more patterns between two patterns in Codebook A. Since the patterns are still created with 2 antenna elements, the maximum array gain is unchanged, and the maximum gain loss for the 4 pattern codebook is around $3.01 - 10\log(1.8477) = 0.34$dB.

Figure 5 shows the gain loss due to the phase shift errors at the maximum gain direction. Codebook B has the same robust

TABLE II
CODEBOOK OF 4 PATTERNS GENERATED BY 2 ELEMENTS

Codebook Column Index	θ_{max}	HPBW	D_{max}
0	0^o	120^o	3.01dBi
1	60^o	90^o	3.01dBi
2	90^o	60^o	3.01dBi
3	120^o	90^o	3.01dBi

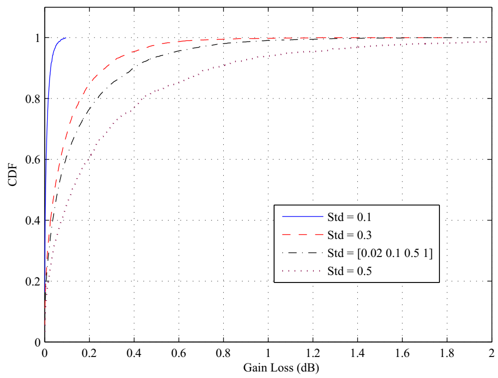

Fig. 5. Gain loss due to phase shift errors (4 patterns generated by 2 elements)

performance as Codebook A. We further find that the robust performance to the phase shift errors is not affected by the number of the patterns inside the codebook, but only depends on the number of antenna elements.

C. Codebook C: 4 patterns created by 4 antenna elements

In the section B, we generated 4 patterns with only 2 antenna elements. However if 4 patterns are generated by 4 antenna elements, we may find some differences. The following matrix creates 4 patterns shown in Figure 6 and the parameters of each pattern are shown in Table III.

$$\mathbf{W}_C = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & -j & 1 & j \\ 1 & -1 & 1 & -1 \\ -1 & j & 1 & -j \end{bmatrix} \tag{10}$$

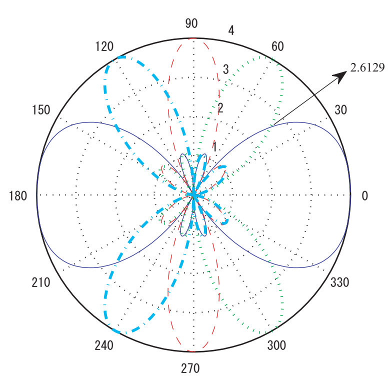

Fig. 6. Codebook of 4 patterns generated by 4 elements

TABLE III
CODEBOOK OF 4 PATTERNS GENERATED BY 4 ELEMENTS

Codebook Column Index	θ_{max}	HPBW	D_{max}
0	0^o	79^o	6.02dBi
1	60^o	31^o	6.02dBi
2	90^o	26^o	6.02dBi
3	120^o	31^o	6.02dBi

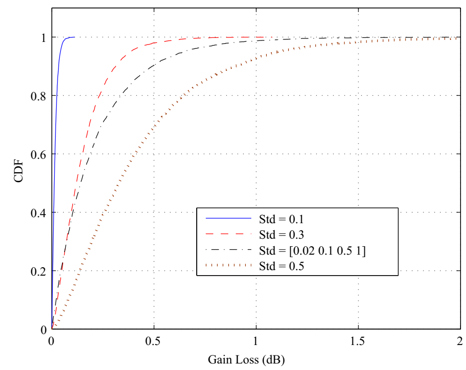

Fig. 7. Gain loss due to phase shift errors (4 patterns generated by 4 elements)

As we all know, by using more antenna elements, we may generate narrower beams with larger antenna gain. In this case, the maximum array gain is around $10\log(4) = 6.02$dBi. It is shown in Figure 6 that, the maximum gain loss at the intersections of any two beams is around $6.02 - 10\log(2.6129) = 1.58$dB, larger than Codebook A and B.

In Figure 7, we found that the gain loss at the maximum gain direction of Codebook C is larger than Codebook A and B. This is reasonable since the narrower beams generated by more antenna elements are more vulnerable to phase shift errors.

D. Codebook D: 8 beams created by 4 antenna elements

Similar extension from 2 patterns to 4 patterns for 2 antenna elements is applied for 4 antenna elements. The maximum gain loss at the intersections of any two beams can be mitigated by adding more patterns in Codebook C. The following matrix creates 8 patterns shown in Figure 8 and the parameters of each pattern are shown in Table IV. In Figure 8, we also find some beams that can not reach the maximum gain (6.02dB), this is because we can not create an optimal beamforming weight vector for some directions by using only the limited number of 4 phase shifts per elements.

$$\mathbf{W}_D = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ -1 & -j & -j & -j & 1 & j & j & j \\ 1 & j & -1 & -j & 1 & j & -1 & -j \\ -1 & 1 & j & -1 & 1 & -1 & -j & 1 \end{bmatrix} \tag{11}$$

Figure 8 shows that the maximum gain loss at the intersections of two beams is $6.02 - 10\log(3.3422) = 0.78$dB, much lower than Codebook C.

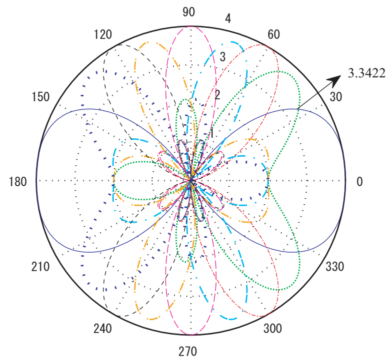

Fig. 8. Codebook of 8 patterns generated by 4 elements

TABLE IV
CODEBOOK OF 8 PATTERNS GENERATED BY 4 ELEMENTS

Codebook Column Index	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

Due to the page limitation, only 4 examples were given in the paper, however we may further find the following conclusions:

(1) If the number of patterns in the codebook is equal to the number of antenna elements, the gain loss at the intersections of two beams are more than 1.5dB. Additionally the more antenna elements a antenna array has, the larger the gain loss at the intersections. For example, 1.505dB (2 patterns, 2 elements)$<$ 1.85dB (4 patterns, 4 elements)$<$ 2.30dB (8 patterns, 8 elements).

(2) If the number of patterns in the codebook is more than the number of antenna elements, the gain loss at the intersections of two patterns is less than case (1). For example, 0.34dB (4 patterns, 2 elements) $<$ 1.505dB (2 patterns, 2 elements).

(3) If the same number of antenna elements is used to generate different numbers of patterns, the more patterns in the codebook, the lower the gain loss at the intersections of two patterns. For example, 2.3dB (8 patterns, 8 elements) $>$ 1.19 dB (12 patterns, 8 elements) $>$ 0.44 dB (16 patterns, 8 elements).

(4) If the number of patterns is more than or equal to 2 times of the number of antenna elements, the gain loss at the intersections of two beams is less than 1 dB. For example, 0.34 (4 patterns, 2 elements); 0.78 (8 patterns, 4 elements); 0.44 (16 patterns, 8 elements).

(5) The codebooks are robust to phase shift errors: the gain loss is lower than 1dB with only 10% outage probability even when standard deviation of phase shift errors at phase shifters is 0.5 [28.6 degree].

V. CONCLUSION

The paper proposed a codebook design to support beamforming in 60GHz wideband WPANs. The codebooks are designed symmetrically in order to mitigate the possible beam shift due to the large differences of wave lengthes at different sub-band of a wide band communication system. To minimize the power consumption of electrical devices in the 60GHz band , the codebooks were created with only 4 phase shifts (0 90 180 270 degree) per element without amplitude adjustment. The paper presented the codebook design mechanism and also provided some codebook examples, from which we found that the gain loss at the intersections of any two patterns would be less than 1dB if the number of patterns defined in the codebook is twice of the number of antenna elements. Some analysis on gain loss due to phase shift errors were also done on the designed codebooks. Simulation results shows that designed codebooks are robust to phase shift errors, the gain loss is less than 1dB with 10% outage probability when standard deviation of phase shift errors at phase shifters is 0.5 [28.6 degree]. The codebooks are designed for different numbers of antenna elements, available for different antenna array configuration, they are a key basis for MAC layer beamforming in 60GHz WPANs.

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