Beamforming Weight Vectors Designing for 60 GHz Wireless Communication Systems

Forgin Harlad Komba, Xu Pingping, Chu Hongyun
(National Mobile Communications Research Lab, Southeast University, NanJing 210096)

Abstract: In this paper, we design codebooks for supporting beamforming in 60 GHz frequency band. The proposed codebooks support both discrete and continuous phase resolution, respectively. The codebooks with discrete resolution were derived following the concept initiated by TG3c in IEEE 802.15.3c standard while the codebook with continuous resolution is based on Kaiser-Bessel windowing function. The designed codebooks give weight vectors that have reasonable level of side lobe and can be used in 60 GHz systems employing analog and digital phase shifters. The codebooks were created by considering the main features of linear array such as array gain, side lobe level, directivity loss and half-power beamwidth of the radiation pattern. The simulation results show that the weight vectors of the designed codebooks improve the performance of linear arrays in terms of power of side lobe, directivity loss, and output SNR of beamforming receiver. The designed weight vectors are frequency independent; in this case, they are both applicable in wideband and narrowband beamforming systems.

Keywords: Weight vector; codebook; array gain; beam pattern

0 Introduction

A technological revolution in multimedia has facilitated the development of new multimedia contents such as uncompressed high-definition video files. Unfortunately, uncompressed high-definition video files require up to 1Gbps as the transmission rate. However, the current wireless standards such as ultra wideband, Wi-Fi and Bluetooth support data rate less than 1Gbps [1]. To overcome this phenomenon, most researchers suggested the application of phased antenna array with the combination of MIMO and beamforming techniques to be the candidates that can deliver high date rate for supporting the emerging multimedia contents in 60 GHz frequency band [2, 3].

A frequency band near 60 GHz is referred to as millimeter wavelength (57GHz-66GHz). Nowadays, the 60 GHz band has received much attention in Wireless Personal Area Networks (WPANs) due to its vast unlicensed bandwidth that provide ultra high data transmission rate. Another important reason for using Millimeter-Wave Radio for WPANs is the small coverage distance related to millimeter wavelength radio wave which leads to higher spatial re-use. Waves with a high frequency have small wavelength. Since the physical antenna size is in orders of the wavelength, the transceiver antennas system will also be small than one of a lower-frequency system. This feature enables the transceivers to be equipped with multiple antenna elements for boosting data rate in indoor wireless communications via 60 GHz [4].

In order to utilize the 60 GHz band efficiently, smart antennas are regarded as a key technology for supporting beamforming in mmWave frequency band. A smart antenna consists of an array of elements connected to a digital signal processor in a specific geometry; such architecture enhances the capacity of a radio link through the combination of diversity gain, array gain, and interference mitigation. They can also be interpreted as a beamformer; beamforming means the application of weight vector to the inputs of an array of antennas to focus the reception of the array in a given direction, called the look direction [5]. This paper discusses the antenna weight vectors generated by 2-bit codebook under TG3c and the designed weight vectors of

Brief author introduction: Forgin Harlad Komba, Male, Master degree candidate, 60GHz mmWave WPANs.
Correspondance author: Xu Pingping, (1957-), female, Processor, wsn and mmWave wireless communication. E-mail: xpp@seu.edu.cn

codebooks in this work. The performance evaluation of the weight vectors was analyzed based on maximum gain of beam patterns, side lobe level, half-power beamwidth, output SNR and magnitude of beamformed signal Y of each beam pattern in the corresponding codebooks.

1 Fixed Weight Beamforming

Fixed weights beamforming involves the use of the pre-defined beamforming weight vectors to compensate the transmission effects of the signal at the receiving array. As indicated in *figure 1;* w_1, w_2….w_M are antenna weights forming a weight vector K for elements 1, 2...M, the length of this vector depends on the number of array elements in a linear array. The approach of using pre-defined antenna weight vectors for beamforming in 60 GHz frequency band is termed as beam-switching beamforming. In this case both transmitter and receiver employ a pool of pre-defined beam patterns or weight vectors; this pool is called a codebook [6, 7]. A codebook is a matrix where each column specifies the beam former vector at the transmitter or combiner vector at the receiver to be used, each column also point to a specific direction. The set of columns standing for the beam patterns span the entire space, which is 360^0, and the numbers of rows specify the number of antenna elements in a linear array. The transmitter-receiver beam pattern pair that optimizes a certain cost function is exhaustively searched during beamforming according to agreed criterion [8, 9]. In this work, we have used output SNR (Signal to Noise Ratio) of beamforming receiver as a metric parameter to elaborate the mechanism of beam-switching process.

We assume the plane wave X with $\eta[n]$ as noise and interference terms is impinging a beamforming receiver with a linear array that has M elements as shown in *figure 1. In figure 1*, $X = s[n] + \eta[n]$, and $s[n]$ is the signal component of X which has no noise, h represents multiple copies of signal $s[n]$ at the receiving array.

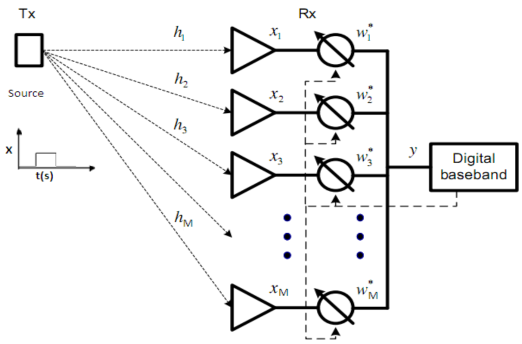

Fig. 1 Phased array beamforming receiver model

And the corresponding output SNR at the beamforming receiver is expressed mathematically in *equation 1*.

$$SNR_{out} = \frac{E\{|y_s[n]|^2\}}{E\{|y_\eta[n]|^2\}} == \frac{E\{w^H s[n] s^H[n] w\}}{E\{w^H s[n] s^H[n] w\}} = 10\log_{10}\left(\frac{w^H R_s w}{w^H R_\eta w}\right) \tag{1}$$

Where, E is the expectation operator; H is the transpose operator, y_s is the beamformer output signal, y_η beamformer noise, w array weights, R_s is the correlation matrix for signal $s[n]$ and R_η is the correlation matrix for noise $\eta[n]$.

1.1 Uniform linear arrays for 60 GHz frequency band and related parameters

A uniform linear array is an array with antenna elements arranged along a line with fixed separation. The antenna elements of a uniform linear array operating in 60 GHz frequency band are separated by a fixed distance ($d = \lambda / 2$), where $\lambda = 5mm$. A uniform linear array of interest is shown in figure 2. It has 4 antenna elements located on the horizontal axis with uniform spacing set to d. The origin of the local coordinate system is the phase center of the array. Its elements are located along the *y*-axis. In this phenomenon, the *y*-axis is referred to as the array axis as in *figure 2*. The elements along the y-axis are isotropic and symmetric with the respect to the phase center of the linear array.

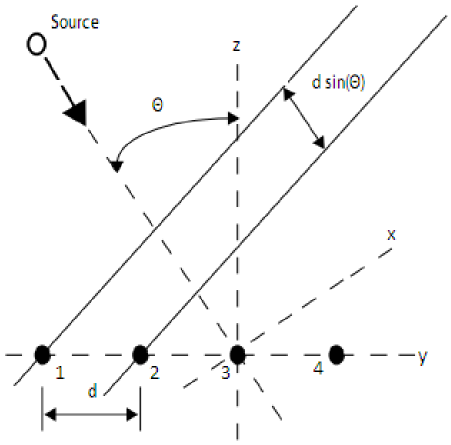

Fig. 2 A geometric illustration of linear array with 4 elements positioned at $(0,y_n,0)$, where n=1,2,3,4.

The following are the essential parameters that characterize the linear arrays operating 60 GHz frequency band:

• **Steering Vector**: A steering vector represents relative phase shifts or set of phase delay for the incident far-field waveform across the array elements. It's also known as array propagation or manifold vector given in equation 2.

$$v = \sum_{-(M-1)/2}^{(M-1)/2} e^{-j2\pi n(d/\lambda)\sin\theta_0} \tag{2}$$

Where v is the steering vector, n is the numbering of antenna elements relative to the center of the array, M is the total number of elements of an array, d is the antenna elements spacing and λ is the wavelength at 60 GHz and θ_0 is the steering angle or AOA

• **Array Factor**: The array factor depicts the spatial response of antenna array in space. From the spatial response, one can exploit necessary parameters that are useful for evaluating the performance of an array; such parameters include the array directivity, the power of sidelobe, and half-power beamwidth of radiation patterns and maximum gain direction of beam pattern. The array factor for one dimension uniform linear arrays (figure 2) generated by the k-th weight vector in the codebook is given in equation 3.

$$AF(\theta) = \sum_{m=0}^{M-1} w_m \times \sum_{n=-(M-1)/2}^{(M-1)/2} e^{j2\pi n(d/\lambda)\sin\theta} \tag{3}$$

Where w_m is the antenna weight of k-th weight vector for M ($0 < m < M-1$) elements of an array, k is the weight vector or a given column in a codebook ($0 < k < K-1$), K is the available beam patterns or weight vectors in the codebook, and θ is the polar angle. The beam patterns or array radiation pattern presented in this work are based on the principle of pattern multiplication given in equation 4.

$$Array\ \ beam\ pattern = EP(\theta) \times AF(\theta) \tag{4}$$

Herein,

$$EP(\theta) = \sum_{-(M-1)/2}^{(M-1)/2} e^{j2\pi n(d/\lambda)\cos\theta_0} \tag{5}$$

Where $EP(\theta)$ is the array element pattern. It represents the pattern of individual array element, θ is a polar angle and $AF(\theta)$ is the array factor.

- **Antenna Weights**: The antenna weights are phase shifts that are used to control side lobe and eradicate the propagation effects of signal at the receiving array. Antenna weights can take either discrete or continuous values. The weights of antenna elements in an array play an important role in spatial filtering. The chosen weights determine the spatial filtering characteristics of the array of a given geometry. In communication systems, signals impinging the receiving array from a particular direction usually are not aligned (not in phase).Therefore, the weights at the receiving array are used to introduce appropriate phase shift and alignment to signals out of each element before are being summed to form a beam formed signal Y. In order to align the signals impinging the array, a narrowband beamformer applies the antenna weights (phase shifts) to a signal received at each antenna element. Due to phase shifting the signals received at each antenna element are made to seem as if they arrive at the receiving array at the same time.

1.2 Discrete resolution codebooks

In this work, we have developed a multiresolution n-bit codebook that can generate various antenna weight vectors using discrete phase resolution for supporting beamforming in 60 GHz. In n-bit codebook, the appropriate weight vectors for beamforming are created only by considering discrete phase resolution (e.g. 5.625^0, 11.25^0, 22.5^0, 45^0, and 90^0). Here, the value of n represents the number of bit of digital phase shifters. The n-bit codebook is represented mathematically in equation 6.

$$W(m,k) = j^{\frac{((m-1)\times(k-1)-K/2)}{\beta/4}} \tag{6}$$

Where β stands for the number of phase states, K ($0 \le k \le K-1$) is the total number of beam patterns in the codebook, and M ($0 \le m \le M-1$) represents the total number of elements in a linear array.

Deploying the model in equation 6 in phase shift beamformers with linear array, not only all beam patterns would reach the maximum gain but also optimal beamforming weight vectors can be created in all directions. The 2-bit codebook proposed in IEEE 802.15.3c [6, 7] can't achieve maximum gains in some directions; its optimal performance holds for a small linear array with both K and M limited to 4 or less than. To resolve this problem adaptive beamforming receivers have gained much attention to mitigate the barriers accompanied with the 2-bit beam codebook. Frankly speaking, the design of adaptive beamforming receivers is not feasible due to the cost of the implementation and complexity [10]. Table 1 summarizes the codebooks that can be generated using the multiresolution n-bit codebook in equation 6.

Tab. 1 Multiresolution n-bit codebook

$\beta = 2^n$	Codebooks parameters	codebooks category	Phase resolution	Phase shifter
4, n=2	M=2 or 4, K=4	2-bit codebook	90^0	2 bits
8, n=3	M=4 or 8, K=8	3-bit codebook	45^0	3 bits
16, n=4	M=8 or 16, K=16	4-bit codebook	22.5^0	4 bits
32, n=5	M=16 or 32, K=32	5-bit codebook	11.25^0	5 bits

1.3 Continuous resolution codebook

A proposed continuous resolution codebook bases the on conception of Kaiser-Bessel weighting function. It gives antenna weights whose beam patterns have the lowest power of side lobe compared to beam patterns generated using discrete resolution codebooks. These beam patterns work well with continuous phase shifting to provide unlimited resolution in communication systems that involve bulk phase shifting like the phased arrays in radar systems. The continuous resolution codebook is given in equation 9.

$$W(m,k) = w(m) \times j^{(\frac{m \times k}{K/4})} \tag{9}$$

Herein,

$$w(m) = kaiser(m,\alpha) \tag{10}$$

$w(m)$ is the Kaiser-Bessel window function, α is the parameter that determines trade-off between the peak height of the side lobe and the beamwidth of the main lobe. The value of α can be chosen to achieve a certain level of performance. Most conventional weighting functions available in the literature can only give one set of weight vector. In this case, the same weight vector is used to generate a beam pattern that is steered in one or multiple directions [11]. With equation 9, we can create different beam patterns from different weight vectors that are steerable in different directions with controllable power of side lobe and beamwidth.

2 Simulation results and analysis

Simulation results presented in this paper were conducted by using Matlab Phased Array Toolbox (R2011b) to set-up an algorithm for creating antenna weights, the simulation of radiation patterns of the linear array and narrowband phase shift beamforming receiver. The simulation results mainly focus on discrete resolution codebooks, 2-bit codebook (IEEE 802.15.3c) and the 3-bit codebook proposed in this work. The demonstration are provided for the case when n = 3 for 3-bit codebook which uses 45^0 as phase resolution. The detailed performance comparison between 2-bit codebook [7] and our 3-bit codebook are provided and illustrated.

2.1 A linear array with 4 elements and 8 beam patterns

This section compares array spatial response of 2-bit codebook, 3-bit codebook $\beta = 8$ and that of modified Kaiser-Bessel weighting function in *equation 9* using an array with M=4 and K=8, *figures 3, 4* and *5* show the performance of beam patterns for all 3 cases. In *figure 3*, the beam patterns designed based on continuous resolution scenario gives side lobe with lower power than the beam patterns based on discrete resolution *in figure 4* and *5*.

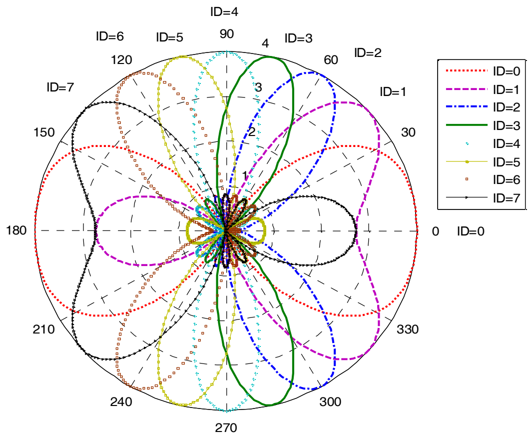

Fig. 3 Radiation pattern of modified Kaiser-Bessel function (M=4, K=8, $\alpha = 1$)

According to *figure 4*, with 2-bit codebook some beam patterns can't attain the maximum gain due to limited phase shifts per antenna element. This situation can be realized when the number of beam patterns increases beyond 4. Appropriate beam pattern can't be created in some directions since only 4 phase shifts (0^0, 90^0, 180^0 and 270^0) are available per element in an array using this 2-bit codebook. Authors in [6] suggest the numbers of beam patterns to be twice the number of array elements as the method to mitigate gain loss; such scenario enhances side lobe. With 2-bit codebook, if the array grows the power of side lobe tends to rise drastically because its optimal performance holds for an array with 4 elements and 4 patterns. Practically, such array is not suitable for supporting high data rate in 60 GHz frequency band due to its limited gain.

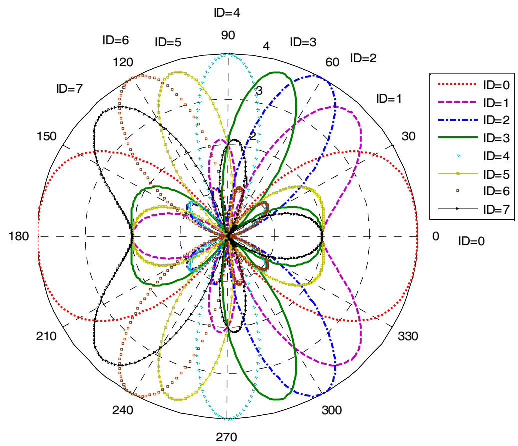

Fig. 4 Radiation patterns of 2-bit codebook with M=4 and K=8.

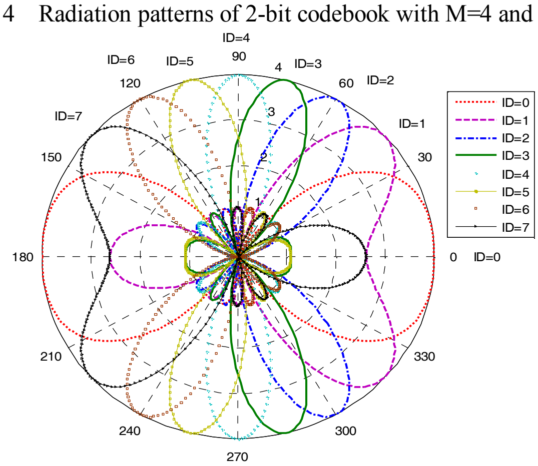

Fig. 5 Radiation patterns of 3-bit codebook with M=4 and K=8.

In *figure 5*, all 8 beam patterns can reach maximum gain because 3-bit codebook provides 8 phase shifts per element (0^0, 45^0, 90^0, 135^0, 180^0, 225^0, 270^0 and 315^0).

2.2 A linear array with M=8 and K=8

Figure 6 illustrates the radiation patterns of the 2-bit and 3-bit codebook for a linear array with M=8 and K=8. It's noticeable that the beam patterns of the 2-bit codebook have higher side lobe level and loss in directivity than its counterpart. The high power of side lobe and the loss in directivity are due to the fact that the appropriate weight vectors (antenna weights) can't be created in these directions because of the absence of phase shifts for these directions in 2-bit codebook especially at 45^0, 135^0, 225^0, and 315^0.

Tab. 2 Performance of 2-bit and 3-bit codebook using directivity and side lobe as metrics for a linear array with M=8 and K=8.

Beam IDs	θ_{max}	Directivity(dB) 2-bit	Directivity(dB) 3-bit	Sidelobe 2-bit(dB)
0	0^0	**9.03**	**9.03**	1.47
1	40^0	8.55	**9.03**	**5.12**
2	60^0	**9.03**	**9.03**	2.59
3	75^0	8.55	**9.03**	**3.03**
4	90^0	**9.03**	**9.03**	2.33
5	108^0	8.55	**9.03**	**3.91**
6	120^0	**9.03**	**9.03**	2.59
7	135^0	8.55	**9.03**	**5.26**

In both cases, the target area of 360^0 is covered by 8 beam patterns using 8 antenna elements. The maximum gain for this array is $10\times\log_{10}(8)=9.03dBi$. Applying 3-bit codebook to this linear array (K=8 and M=8); the maximum gain can be attained in arbitrary direction with minimum level of side lobe. The 2-bit codebook (IEEE 802.15.3c) wouldn't attain the maximum gain in all directions because of reduction in directivity ((9.03-8.55) dB = 0.48dB) at some angles. It can lead into gain loss of about 0.48dB in some directions. The maximum gain directions (θ_{max}) and half-power beamwidth for the two codebooks are slightly different, the beam patterns in directions $0^0/180^0$, $60^0/300^0$, $90^0/270^0$ and $270^0/90^0$ are perfectly aligned with similar maximum power.

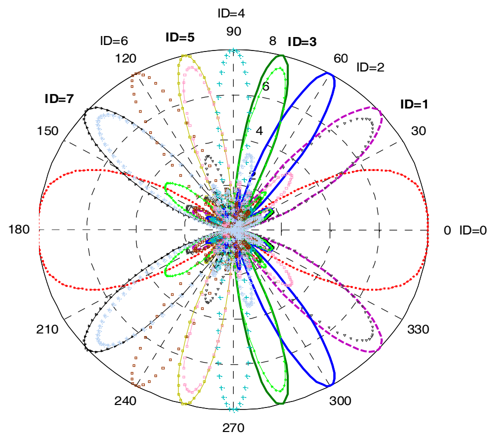

Fig. 6 The radiation patterns of 2 and 3-bit codebooks for M=8, K=8.

From the analysis provided *in table 2* and *figure 6*, we concluded that the beam patterns which can't reach the maximum required gain also tend to have high power of side lobe. In 2-bit codebook the power of side lobe experienced by beam patterns is not uniform. Under the same situation, in 3-bit codebook the power of side lobe for all beam patterns is even and uniform (2.22dB). This is due to the presence of all phase states at each antenna element in this array when the 3-bit codebook is in use.

2.3 Output SNR of Narrowband beamformer

This part contains numerical values of beamformer output SNR computed using all weight vectors from the two codebooks (2-bit and 3-bit codebooks) at a time. It's assumed that signals impinge the beamforming receiver from the directions that the beam patterns point as in table 3. The weight vectors from the codebooks were manually selected to compute beamformer output SNR in angles of arrival pointed by beam patterns. In this case of maximum SNR beamforming receiver, both identically distributed (i.i.d) noise and interferers were considered.

Tab. 3 Summarizes the performance of narrowband beamformer Rx with 2 and 3 bit-codebook using SNR output (dB) as metric (M=8 and K=8)

Pattern ID	θ_{max} (AOA)	2-bit codebook SNR(dB)	3-bit codebook SNR(dB)
0	0^0	29.53	29.53
1	40^o	38.24	38.90
2	60^o	38.99	38.99
3	75^o	38.29	38.99
4	90^o	39.00	39.00
5	108^o	37.20	38.21
6	120^o	38.99	38.99
7	135^o	37.87	38.46

A plane wave sent by the transmitter (as in figure 1) is assumed to impinge the receiving array, interferers and noise terms were considered. The antenna weights generated by 2-bit and 3-bit codebooks with 8 elements (M) and 8 beam patterns (K) in space to cover an area of 360^0 were used to create a linear array of a maximum SNR beamforming receiver as shown in figure 2.4.Table3 describes the process of beam patterns searching when SNR is used as a parameter of interest. In most cases, a beamformer that bases on maximizing output SNR employs special training mechanisms to track down the AOA of the signal of interest. When this angle is known; the weight vector or beam pattern that provides higher value of SNR than the rest in the direction of AOA in the codebook (pool of weight vectors) gets selected. According to the results in table 3, one can see that the beam pattern of 2-bit codebook that have low gain and high power of side lobe also have low value of output SNR compared to beam pattern in 3-bit codebook. Furthermore the beam patterns in 2-bit codebook that can't attain the maximum gain tend to reduce the magnitude of the received signal Y (beamformed signal) at beamformer output after signals at each element are weighted and summed (*figure 7*). The values of SNR in *table 3* vary according to power of noise, angle of arrival of signals, antenna weights and interferer.

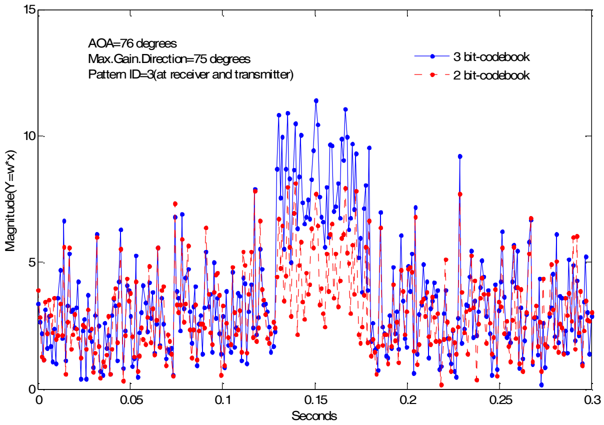

Fig. 7 Beamformed signal Y at AOA=76^0 with pattern ID=3 (M=8 and K=8)

3 Conclusion and suggestions

The investigation performed on the simulation results signified that, the phased linear arrays employing predefined antenna weight vectors in 60 GHz frequency band would give optimal performance if and only if the numbers of weight vectors in the codebook and antenna elements in an array are equal to the number of phase states of the phase shifter in use as specified in table 1. However, that cannot be accomplished with the 2-bit codebook (TG3c) because its phase resolution is constant and limited to 90^0. Due to this reason, a proposed multiresolution n-bit codebook can be used to provide high degree of flexibility for linear arrays operating in 60 GHz. Introducing equivalence among the aforementioned parameters, not only side lobe and gain loss in maximum gain directions will be improved but also the appropriate weight vectors would be formed in arbitrary direction. The application of 60 GHz band for short range communications might be feasible if antenna can reach high gain of about 9Bb to 15dB in an arbitrary direction using at least 3-bit phase shifter to provide satisfactory scanning capability. Array of 8 or 16 antenna elements with appropriate weight vectors and very simple digital phase shifters will give the needed performance for a 1Gbps wireless link at 60GHz in CMOS.

Acknowledgements

This work is supported by Chinese National High Tech. (863) Plan with Grant No.2011AA010201, National ST Major Project of China (N0.2011ZX03005-002) and the Research Fund of NCRL, Southeast University (N0.2012A03).

References

[1] Singh, H., Oh, J., Kweon, C.Y., Qin, X., Shao, H.-R., and Ngo, C.A 60GHz wireless network for enabling uncompressed video communication[J] IEEE Com.Mag, 2008, 46(12)：71-78.
[2] R. Hardacker.Method and System for Multiple 60 GHz System Antennae[P]. U.S. 20060160489, Jul. 20, 2006.
[3] S. K. Yong and C. C. Chong. An Overview of Multi-Gigabit Wireless Through Millimeter Wave Technology: Potentials and Technical Challenges[J]. EURASIP J. Wireless Commun. Net, 2007.
[4] Maltsev, A.; Maslennikov, R.; Sevastyanov, A.; Lomayev, A.; Khoryaev, A.; Davydov, A.; Ssorin, V. Characteristics of indoor millimeter-wave channel at 60 GHz in application to perspective WLAN system[Z]. Barcelona: Proceedings of the Fourth European Conference on Publication, 2010.
[5] II Leon W. Couch. Digital and Analog Communication Systems[M]. NJ,USA: Prentice Hall PTR,Upper Saddle River, 2000.
[6] J. Wang, Z. Lan, C. Pyo, C. Sum, T. Baykas, J. Gao, A. Rahman, R Funada, F. Kojima, H. Harada, S. Kato. Beamforming Codebook Design and Performance Evaluation for Millimeter-wave WPAN[Z]. Anchorage, USA: IEEE VTC 2009, Sep. 20 -23, 2009.
[7] IEEE Standards 802.15.3c,Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs)[S].

[8] J. Wang, Z. Lan, C. Pyo, T. Baykas, C. Sum, A. Rahman, R. Funada,F. Kojima, I. Lakkis, H. Harada and S. Kato. Beam Codebook Based Beamforming Protocol for Multi-Gbps Millimeter-Wave WPAN Systems[Z]. Hawaii, USA: IEEE Globecom 2009, Nov.31-Dec.4, 2009.

[9] Hyun-Ho Lee, Young-Chai Ko. Low Complexity Codebook-Based Beamforming for MIMO-OFDM Systems in Millimeter-Wave WPAN[J]. IEEE Transactions on Wireless Communications, 2011, 10(11): 3607-3612.

[10] C.-S. Choi, M. Elkhouly, E. Grass, and J. C. Scheytt. 60-GHz adaptive beamforming receiver arrays for interference mitigation[Z]. Istanbul, Turkey: IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), sept. 2010.

[11] Y. Yorozu, F. Gross. Smart antennas for wireless communication[M]. US: McGrawHills, 2007.

60GHz 无线通信系统波束形成的权重矢量设计

付京，徐平平，褚宏云

（东南大学移动通信国家重点实验室，南京 210096）

摘要：本文提出了一种支持 60GHz 频段波束成形的码本. 设计的码本支持离散和连续相位精度.离散精度的码本基于 TG3c 提出的 IEEE 802.15.3c 标准中的码本权重概念，而连续精度的凯塞贝塞尔窗函数。设计的码本的权重矢量可以得到合理的旁瓣等级并且可用于采用模拟和数字相位偏移的 60GHz 系统。提出的码本考虑了线性阵列的主要特性，如阵列增益、旁瓣等级、定向损耗和辐射图的半功率带宽。仿真结果表明设计的码本的权重矢量改进了线性阵列在旁瓣功率、定向损耗和波束形成接收机的输出信噪比。设计的权重矢量与频率无关，所以设计的码本可以应用到宽带和窄带波束形成系统中。

关键词：权重矢量；码本；阵列增益；波束图

中图分类号：TN928