Multi-stage beamforming codebook for 60GHz WPAN

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***Abstract*—Beamforming(BF) based on codebook is regarded as an attractive solution to resolve the poor link budget of millimeter-wave 60GHz wireless communication. Because the number of the elements of antenna array in 60GHz increases, the beam patterns generated are more than common BF , and it causes long set-up time during beam patterns searching. In order to reduce the set-up time, three stages protocol, namely the device (DEV) to DEV linking, sector-level searching and beam-level searching has been adopted by the IEEE 802.15.3c as an optional functionality to realize Gbps communication systems. However, it is still a challenge to create codebook of different patterns to support three stages protocol from common codebook of beam pattern. In this paper, we proposes a multi-stage codebook design and the realization architecture to support three stages BF. The multi-stage codebook can create different granularity of beam patterns and realize progressive searching. Simulation results for eight elements uniform linear array (ULA) show that this design can divide the beam searching to three stages searching without increasing the system complexity.**

***Index Terms*—beamforming,codebook,60GHz**

I. Introduction

In early 2000, Federal Communications Commission (FCC) allocated the 57-64 GHz band (also known as the 60 GHz millimeter wave band) for unlicensed use which makes mm-wave 60GHz communication very attractive to realize ultra high rate indoor wireless applications such as uncompressed high definition video streaming. However, One of the major challenges for 60 GHz mm-wave communications is the poor link budget, as radio signal propagating in the mm-wave frequency band experiences significant path loss, reflection loss and other degradation[1]. [2] indicates that the path loss in 60 GHz is as high as 68 dB at a distance of 1 m and 88 dB at a distance of 10m. On the other hand, due to the extremely short wavelength of 5 millimeter on the 60 GHz band, it becomes possible to integrate a large number of antenna elements. Beamforming (BF) based antenna array thus emerges as an attractive solution to solve the poor link budget problem[3].

Several works have been conducted for BF of 60GHz communication. There are generally 2 kinds of method to realize BF. One is based on estimated channel state information (CSI) such as [4][5]. However, as the number of the elements of antenna array in 60GHz is large such as 8×8, 16×16, this method needs long training sequence and is complex and time consuming to realize. The other one is based on BF codebook which is pre-designed at both transmitter and receiver [7][8]. The realization of the BF process is to find the optimal transmit and receive antennas weight vector form BF codebook. Because this BF method can be realized without the necessity of AOD/AOA or CSI estimation and the BF codebook can employ only discrete phase shifts, which simplifies the DEVs' structure when compared to conventional BF with phase-and-amplitude adjustment, the method shows huge advantage for 60GHz communication.

In order to minimize the BF set-up time for BF codebook based method, a BF protocol is proposed in [6] which divide the process of BF into 3 stages, namely the DEV to DEV linking, sector-level searching and beam-level searching. three kinds of beam pattern support the three stages of BF, namely quasi-omni pattern, sector pattern and beam pattern. This division significantly reduces the setup time of BF comparing to exhaustive searching mechanisms. However the current BF codebook does not support the three-stages BF process As a solution to above problem, a multi-stage codebook design and the realization architecture to support the three-stages BF is proposed in the paper . The multi-stage codebook can create different granularity of beam patterns and realize progressive searching during the process of BF. For example, after finishing the sector searching, we can begin the beam searching during the sector we setup before. The rest of the paper is organized as follows: section II describes the system model which includes the BF model and the different kinds of BF patterns for 60GHz communication. In section III, we analyze the common beam codebook and propose the muti-stage codebook. In section IV, we give simulation results for eight ULA based on the muti-stage codebook. Conclusions are drawn in section V.

II. System Model

A. BF model

The BF model of DEV1 transmitting to DEV2 is in Figure 1. DEV1 has N transmit antennas and DEV2 has M receive antennas. At the DEV1 which is the transmitter, the data stream is up-converted to the RF band after baseband signal processing. Then the phase of RF signal is shifted by weight vector $W_k\,(k = 1, \ldots, N)$ and is emitted to the free space. At the DEV2, the received RF signal is shifted by the receiver

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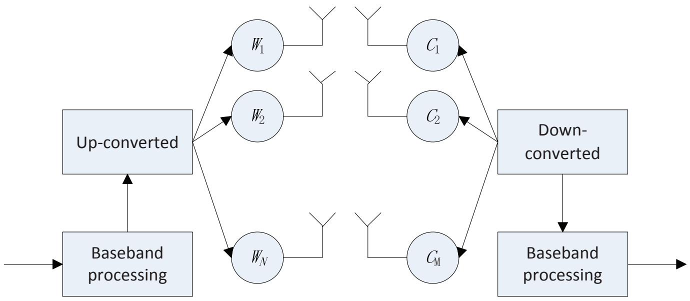

Fig. 1. BF model

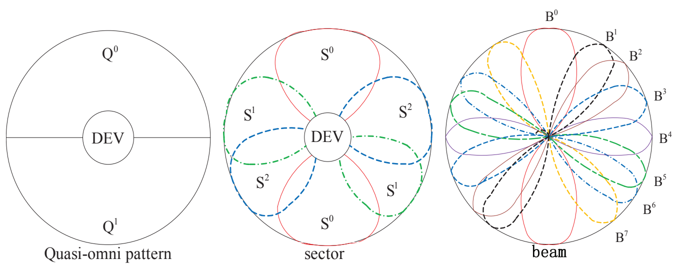

Fig. 2. 3 kinds of beam pattern

weight vector $C_m(m = 1, \ldots, M)$ and then down-converted into baseband for baseband processing.

The objective of BF is to find the optimal weight vectors for both transmit and receive antennas in order to optimize a cost function that measures the link quality such as SINR.

B. The 3 kinds of 60GHz communication BF pattern

As it is described in the 802.15.3c-2009, three kinds of beam pattern support the three-stages of BF, namely quasi-omni pattern, sector and beam. In Figure 2, the pattern of the three levels is showed respectively. And the Beams level can also be divided into fine beams and HRS(high resolution) beams.

The term quasi-omni pattern is the lowest resolution pattern and is used to refer to an antenna pattern that covers a very broad area of the region of space of interest around a DEV .The term sector is the second level resolution pattern and is used to refer to an antenna direction or an array pattern that covers a relatively broad area of multiple beams. A sector can cover a set of consecutive or nonconsecutive beams and different sectors can overlap. Beam is a highest resolution pattern specified in the codebooks. The final objective of BF is to find the best beam pair of transmitter and receiver for data streaming. However only beam is specified in the codebooks, how to specify the sector and quasi-omni pattern from the beam codebooks without causing complexity to the system is the problem we need to research.

III. BF CODEBOOK

The BF codebook is a $N \times K$ matrix for an antenna array of N antennas where each column specifies a BF weight vector. Each column also specifies a pattern. An $N \times K$ BF codebook describes K patterns. The set of columns spans the entire space, which is 360 degrees around a DEV.

A. Beam BF codebook

The codebook designed for 1-D uniform linear antenna can be described as (1):

$$\omega = \begin{pmatrix} \omega(0,0) & \omega(0,1) & \ldots & \omega(0,K-1) \\ \omega(1,0) & & \ldots & \vdots \\ \vdots & & & \\ \omega(N-1,0) & \omega(N,1) & \ldots & \omega(N-1,K-1) \end{pmatrix} \tag{1}$$

The array factor of the 1-D uniform-spaced antenna array, generated by the k th weight vector of the codebook, can be represented as (2)where we assume that the antenna array element factor is 1. $\omega(n,k)(n = 1, \ldots, N)$ is the k th weight vector of the codebook, d is the distance between the array elements, λ is wavelength and θ is the polar angle with respect to y-axis if the antenna elements are located along x-axis. Then if the spacing of the array elements d equals $\lambda/2$, (2) can be written as (3).

$$A(k,\theta) = \sum_{n=0}^{N-1} \omega(n,k) \exp(j \times 2\pi n \times \frac{d}{\lambda} \times cos\theta) \tag{2}$$

$$A(k,\theta) = \sum_{n=0}^{N-1} \omega(n,k) \exp(j \times \pi n \times cos\theta) \tag{3}$$

In order to make the interference of different beam patterns to the minimum, the columns of the codebook must be 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. So the number of columns K should be less than the number of antenna elements N, that is $K \leq N$. In order to get the maximum number of BF patterns, we ordinarily make $K = N$ for codebook.

To minimize the complexity of 60GHz RF band electrical devices, the codebooks are generated with phase shifts which are without amplitude adjustment, and the phase shifts have uniform spaces so it can be realized with one kind of phase shift.In the paper we designed the phase shifts based codebook as (4):

$$\omega(n,k) = \exp(\frac{j \times 2\pi n \times k}{N}) \tag{4}$$

For example with this codebook design, a codebook design for four elements antenna array is given as follows(5):

$$\omega = \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & j & -1 & -j \\ 1 & -1 & 1 & -1 \\ 1 & -j & -1 & 1 \end{pmatrix} \tag{5}$$

Based on this codebook design, we will introduce a multistage BF codebook design to support different levels of BF search and this design can achieve the beam searching from lower resolution pattern to higher resolution pattern which we will explained in the next subsection.

B. multi-stage BF codebook

The codebook of 4 elements (5) can produce 4 patterns of beam. If we add column1 and column2, column3 and column4. The new matix is shown as (6). If we add column1 and column3, column2 and column4. The new matix is given as (7).

$$\omega = \begin{pmatrix} 1 & 1 \\ \frac{1+j}{2} & -\frac{1+j}{2} \\ 0 & 0 \\ \frac{1-j}{2} & -\frac{1-j}{2} \end{pmatrix} \tag{6}$$

$$\omega = \begin{pmatrix} 1 & 1 \\ 0 & 0 \\ 1 & -1 \\ 0 & 0 \end{pmatrix} \tag{7}$$

The column1 of matix (6) can produce the pattern of sector1 which can be seen as the pattern of beam1 and beam2 transmitted together and the sector2 of column2 can be seen as the pattern of beam3 and beam4 transmitted together. The column1 of matix (7) can produce the pattern of sector1 which can be seen as the pattern of beam1 and beam3 transmitted together and the sector2 of column2 can be seen as the pattern of beam2 and beam4 transmitted together. It is clearly to see that sectors created by sector codebook (7) cause less complexicity to the system compared to sector codebook (6), because codebook (7) can be realized with only phase shifts which are already used in beam codebook.

In order to design the low complexity codebook of the lower resolution from the higher resolution, we will discuss the general principal to design the multistage BF codebook in the following paper. Because the BF codebook principal we designed in (4) is symmetrical. We can perform transform on the array factor of the 1-D uniform-spaced antenna array (3) as follows:

$$\begin{aligned} A(k,\theta) &= \sum_{n=0}^{N-1} \omega_N(n,k)\exp(j\pi n\cos\theta) \\ &= \sum_{n=0}^{N/2-1} \omega_N(2n,k)\exp(j\pi 2n\cos\theta) + \\ &\quad \sum_{n=0}^{N/2-1} \omega_N(2n+1,k)\exp(j\pi(2n+1)\cos\theta) \\ &= \sum_{n=0}^{N/2-1} \omega_{N/2}(n,k)\exp(j\pi 2n\cos\theta) + \omega_N(1,k) \\ &\quad \sum_{n=0}^{N/2-1} \omega_{N/2}(n,k)\exp(j\pi(2n+1)\cos\theta) \\ &= G(k,\theta) + \omega_N(1,k)H(k,\theta)(k=1,\ldots,\frac{N}{2}) \end{aligned} \tag{8}$$

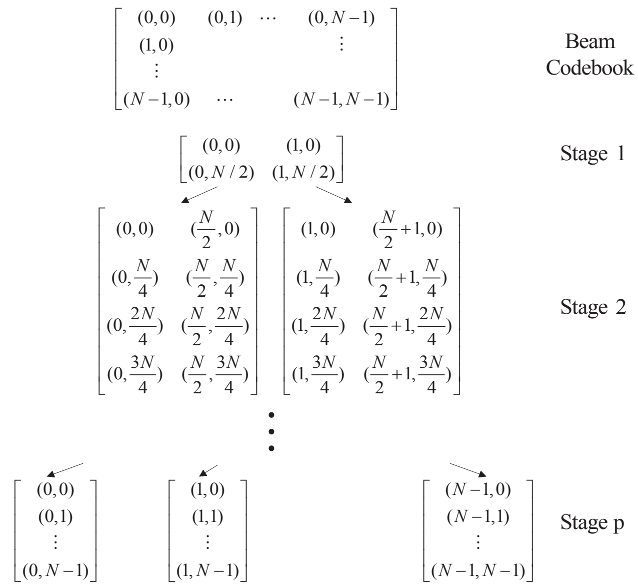

Fig. 3. codebook of different stages

And

$$G(k,\theta) = \sum_{n=0}^{N/2-1} \omega_{N/2}(n,k)\exp(j\pi 2ncos\theta) \tag{9}$$

$$H(k,\theta) = \sum_{n=0}^{N/2-1} \omega_{N/2}(n,k)\exp(j\pi(2n+1)cos\theta) \tag{10}$$

Similarly, we can get:

$$A(k+\frac{N}{2},\theta) = G(k,\theta) - \omega_N(1,k)H(k,\theta)(k=1,\ldots,N/2) \tag{11}$$

This transform means that the process of searching the best column of the beam codebook $\omega(n,k)(k=1,\ldots,N)$ can be divided into two stages. With this method, the process of searching best weighs from beam codebook can finally be divided into p stages where which is shown in Figure 3.

The codebook of every stage is composed of phase shifts which are already used in codebook of beam. The codebook of stage $n(n=2,\ldots,p)$ is given as (12) where $k=(1,\ldots,2^n-1)$

$$\begin{pmatrix} (k,0) & (k+\frac{N}{2^{n-1}},0) \\ (k,\frac{N}{2^n}) & (k+\frac{N}{2^{n-1}},\frac{N}{2^n}) \\ \vdots & \vdots \\ (k,\frac{(2^n-1)N}{2^n}) & (k+\frac{N}{2^{n-1}},\frac{(2^n-1)N}{2^n}) \end{pmatrix} \tag{12}$$

The codebook of stage $n(n=2,\ldots,p)$ is based on the choice of codebook of stage $n-1$. The pattern of stage $n-1$ which we choose is divided into two higher resolution patterns. It can be shown as Figure 4:

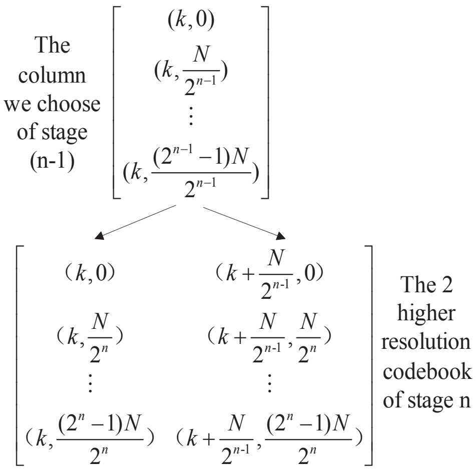

Fig. 4. codebook from stages $n-1$ to n

IV. SIMULATION RESULTS

This section presents some example codebooks with antenna spacing of half wavelength, the codebooks are generated based on the designing mechanism in last section.

We use the way to design multi-stage BF codebook to design three-stages codebook for 8 elements ULA. The three-stages codebook can divide the process of BF to three-stages that is quasi-omni pattern, sector and beam.

The first stage codebook is for antennas whose number is 1 and 5, the second stage codebook is for antennas whose number is 1,3,5 and 7. The third is for all eight elements. Every stage codebook is depend on the choice of the former codebook. The relationship can be explained in Figure 5.

Figure 6 is the factor of the quasi-omni pattern. The 1,5 element use the first stage codebook to divide the 360^o space to two quasi-omni patterns(pattern1 and pattern2).

The factor of the sector is shown in Figure 7. After finishing the search of the quasi-omni pattern, we choose the best weight for element 1,3,5 and 7 form the second stage codebook. Then the pattern1 is divided into sector1-1 and sector1-2 and the pattern2 is divided into sector2-1 and sector 2-2, as is shown in Figure 7. The 360^o space is divided into four sectors.

After finishing the sector searching, the third stage codebook is for beam searching. The sector1-1 is divided into beam1-1-1 and beam1-1-2, the sector 1-2 is divided into beam1-2-1 and beam1-2-2, the sector2-1 is divided into beam2-1-1 and beam 2-1-2 and the sector2-2 is divided into beam2-2-1 and beam2-2-2. The 360^o space is divided into eight beams which is shown in figure 8.

V. CONCLUSION

In this paper, we propose a complete BF multi-stage codebook design based on discrete phase shift codebooks. The multi-stage codebook is in order to realize three-stages BF in millimeter-wave 60GHz WPANs proposed in IEEE 802.15.3c to reduce the set-up time of beam searching. The proposed multi-stage codebook can realize the process of BF from lower resolution pattern to higher resolution pattern and the multi-stage codebook can be realized with phase shifts already used in beam codebook, so the proposed muti-stage codebook can be easily realized without causing more complexity to the system. Simulation results of the eigth element ULA to produce three-stages BF shows that the proposed multi-stage codebook design divides the beam searching to three stages and the three stages are quasi-omni pattern searching of two quasi-omni patterns, sector searching of two sectors based on the aligning quasi-omni pattern and beam searching of two beams based on the aligning sector. The proposed multi-stage codebook design can support and realize three-stages BF.

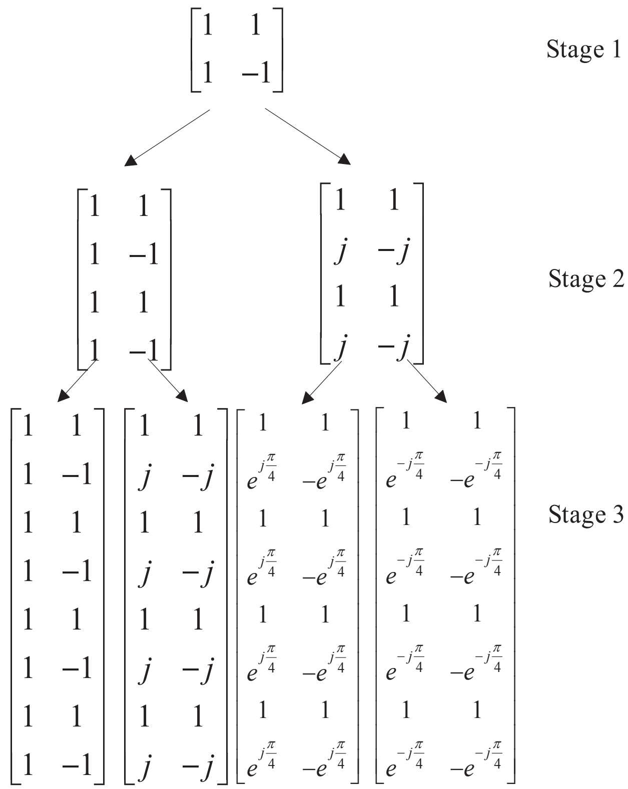

Fig. 5. 3 stages codebook for 8 ULA

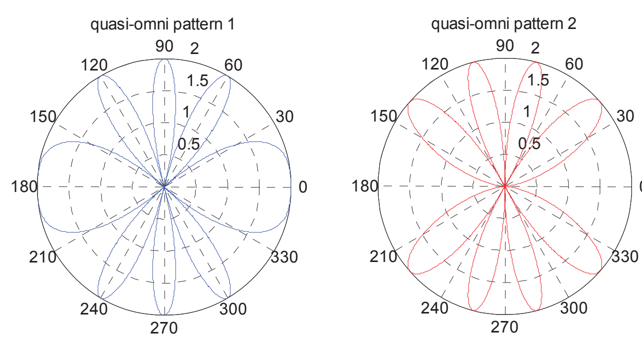

Fig. 6. quasi-omni patterns of ULA8

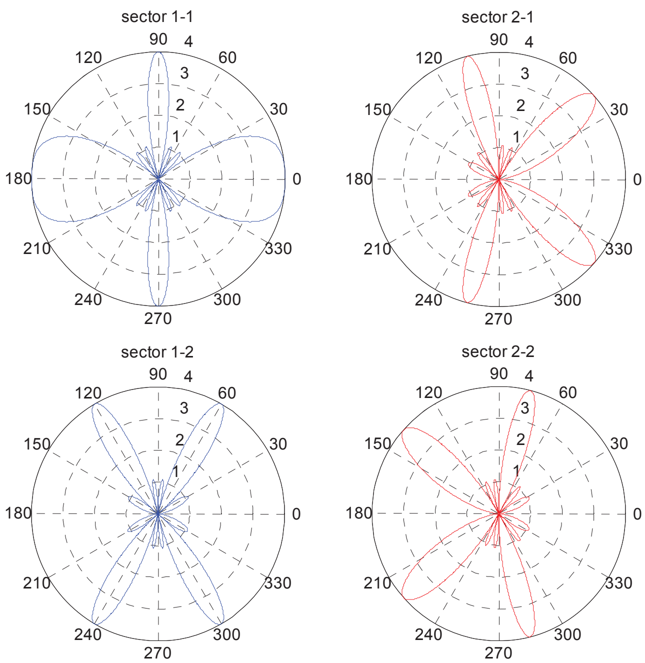

Fig. 7. sector patterns of ULA8

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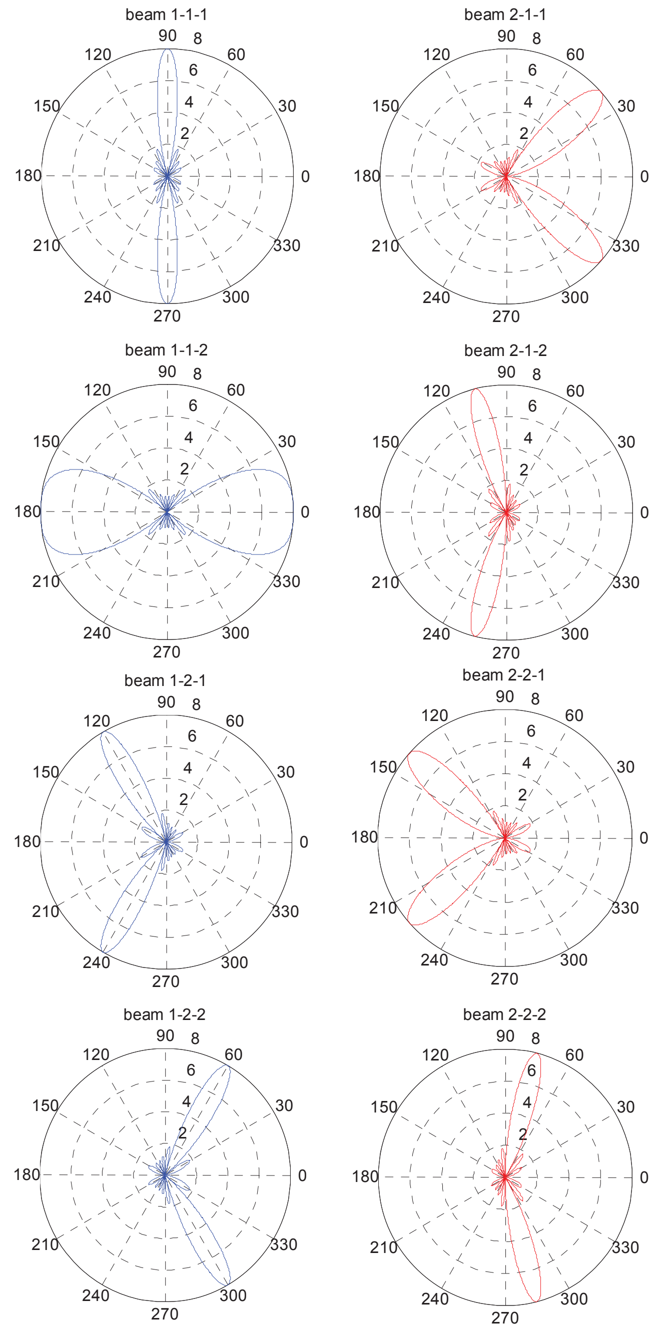

Fig. 8. beam patterns of ULA8