Performance Analysis of Quantized TxBF for SC System in mm-Wave MIMO WLAN

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***Abstract*—Transmit beamforming (TxBF) is always used in closed-loop wireless communication system to improve system performance and suppress spatial interference. Different from orthogonal frequency division multiplexing (OFDM) modulation, single carrier (SC) modulation in IEEE 802.11aj (45GHz) is implemented in time domain, so TxBF should be applied differently. This paper describes a quantized TxBF scheme for SC system in IEEE 802.11aj (45GHz), which is based on singular value decomposition (SVD) and Givens rotation. In order to reduce feedback amount, we also present two feedback methods, including subchannel clustering feedback (SCF) which depends on average information of V matrices for each clustering and subchannel interval feedback (SIF) which only gives feedback of interval V matrices. Based on the correlation of frequency domain subchannels, subchannel correlation based segment interpolation algorithm (SCSIA) is proposed to optimize SIF. We evaluate the performance of TxBF in this paper. TxBF with few feedback bits improves packet error rate (PER) performance greatly, and these two feedback methods reduce feedback overhead significantly.**

***Index Terms*—Quantized TxBF, SC modulation, Feedback, Segment interpolation, Subchannel correlation**

I. Introduction

The scarcity of spectrum resources becomes a serious problem in recent years. In order to satisfy spectrum demand, millimeter-wave wireless communication has drawn wide attention in academic and industry. The fifth generation mobile communication and the next generation wireless local area network (WLAN) are both trying to exploit millimeter wave frequency band. For example, IEEE 802.11ad wireless local area network standard, aiming to realize indoor wireless communication at 60GHz frequency band, is released in 2012 [1]. In China, IEEE 802.11aj (45GHz) is being studied, which focuses on the WLAN communication on the large space frequency band between 42GHz and 49GHz.

Different from directional antenna array technology in IEEE 802.11ad, IEEE 802.11aj (45GHz) intends to adopt Multiple-Input Multiple-Output (MIMO) antennas technology, which is known as mm-wave MIMO. IEEE 802.11aj (45GHz) standard will support two modulation models, including orthogonal frequency division multiplexing (OFDM) modulation and single carrier (SC) modulation. However, the problems brought by the combination of SC modulation and mm-MIMO, such as transmit beamforming (TxBF), are still needed to be solved.

Transmit beamforming is an effective scheme to improve performance and suppress interference [2]. Many TxBF methods have been proposed in recent years, such as TxBF with limited feedback, TxBF with CSI matrix feedback, TxBF with beamforming steering matrix feedback and so on [2–5]. Cellular network communication always leverage limited feedback to realize TxBF [2]. IEEE 802.11n has two feedback schemes, explicit feedback and implicit feedback [6]. But only compressed beamforming steering matrix (V matrix) feedback is used to implement TxBF IEEE 802.11ac [7, 8]. V matrix feedback is an classic and achievable scheme, which has also been considered as an optional technology for the OFDM system in IEEE 802.11aj (45GHz). The receiver can get V matrices by sigular value decomposition (SVD) of the estimated channel matrices and compress them by Givens rotation and angle quantization [6–8]. Through the feedback mechanism, the information of V matrix can be known by transmitter [7]. Then transmitter use all V matrices to precode every data streams.

For SC system, baseband signal is processed in time domain, so the realization for TxBF become very difficult. In this paper, we describe a quantized TxBF scheme for SC system by frequency domain signal processing. Subchannel clustering feedback (SCF) is presented to reduce feedback amount of V matrices. In order to compensate the performance loss caused by SCF, this paper also proposes a subchannel interval feedback (SIF) method and an subchannel correlation based segment interpolation algorithm (SCSIA).

This paper is organized as follows. Section II describes SC system model and quantized TxBF. In Section III, SCF, SIF and SCSIA are introduced. Numerical simulation results are presented in Section IV. And conclusions are summarized in Section V.

Notation: A^* denotes the conjugate transpose matrix of A matrix, A^T denotes the transpose matrix of A matrix, $|a|$ denotes the absolute value of a, $\lfloor a \rfloor$ denotes the largest integer no smaller than a, $\tilde{a}$ denotes the estimated value of a.

II. System Model and Quantized TxBF

A. System Model

IEEE 802.11aj (45GHz) WLAN standard will support multiple spatial streams and MIMO technology, so multiplexing gain and diversity gain can be acquired for SC system. The transmitter block diagram is shown in Fig. 1, where precoding should be finished in spatial mapping module.

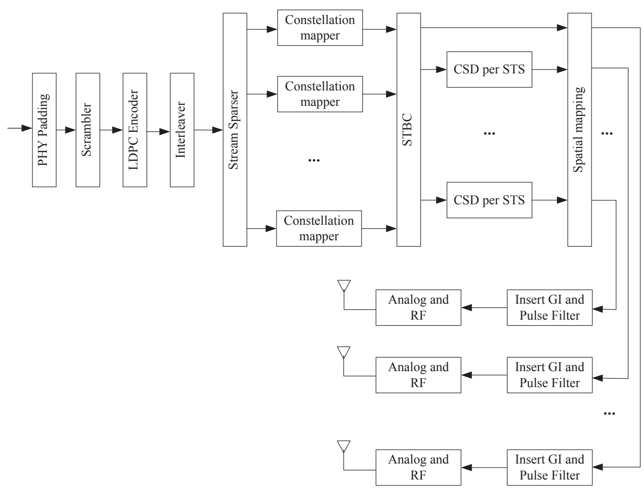

Fig. 1: Transmitter block diagram for SC system

In Fig. 1, the baseband signal at transmitter in SC system is processed in time domain, so in order to precode data streams in frequency domain, a FFT module and an IFFT module are added in spatial mapping module, which is shown in Fig. 2. In this paper, MMSE frequency domain equalization (FDE) is adopted at receiver, presented in Fig. 2. Actually, the FFT module and IFFT module of an access point/station (AP/STA) can be a part of FDE if the user is receiver or a part of spatial mapping if the AP/STA is transmitter. Therefore, TxBF does not bring any overhead to SC-FDE system.

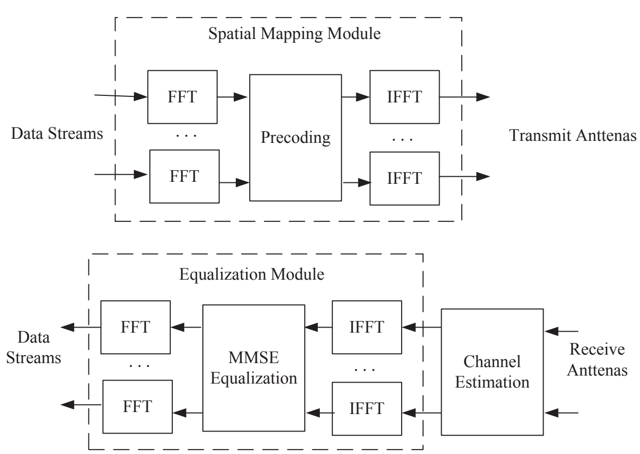

Fig. 2: Simplified processing modules for TxBF

Through the description above, the system model can be formulated by

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{V}\boldsymbol{x} + \boldsymbol{n} \tag{1}$$

where $\boldsymbol{H}$ denotes the frequency domain channel, $\boldsymbol{V}$ denotes the precoding matrix, $\boldsymbol{x}$ and $\boldsymbol{y}$ denote the transmit signal and receive signal respectively, $\boldsymbol{n}$ denotes the frequency domain noise and interference.

B. Quantized TxBF

Suppose that SC-MIMO system has N_T transmit antennas and N_R receive antennas, where $N_T \geq N_R$. Channel matrix H with N_R rows and N_T columns for each subchannel could be obtained at channel estimation module. Then, the receiver should follow the steps in Fig. 3. The specific steps is described as follows.

Firstly, get V matrix by SVD. H matrix for each subchannel can be decomposed into three matrix by SVD [6, 7]. The expression is

$$H_k = U_k S_k V_k^* \tag{2}$$

where U_k and V_k denote unitary matrices for the kth suchannel whose sizes are $N_R \times N_R$ and $N_T \times N_T$, S_k denotes an diagonal matrix whose size is $N_R \times N_T$ for the kth suchannel, k satisfies $0 \leq k \leq N_f - 1$, N_f is the number of subchannels.

Secondly, use Givens rotation to get angle information about V matrix. The formula of Givens rotation can be expressed as

$$\begin{bmatrix} cos\,(\psi) & sin\,(\psi) \\ -sin\,(\psi) & cos\,(\psi) \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} y \\ 0 \end{bmatrix} \tag{3}$$

where we can get

$$\psi = arccos\left(\frac{x_1}{\sqrt{x_1^2 + x_2^2}}\right) \tag{4}$$

Thus, V_k can be decomposed as

$$V = \tilde{D} \prod_{i=1}^{\min(N_R, N_T - 1)} \left[D_i \prod_{j=i+1}^{N_T} G_{ji}^T\left(\psi_{j,i}\right) \right] \times \tilde{I}_{N_T \times N_R} \tag{5}$$

where G_{ji} is the Givens rotation matrix to nullify the (j, i)th entry and can be represented by the angle $\psi_{j,i}$, D_i is the diagonal rotation matrix to remove the imaginary parts from the ith column, and can be represented by the angles $\phi_{i+1,i}, ..., \phi_{N_T-1,i}$, $\tilde{I}_{N_T \times N_R}$ is an identity matrix with extra rows filled with zero.

Finally, quantize each ψ and ϕ. The quantization formula for each ϕ is

$$\phi = \pi\left(\frac{1}{2^{N_\phi}} + \frac{k_\phi}{2^{N_{\phi-1}}}\right) \tag{6}$$

where $k_\phi = 0, 1, ..., 2^{N_\phi - 1}$, N_ϕ denotes the number of bits to quantize each ϕ. The quantization formula for each ϕ is

$$\psi = \pi\left(\frac{1}{2^{N_{\psi+2}}} + \frac{k_\psi}{2^{N_{\psi+1}}}\right) \tag{7}$$

where $k_\psi = 0, 1, ..., 2^{N_\psi - 1}$, N_ψ denotes the number of bits to quantize each ψ.

After receiving the feedback information which represents V matrices, the transmitter can retrieve V matrices and use them to implement TxBF. In this scheme, the total feedback amount is

$$N_{total} = N_f N_a (N_\phi + N_\psi)/2 \tag{8}$$

where N_a is the number of angles which should be quantized.

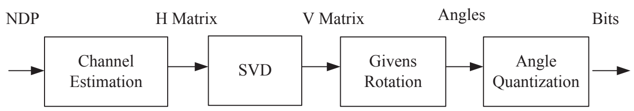

Fig. 3: Procedure for quantized TxBF

III. SCF, SIF AND SCSIA

A. Subchannel Clustering Feedback (SCF)

Through the descriptions above, we can find that the overhead brought by feedback is enormous in this TxBF scheme because of the large number of subchannels. Some methods have been proposed to reduce feedback amount in wireless communication, for example, subcarriers grouping in WLAN-OFDM system [9]. Thus, SCF is illustrated in this subsection.

In SCF, frequency domain channel is divided into N_{clust} subchannel clusterings and each clustering will have N_g subchannels, which is presented in Fig. 4. N_g should be a divider for N_f. For each clustering, average H matrix will be estimated in channel estimation module, the formula can be expressed as

$$\tilde{H}_m = \frac{1}{N_g}\sum\nolimits_{n=1}^{N_g} \tilde{H}_{m,n} \tag{9}$$

where $\tilde{H}_m$ denotes the average estimated H matrix for the ith clustering, $\tilde{H}_{m,n}$ is the estimated H matrix for the (i, j)th subchannel, $0 \le m \le N_{clust} - 1$ and $0 \le n \le N_g - 1$. After the processing programs in Fig. 3, the information bits representing for average V matrix of one channel clustering are obtained. At transmitter, spatial mapping can using average V matrix instead to precode frequency symbols in the corresponding subchannel clustering.

when SCF is used in system, the feedback amount can be reduced to

$$N'_{total} = N_{clust} N_a (N_\phi + N_\psi)/2 \tag{10}$$

where $N_{clust} = N_f/N_g$. Therefore, the feedback amount for SCF is only $1/N_g$ of that for all subchannels feedback.

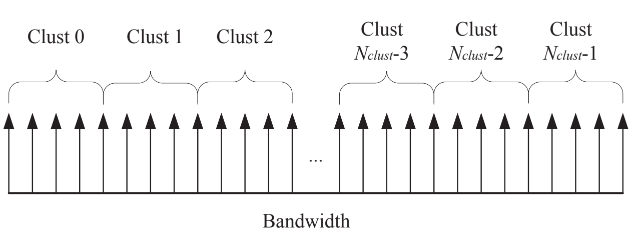

Fig. 4: subchannel clustering for quantized TxBF

B. Subchannel Interval Feedback (SIF) and Subchannel Correlation based Segment Interpolation Algorithm (SCSIA)

Although SCF can reduce the feedback amount for the quantized TxBF, but it will lead to performance loss, especially when N_g is a larger number. So we discuss SIF in this subsection, which is kind of like subcarrier grouping in OFDM system in IEEE 802.11ac [7]. In SCF, the feedback information is the average V matrix corresponding to average H matrix for one subchannel clustering, but in SIF, only some V matrices for corresponding subchannels are fedback. These subchannel indexes are $0, N_g, ..., (N_{clust} - 1)N_g, N_f - 1$. There are still N_{clust} channel clusterings.

In this method, different interpolation algorithm can be adopted at transmitter. In [10, 11], linear interpolation algorithms are presented to reconstruct all V matrices. Besides, in IEEE 802.11aj (45GHz), neighboring frequency domain subchannels has strong correlation. Therefore, basing on linear interpolation and subchannel correlation, SCSIA can be realized as follows.

Step 1: calculate subchannel correlation coefficient $|\rho|(0 \le |\rho| \le 1)$. The formula is

$$\begin{aligned} |\rho_{\Delta k}| &= \frac{\sum_{Ti=0}^{N_T-1} |\rho_{\Delta k, Ti, Ri}|}{N_T N_R} \\ &= \frac{\sum_{Ti=0}^{N_T-1} \sum_{Ri=0}^{N_R-1} |E\left\{H_{k+\Delta k, Ti, Ri} H^*_{k, Ti, Ri}\right\}|}{N_T N_R} \end{aligned} \tag{11}$$

where $k(0 \le k \le N_f - 1)$ is the subchannel index, Δk is the subchannel interval, Ti and Ri are the transmit antenna index and receive antenna index respectively. Since multiple paths of time domain channel are independent, for each Ti and Ri, $\rho_{\Delta k, Ti, Ri}$ can be expressed as

$$\begin{aligned} \rho_{\Delta k, Ti.Ri} &= E\left\{H_{k+\Delta k, Ti, Ri} H^*_{k, Ti, Ri}\right\} \\ &= \sum_{l=0}^{L} \sigma^2_{l, Ti, Ri} e^{-j2\pi\tau_l \Delta f \Delta k} \end{aligned} \tag{12}$$

where $\sigma^2_{l,Ti,Ri}$ denotes the power for the lth path from transmit antenna Ti to receive transmit antenna Ri, τ_l denotes the multipath delay for the lth path, $\Delta f = 1/T_S$, T_S is the time length of one symbol block.

Step 2: set up correlation reference coefficient $\rho_{ref}\,(0 \le \rho_{ref} \le 1)$ and calculate the reference number of subchannels for one channel segment M_{ref}. ρ_{ref} should be large enough to ensure that all the subchannels in the channel segment have strong correlation. In this paper, ρ_{ref} satisfies $\rho_{ref} \ge 1/2$ and M satisfies

$$\rho_{M_{ref}} \ge \rho_{ref} \ge \rho_{M_{ref}+1} \tag{13}$$

where $\rho_{M_{ref}}$ and $\rho_{M_{ref}+1}$ are the correlation coefficient values when subchannel intervals are M_{ref} and $M_{ref} + 1$, respectively.

Step 3: calculate the number of subchannel clusterings N_s for one channel segment. The formula can be described as

$$N_s = \lfloor \frac{M_{ref}}{N_g} \rfloor \tag{14}$$

Then, we can get the number of subchannels M for one channel segment, which equal to $N_s N_g$. If $N_f/N_s N_g$ is not an integer, the last channel segment would have $N'_s = N_f/N_g - N_s \lfloor N_f/N_s N_g \rfloor$ subchannel clusterings. In this paper, N_g is a divider of N_f, so N_f/N_g is an integer.

Step 4: do interpolation for each segment. First, subchannel N_f is defined, and $V(N_f = V_{N_f-1}$, where V_{N_f-1} has to been fedback to transmitter, because it is the last subchannel. Then, if N_f/N_sN_g is a integer, the interpolation formula is

$$V_k = \sum_{n=i_s}^{N_s+i_s} \prod_{m=i_s,m\neq n}^{N_s+i_s} \frac{(k-mN_g)}{(n-m)\,N_g} V_{nN_g} \tag{15}$$

where $i_s\,(0 \leq i_s \leq N_f/N_sN_g - 1)$ is the channel segment index, V_k is the V matrix for the kth subchannel; if N_f/N_sN_g is not an integer, the formula for channel segment $0, 1, ..., \lfloor N_f/N_sN_g \rfloor - 1$ is the same as formula 14, but the formula for the last channel segment is

$$V_k = \sum_{n=i_s}^{N_s'+i_s} \prod_{m=i_s,m\neq n}^{N_s'+i_s} \frac{(k-mN_g)}{(n-m)\,N_g} V_{nN_g} \tag{16}$$

Step 5: normalize all V matrices. Each column of the interpolated V matrix is normalized in order to ensure the unitarity of precoding matrix.

Through the description above, we can find that SCSIA is an adaptive interpolation, which can use subchannel correlation to change N_s and guarantee the accuracy of interpolation algorithm. SCSIA also makes SIF more effective, so transmitter can leverage the most useful information to do TxBF. The complexity of SCSIA will decrease when ρ_{ref} and N_g become larger.

IV. Simulation Results

In this paper, numerical simulations are performed to demonstrate the effectiveness of the quantized TxBF scheme. Only two antenna configure scenarios, including 2x1 for single space-time stream and 4x2 for two space-time streams, are considered in our simulations. There are 256 data symbols for each block and the cyclic prefix is 64 symbols, which is enough for eliminating inter-symbol interference. In the spatial mapping module and channel equalization module, the number of points used for IFFT and FFT is 256. The discrete channel model has 9 taps and multipath delay τ is 1.152ns for all paths. The noise adds to the system model has zero mean and unit variance. MMSE detection is applied at receiver, and perfect channel is used instead of estimated channel. The other simulation parameters are shown in TABLE 2.

TABLE I: Simulation Parameters

Parameters	Packet length	channel realizations	LDPC code length	Code rate	Band width
Values	4096 bytes	5000	672	1/2	540 MHz

In this section, we first compare the performance of STBC, spatial extending (SE), single-input single-output(SISO) and TxBF scheme with different modulation schemes. Then, the performance of quantized TxBF with different quantized bits are analyzed. Finally, we evaluate the performance of SCF, SIF and SCSIA. The STBC scheme adopted in our simulations is the same scheme in [12], but it is realized in time domain. The spatial extending matrix is $Q_{2\times 1}$ for single stream and $Q_{4\times 2}$ for two streams, where cyclic shift is performed in time domain [7]. $Q_{2\times 1}$ and $Q_{4\times 2}$ are

$$Q_{2\times 1} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -128T_C \end{bmatrix} \tag{17}$$

$$Q_{4\times 2} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ -64T_C & 0 \\ 0 & -64T_C \end{bmatrix} \tag{18}$$

where T_C equal to the multipath delay τ.

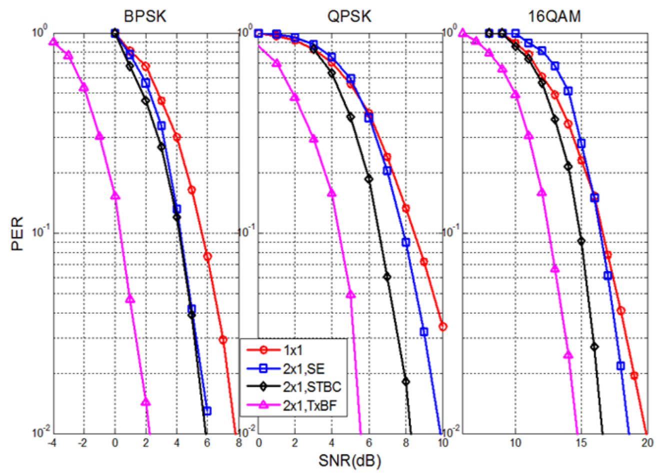

Fig. 5: PER performance with different schemes (2x1)

Fig. 5 presents the performance of STBC, SE, SISO and TxBF scheme. The TxBF scheme uses the perfect V matrix, which does not be decomposed and quantized. When modulation order is BPSK, TxBF outperforms STBC and SE about 4 dB and there is more than 5dB gain compared with SISO. This is because the interference between different antennas can be eliminated when use V matrix to precode transmit signal and multiple transmit antennas bring diversity gain for system. Besides, the simulation results also indicate that the performance improvement became smaller with modulation order increasing. The performance of the proposed TxBF illustrates that TxBF should be applied to SC system in IEEE 802.11aj (45GHz).

A. Quantized TxBF simulation results

In Fig. 6 and Fig. 7, six kinds of quantized values are used to simulate. The results demonstrate that [3,1] quantized bits for $[\psi, \phi]$ angle lead to 1dB-3dB performance loss. Fig. 6 shows that the performance with [5,3] quantized bits is close to the performance with perfect V matrix feedback when antenna configure is 2x1. And Fig. 7 presents that [6,4] bits for angle quantization are enough for our quantized TxBF scheme. The simulation results indicate that with the quantized bits increasing, the performance loss brought by quantization becomes smaller. All these illustrate that quantized TxBF with few bits for each angle perform well

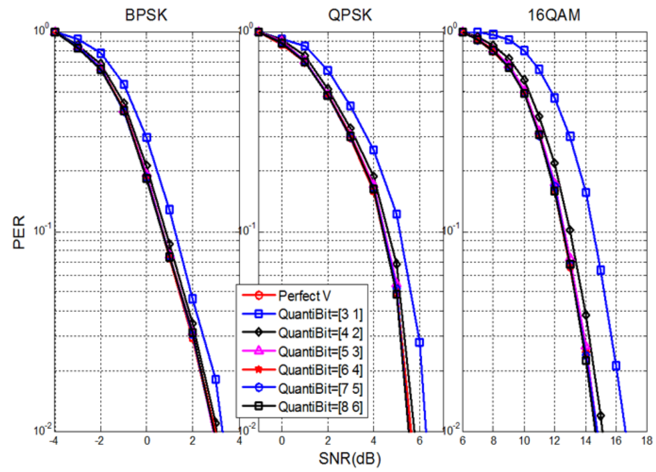

Fig. 6: PER performance with different quantized bits (2x1)

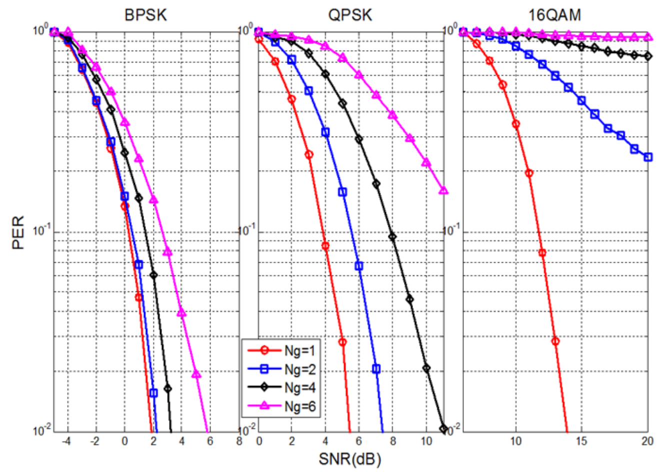

Fig. 8: PER performance for SCF with different N_g (2x1)

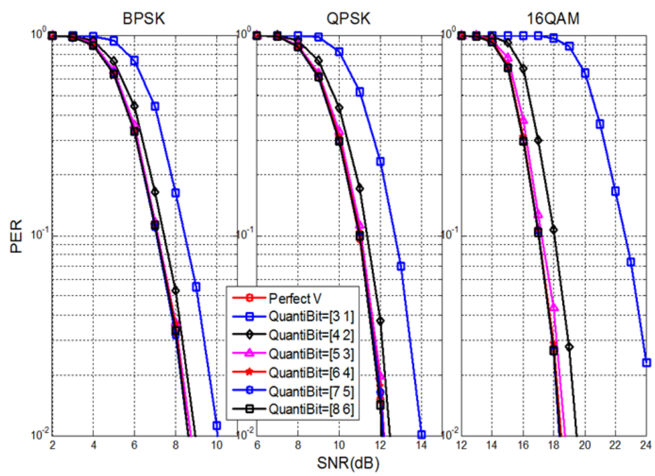

Fig. 7: PER Performance with Different Quantized Bits (4x2)

B. SCF,SIF and SCSIA Simulation Results

The performance are compared with different N_g, so that a best SCF scheme can be adopted to SC system. Only $Ng = 1, 2, 4, 6$ are simulated when SCF is applied to the system. The SC system adopts perfect V matrix feedback, and no quantization is used to SCF. $N_g = 1$ denotes the perfect feedback for all V matrices. The antenna configure is 2×1.

Fig. 8 shows that SCF leads to large performance loss compared with all V matrices feedback. There are 2.5dB performance loss for $N_g = 6$ when modulation order is BPSK and 1.6dB loss for $N_g = 2$ when QPSK is adopted for system. SCF should not be supported for 16QAM. Compared with STBC above, we can get the conclusion that SCF could support $N_g = 2, 4, 6$ for BPSK and $N_g = 2$ for QPSK. To a certain extent, SCF is a good option for quantized TxBF.

Fig. 9 shows the correlation coefficient for the antenna configure 4×2. When SIF and SCSIA are applied to the system, assume $\rho_{ref} = 0.95$ and $N_g = 4$, then by formula(13), we can get $N_s = 2$. So the number of channel segments is 32. At transmitter, we can reconstruct all V matrices by the formula (7).

Fig. 10 presents the performance of SIF and SCSIA. Compared with SCF, there is 1dB performance gain, when modulation scheme is BPSK. With the modulation order increasing, the performance improvement become smaller. The simulation results also illustrate SIF and SCSIA are good schemes for SC quantized TxBF.

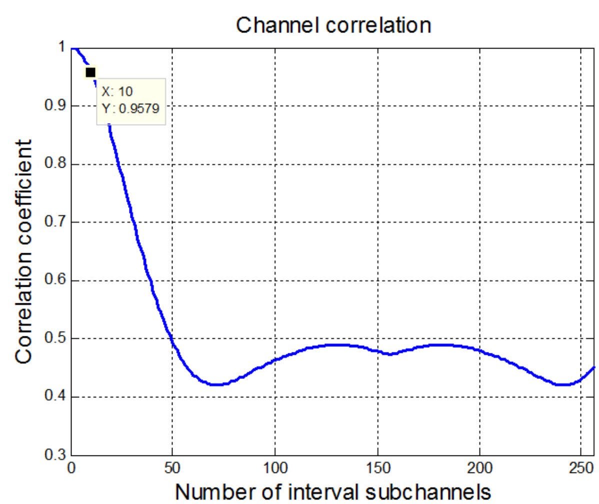

Fig. 9: Subchannel correlation coefficient (4x2)

V. Conclusions

This paper evaluated the proposed TxBF scheme for SC system in next generation mm-MIMO WLAN through numerical simulations. This scheme adopts time-frequency domain signal transformation to precode signal in frequency domain. SVD and angle quantization are used to realize TxBF. The proposed quantized TxBF outperforms STBC and SE. Different quantized bits lead to different performance loss compared with

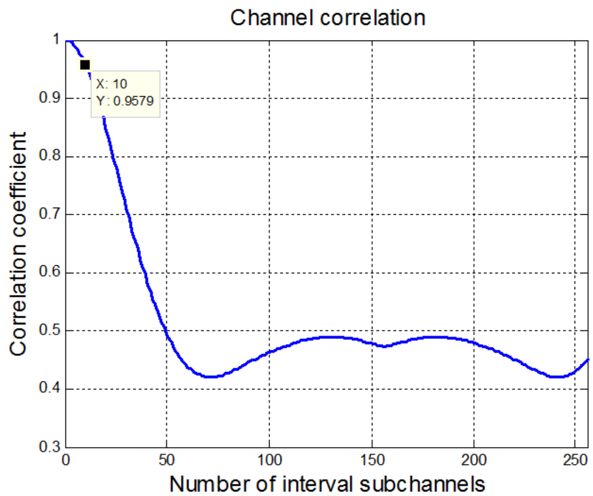

Fig. 10: PER performance for SIF and SCSIA (4x2)

perfect V matrix feedback. With the increasing of feedback amount, the performance will be gradually closer to perfect V matrix feedback. In this paper, SCF was proposed to reduce the feedback amount brought by quantization. And in order to compensate the performance loss caused by SCF, SIF and SCSIA were presented. The combination of SIF and SCSIA perform much better than SCF. Quantized TxBF can be an optional technology for SC system in IEEE 802.11aj (45GHz) and other wireless communication standards.

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