Performance Analysis of Directional Modulation with Finite-quantized RF Phase Shifters in Analog Beamforming Structure

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Abstract—The radio frequency (RF) phase shifter with finite quantization bits in analog beamforming (AB) structure forms quantization error (QE) and results in a performance loss of receive signal to interference and noise ratio (SINR) at Bob. By using the law of large numbers in probability theory, the closed-form expression of SINR performance loss is derived to be inversely proportional to the square of sinc function. Here, a phase alignment method is applied in directional modulation transmitter with AB structure. Also, the secrecy rate (SR) expression is derived with QE. From numerical simulation results, we find that the SINR performance loss gradually decreases as the number $L$ of quantization bits increases. This loss is less than 0.3dB when $L$ is larger than or equal to 3. As $L$ exceeds 5, the SINR performance loss at Bob can be approximately trivial. Similarly, compared to the SR with infinite-precision phase quantizer, the corresponding SR performance loss gradually reduces as $L$ increases. In particular, the SR performance loss is about 0.1 bits/s/Hz for $L \approx 3$ at signal-to-noise ratio $\approx 15$dB.

Index Terms—Directional modulation, quantization error, quantized phase shifter, analog beamforming.

I. INTRODUCTION

DIRECTIONAL modulation (DM), as the key technology of wireless physical layer security, is attracting ever-increasing research interests and activities from both academia and industry world. Traditional technology for directional modulation is proposed on the radio frequency (RF) frontend [1]–[3]. In these literature, the authors proposed an actively driven DM array of utilizing analog RF phase shifters or antenna elements, which lacked the flexibility of design process. Another way to implement the DM synthesis is based on the baseband signal processing. In [4], the authors proposed to form an orthogonal vector, which can be updated in the null space of channel vector at the desired direction, to the transmitted baseband signal as artificial noise (AN), thereby improving the secure transmission. Compared with the design on the RF frontend, this approach enables dynamic DM transmissions and makes the design easier.

In the presence of direction measurement error, the authors in [5], [6] and [7] proposed three robust DM synthesis methods for three different scenarios: single-desired user, multi-user broadcasting and multi-user MIMO by fully exploiting the statistical properties of direction measurement error. In [8], the authors proposed two secure schemes, Max-GRP plus NSP and Max-SLNR plus Max-ANLNR, for multicast DM scenario to improve the security. Secure and precise wireless transmission (SPWT) proposed in [9] combined AN projection, beamforming and random subcarrier selection based on OFDM to achieve SPWT of confidential messages. In previous work as mentioned, the DM synthesis on the baseband signal processing is under the condition of known perfect or imperfect channel state information (CSI). In [10], the authors proposed three DOA estimators based on hybrid structure for finding direction, thereby determining the position. This method makes DM more practical in the coming future.

In [5], [6], and [7], the authors proposed robust methods for imperfect CSI in traditional DM systems, i.e, fully-digital (FD) beamforming systems. Traditional fully-digital beamforming technique is of high cost and power consumption due to each antenna element requiring one dedicated RF chain. Hybrid analog/digital (HAD) beamforming structure [11]–[13] with analog phase shifters and a reduced number of RF chains was proposed to strike a good balance between the system complexity and the beamforming precision. Compared with HAD and FD beamforming structures, analog beamforming (AB) structure with digitally-controlled phase shifters have attracted substantial research attentions from both industry and academic worlds, due to its lowest circuit cost and high energy efficiency [14]–[17]. In general, AB structure has only single RF chain linked to all antennas. However, AB as described in [15], [17] is subject to additional constraints, for example, the digitally-controlled phase shifters with finite-quantized phase values and constant-envelope. Here, due to finite-quantized phase values, there exists quantization error (QE). This type of error will lead to a performance loss such as SINR and SR. It is crucial to derive and analyze the impact of QE on SINR and SR due to the accuracy of quantization of phase shifter. To achieve an allowable performance loss, what is the minimum number of quantization bits compared with infinite-bit quantization (no QE, NQE)? In what follows, we will address this issue.

In this paper, we will mainly make an analysis of the effect of QE from finite-quantized phase shifters on the performance of DM system using AB structure. Here, the transmitter...
Alice is equipped with an AB structure, while the desired receiver at Bob works in full-duplex model and helps Alice by transmitting AN with fully-digital beamforming structure to degrade the performance of the illegitimate receiver at Eve. The main contributions of this paper are summarized as follows:

1) In AB structure, the RF phase shifter usually has finite quantization bits. This will result in a receive SINR performance loss at Bob. What is the approximate expression of the SINR performance loss? By using the law of large numbers in probability theory, the approximate closed-form expression of SINR performance loss is derived to be inversely proportional to the square of sinc function. This will greatly simplify the analysis of how many bits is sufficient such that the SINR performance loss can be omitted in the AB structure.

2) From simulation results, it follows that this approximate expression holds even for a small-scale number of transmit antennas at Alice. Additionally, we also find an important result that the SINR performance loss is less than 0.3dB when the number $L$ of quantization bits is larger than or equal to 3. As the number of quantization bits exceeds 4, the SINR performance loss at Bob can be completely omitted.

3) In the presence of QEs, the expression of secrecy rate is also derived and simplified. Simulation results indicate that the SR performance loss is about 0.1 bits/s/Hz when $L = 3$. More importantly, as the value of $L$ increases, the SR performance loss decreases gradually and monotonically. Thus, we can make a conclusion that $L \geq 3$ is a reasonable choice for RF phase quantizer in AB structure.

The remainder of this paper is organized as follows. Section II describes the system model. In Section III the expression of SINR loss is derived by modeling quantization error as a uniform distribution, and at the same time the corresponding SR expression is given in the presence of QE. Simulation results are presented in Section IV. Finally, we make our conclusions in Section V.

Notations: throughout the paper, matrices, vectors, and scalars are denoted by letters of bold upper case, bold lower case, and lower case, respectively. Signs $(\cdot)^{T}$, $(\cdot)^{H}$ and $|\cdot|$ denote transpose, conjugate transpose, and modulus respectively. Notation $E\{\cdot\}$ stands for the expectation operation.

II. System Model

We consider a DM network with a Gaussian wiretap channel in Fig. I where Alice is equipped with $N_{a}$ antennas, Bob is equipped with $N_{b}$ antennas, and Eve is equipped with single antenna. Alice intends to send its confidential message $x$ to Bob, without being wiretapped by Eve. The DM transmitter at Alice adopts an AB structure. This means Alice can send single confidential message stream to Bob by analog beamforming due to only one RF chain. In order to help Alice, Bob operates in a FD mode. In other words, all antennas at Bob are partitioned into two subsets. The first subset of antennas with $N_{b}^{f}$ antennas transmits AN $z$, and the second one with $N_{b}^{t} = N_{b} - N_{b}^{f}$ antennas receives confidential messages from Alice. It is supposed $N_{b}^{t} = 1$ so that Bob owns single antenna to receive as Eve. Since Bob transmits AN while receiving the desired signal, there always exists self-interference at its own receive signal. To describe the effect of residual self-interference we employ the loop interference model of [18], which quantifies the level of self-interference with a parameter $\rho \in [0, 1]$, with $\rho = 0$ denoting zero self-interference. In this paper, we assume there exists the line-of-sight (LOS) path. The transmit signal at Alice and AN at Bob can be respectively written as

$$s_{a} = \sqrt{P_{a}}v_{a}x,$$  \hspace{1cm} (1)

and

$$s_{b} = \sqrt{P_{b}}v_{b}z,$$  \hspace{1cm} (2)

where $P_{a}$ and $P_{b}$ are the transmission powers of Alice and Bob, respectively. Vector

$$v_{a}(\alpha) = \frac{1}{\sqrt{N_{a}}} \left[ e^{j\alpha_{1}}, e^{j\alpha_{2}}, \ldots, e^{j\alpha_{N_{a}}} \right]^{T}$$  \hspace{1cm} (3)

denotes the transmit analog beamforming vector, which forces the confidential message to the desired direction and $v_{b} \in \mathbb{C}^{N_{b} \times 1}$ is the beamforming vector of transmitting AN to interfere with Eve. An AB pattern is generated by a digitally-controlled RF phase-shifter with $L$-bit phase quantizer. This means that each antenna’s phase in (3) takes one nearest value $\hat{\alpha}_{n}$ to the designed value $\alpha_{n}$ from a set of $2^{L}$ quantized phases given by

$$\hat{\alpha}_{n} \in \Theta = \left\{ 0, 2\pi(\frac{1}{2^{L}}), 2\pi(\frac{2}{2^{L}}), \ldots, 2\pi(\frac{2L-1}{2^{L}}) \right\},$$  \hspace{1cm} (4)

which is actually an integer optimization problem. Therefore, the beamforming vector in the AB system is defined with the quantized phases $\alpha_{n}$ and written as $\Theta$. Each phase element is quantized to $L$ bits. In $\Theta$, $x$ is the confidential message of satisfying $E\{x^{H}x\} = 1$. We assume that the AN $z$ transmitted by Bob obeys a Gaussian distribution with zero mean and $E\{z^{H}z\} = 1$.

Taking the path loss into consideration, the signal received at Bob and Eve can be respectively written as

$$y_{b} = \sqrt{g_{ab}h_{ab}^{H}(\theta_{a})}s_{a} + \sqrt{h_{bb}^{H}}n_{b} + n_{b}$$  \hspace{1cm} (5)

$$= \sqrt{g_{ab}P_{a}h_{ab}^{H}(\theta_{a})}v_{a}x + \sqrt{\rho P_{b}h_{bb}^{H}}v_{b}z + n_{b},$$

and

$$y_{c} = \sqrt{g_{ae}h_{ae}^{H}(\theta_{a})}s_{a} + \sqrt{g_{be}h_{be}^{H}}n_{b} + n_{e}$$  \hspace{1cm} (6)

$$= \sqrt{g_{ae}P_{a}h_{ae}^{H}(\theta_{a})}v_{a}x + \sqrt{g_{be}P_{b}h_{be}^{H}}v_{b}z + n_{e},$$

where $g_{ab} = \frac{2}{d_{ab}}$ and $d_{ab}$ denote the loss coefficient and distance between Alice and Bob respectively. $c$ is the path loss exponent and $\epsilon$ is the attenuation at reference distance $d_{0}$. Likewise, $g_{ae} = \frac{2}{d_{ae}}$ and $d_{ae}$ denote the loss coefficient and distance between Alice and Eve, respectively. $g_{be} = \frac{2}{d_{be}}$ and $d_{be}$ denote the loss coefficient and distance between Bob and Eve, respectively. $n_{b} \sim \mathcal{C}\mathcal{N}(0, \sigma_{b}^{2})$ and $n_{c} \sim \mathcal{C}\mathcal{N}(0, \sigma_{e}^{2})$ represent complex additive white Gaussian noise (AWGN) at Bob and Eve, respectively. $h_{ab} \in \mathbb{C}^{N_{a} \times 1}$ denotes the channel...
vector from Alice to Bob, $h_{ac} \in \mathbb{C}^{N_a \times 1}$ and $h_{bc} \in \mathbb{C}^{N_b \times 1}$ denote the channel vectors from Alice and Bob to Eve, respectively. $h_{bb} \in \mathbb{C}^{N_b \times 1}$ represents the self-interference channel vector at Bob. In the following, we assume that $\sigma_b^2 = \sigma_c^2$.

In Fig. 1, the transmitter is deployed with an $N_a$-element linear antenna array. The normalized steering vector (NSV) for the transmit antenna array is denoted by

$$h(\theta) = \left[ e^{j2\pi \Psi_\theta(1)}, \cdots, e^{j2\pi \Psi_\theta(n)}, \cdots, e^{j2\pi \Psi_\theta(N_a)} \right]^T, \quad (7)$$

and the phase function $\Psi_\theta(n)$ is defined as

$$\Psi_\theta(n) = \frac{(n - (N_a + 1)/2)d \cos \theta}{\lambda}, \quad n = 1, 2, \cdots, N_a, \quad (8)$$

where $\theta$ is the direction angle, $n$ denotes the $n$-th antenna, $d$ is the distance of two adjacent antennas, and $\lambda$ is the wavelength. Making use of the definition of NSV, we have $h_{ab}(\theta_d) = h(\theta_d)$ and $h_{ac}(\theta_c) = h(\theta_c)$.

If the beamforming vector $v_a$ is determined, the optimal $v_b$ can be solved by using the Max-SR method [19] and utilizing the GPI algorithm [20].

III. DERIVATION OF SINR AND SR PERFORMANCE LOSS EXPRESSIONS

In this paper, we focus on the influence of quantization error of the phase shifter on SINR and SR performance, which will cause phase mismatch between the NSV $h$ and the AB vector even with ideal measurement of direction. This will degrade the receive performance at Bob, including the receive channel vector at Bob. In the following, we assume that $\hat{\alpha}_n \in \Theta$ is the quantized value of $\alpha_n$ after $\alpha_n$ passes through the corresponding phase quantizer. In the above model, the quantization error $\Delta\alpha_n$ is approximated as a uniform distribution and its probability density function (PDF) is given by

$$p(\Delta\alpha_n) = \begin{cases} \frac{1}{2\Delta\alpha_{max}}, & \Delta\alpha_n \in [-\Delta\alpha_{max}, \Delta\alpha_{max}], \\ 0, & \text{otherwise}, \end{cases} \quad (10)$$

with

$$\Delta\alpha_{max} = \frac{\pi}{2T}, \quad (11)$$

where $L$ is the number of quantization bits.

A. Derivation of SINR Loss due to finite-bit quantization

Given the presdesigned AB vector $v_a(\alpha)$, we have

$$v_a(\hat{\alpha}) = \frac{1}{\sqrt{N_a}} \left[ e^{j\hat{\alpha}_1}, e^{j\hat{\alpha}_2}, \cdots, e^{j\hat{\alpha}_N_a} \right]^T \quad (12)$$

Substituting the above in (11), the RF transmit signal at Alice can be rewritten as

$$s_a(\hat{\alpha}) = \sqrt{P_a} v_a(\hat{\alpha}) x. \quad (13)$$

In this case, the corresponding receive signals at Bob and Eve can be respectively written as

$$y_b(\hat{\alpha}) = g_{bb} h_{bb}^H(\theta_d) s_a(\hat{\alpha}) + \sqrt{P_b} h_{bb}^H s_b + n_b$$

$$= g_{bb} P_a h_{ac}^H(\theta_d) v_a(\hat{\alpha}) x + \sqrt{P_b} h_{bc}^H s_b + n_b,$$

and

$$y_e(\hat{\alpha}) = g_{ee} h_{ee}^H(\theta_e) s_a(\hat{\alpha}) + \sqrt{g_{be} P_e} h_{be}^H s_b + n_e$$

$$= g_{ae} P_a h_{ac}^H(\theta_e) v_a(\hat{\alpha}) x + \sqrt{g_{be} P_e} h_{be}^H s_b + n_e.$$

Suppose that the ideal desired directional angle $\theta_d$ is available, then we have

$$\alpha_n = 2\pi \Psi_\theta(n), \quad \hat{\alpha}_n = 2\pi \Psi_{\hat{\theta}_d}(n) + \Delta\alpha_n. \quad (16)$$
Substituting the above two equations in (14) and (15) yield
\[
\mathbf{h}_b^H(\theta_d)\mathbf{v}_a(\alpha) = \left[e^{-j\alpha_1}, e^{-j\alpha_2}, \cdots, e^{-j\alpha_N_a}\right] (17)
\]
\[
\times \frac{1}{\sqrt{N_a}}[e^{j(\alpha_1+\Delta\alpha_1)}, e^{j(\alpha_2+\Delta\alpha_2)},
\cdots, e^{j(\alpha_{N_a}+\Delta\alpha_{N_a})}]^T
\]
\[
= \frac{1}{\sqrt{N_a}} \sum_{n=1}^{N_a} e^{j\Delta\alpha_n},
\]
and
\[
\mathbf{h}_c^H(\theta_c)\mathbf{v}_a(\alpha) = \left[e^{-j\alpha_{ae,1}}, e^{-j\alpha_{ae,2}}, \cdots, e^{-j\alpha_{ae,N_a}}\right] (18)
\]
\[
\times \frac{1}{\sqrt{N_a}}[e^{j(\alpha_{ae,1}+\Delta\alpha_1)}, e^{j(\alpha_{ae,2}+\Delta\alpha_2)},
\cdots, e^{j(\alpha_{ae,N_a}+\Delta\alpha_{N_a})}]^T
\]
\[
= \frac{1}{\sqrt{N_a}} \sum_{n=1}^{N_a} e^{j(\alpha_{ae,n}-\alpha_{ae},+\Delta\alpha_n)},
\]
respectively. In (18), \(\alpha_n\) is determined by (16), \(\alpha_{ae,n}\) can be expressed similarly as (16) with known \(\theta_c, \alpha_{ae,n} = 2\pi \Psi_{\alpha}(n)\).

In (17), \(e^{j\Delta\alpha_i} (i = 1, 2, \cdots, N_a)\) can be viewed as independently identical distributed (iid) random variables, in accordance with the law of large numbers in probability theory, the mean of samples is approximately equal to the mean of the distribution (21). As \(N_a\) tends to medium-scale and large-scale, we have
\[
\frac{1}{N_a} \sum_{n=1}^{N_a} e^{j\Delta\alpha_n} \approx E(e^{j\Delta\alpha_n}), \quad (19)
\]
where
\[
E(e^{j\Delta\alpha_n}) = \int_{-\Delta\alpha_{max}}^{\Delta\alpha_{max}} e^{j\Delta\alpha_n} p(\Delta\alpha_n) d\Delta\alpha_n = \frac{\sin(\Delta\alpha_{max})}{\Delta\alpha_{max}} = \text{sinc}(\frac{\pi}{2\Delta}) \quad (20)
\]
with
\[
\text{sinc}(x) = \frac{\sin(x)}{x}. \quad (21)
\]
Combining (19) and (20) gives
\[
\frac{1}{N_a} \sum_{n=1}^{N_a} e^{j\Delta\alpha_n} \approx \text{sinc}(\frac{\pi}{2\Delta}). \quad (22)
\]

Now, we compute the expression of signal to interference and noise ratio (SINR) at Bob under the QE and NQE conditions, respectively. The former has no quantization error while the latter has quantization error. From the definition of SINR and (14), we have
\[
\text{SINR}^{NQE}_b = \frac{g_{ab}P_b h_b^H(\theta_d) v_a(\alpha)^2}{\rho P_b h_b v_b^2 + \sigma^2}. \quad (23)
\]
IV. Simulation and Discussion

In this section, we mainly focus on the evaluation of influence of the number of antennas and quantization bits of phase shifters on performance losses including SINR, SR, and BER in an AB structure. In our simulation, system parameters are chosen as follows: quadrature phase shift keying (QPSK) modulation, the total transmission power $P_a = P_b = 70\text{dBm}$, the spacing between two adjacent antennas $d = \lambda/2$, $\rho = 0.5$, the distance between Alice and Bob, Alice and Eve, Bob and Eve $d_{ab} = d_{ae} = d_{be} = 500m$, the path loss exponent $c = 2$, the desired direction $\theta_d = \theta_{ab} = 60^\circ$, and the eavesdropping direction $\theta_e = \theta_{ae} = 120^\circ$. The direction angle from Bob to Eve is $\theta_{be} = 45^\circ$. Alice is equipped with $N_a$ antennas, Bob is equipped with $N_b$ antennas to transmit AN and $N_b^r = 1$ to receive confidential signals from Alice.

Fig. 2 demonstrates the performance curves of bit error rate (BER) versus direction angle at Bob with SNR = 10dB and $N_a = 16$. Here, the ideal condition implies NQE with solid line, i.e., infinite bits for quantization, and the QE case is denoted by dotted line. $L$ stands for the number of quantization bits. From this figure, it can be seen that the BER can achieve a good performance in the desired direction while it becomes worse rapidly as we move to the undesired direction. This is partly because the AN transmitted from Bob can interfere with the confidential signal received at Eve severely along the undesired directions. Compared with the performance with NQE, the BER performance with QE is much worse, especially for $L \leq 2$. As $L$ reaches up to 3, the BER performance difference between QE and NQE is trivial. This means that it is feasible in practice to use a finite-quantized phase shifters with $L \approx 3$.

![Fig. 2. Curves of BER versus direction angle under the ideal condition (with NQE) and finite-quantization condition (with QE) for different numbers ($L$) of quantization bits.](image)

![Fig. 3. SINR performance loss at Bob versus number $L$ of quantization bits for different $N_a$.](image)

![Fig. 4. SINR performance loss at Bob versus $N_a$ for different numbers of quantization bits ($L$).](image)

![Fig. 5. Graph showing the performance loss of SINR at Bob versus the number of quantization bits for different numbers of antennas at Alice ($N_a$).](image)

Fig. 3 plots the curves of SINR performance loss versus number $L$ of quantization bits ranging from 1 to 8 for four different numbers of antennas at Alice $N_a : 4, 16, 64, \text{and } 256$, where SNR is equal to 15dB. Here, the derived expression of SINR performance loss in (25) is used as a performance reference. From this figure, it is seen that the performance loss of simulated SINR decreases as the quantization bits increases. This is mainly because that the range of phase error due to quantization (11) will become smaller as the number $L$ of quantization bits increases, so the QE will become smaller. This will result in a smaller loss of SINR at Bob. A small number of quantization bits of the phase shifter (e.g., $L = 1 \text{ or } 2$) will generate a large quantization error, resulting in a large SINR loss up to 4dB. The SINR performance loss will be less than 0.3dB when the number of quantization bits is more than or equal to 3. When the number of quantization bits is 4, the SINR loss at Bob is less than 0.1dB even if the number of antennas at Alice is small (e.g., $N_a = 3$). This also means the fact that even with a small number of antennas at Alice, the derived expression in (25) coincides...
with the simulated SINR performance loss. In other words, the derived expression in (25) can be used to evaluate the SINR performance loss for almost all cases including small-scale, medium-scale, and large-scale. More importantly, we can conclude that three quantization bits are sufficient for the quantized phase shifters in the AB system.

Since we have the approximate derived simple expression for SINR performance loss, Fig. 4 illustrates the curves of the SINR performance loss versus the number \( N_{a} \) of antennas at Alice for three different numbers of quantization bits: 3, 4, and 5, where the SNR is set to be 15dB. From this figure, it is seen that the simulated value of SINR loss gradually tends to the derived value in (25) as the number of antennas at Alice increases. Even in the case of small number of antennas at Alice, the SINR loss difference between simulated and derived is still only about 0.125dB, which is substantially small. This further verifies the validity of the derived expression in (25).

Fig. 5 shows the curves of SR versus number of quantization bits ranging from 1 to 8 for three typical SNRs: 0dB, 15dB, and 30dB, where \( N_{a} = 16 \). From this figure, it is clearly seen that there is a certain loss on SR for the small number of quantization bits, i.e., \( L = 1 \) or 2. Observing this figure, a 3-quantization-bit phase shifters at Alice will lead to a SR performance loss less than 0.1 bits/s/Hz.

Fig. 6 shows the curves of SR versus number of quantization bits for four different numbers of antennas at Alice \( N_{a} = 4, 16, 64, \) and 256 with three typical SNRs: 0dB, 15dB, and 30dB. The solid lines represent the SR in the absence of QE, and the dotted lines represent the SR in the presence of QE for different \( N_{a} \). In this figure, it is evident that three-quantization-bit achieves a SR performance loss of less than 0.1 bits/s/Hz regardless of the number of transmit antennas at Alice.

In summary, there exists QE in the AB structure due to finite-quantized phase shifters, which will result in a substantial performance loss. In general, from the above simulation results and derived SINR performance loss expression as
shown in (25), we find an important fact that 3, 4, and 5 are sufficient for the number of quantization bits on RF phase shifter such that a performance loss due to QE can be neglected. The derived simple expression in (25) can be approximately used to assess the SINR performance loss at Bob. Additionally, this expression also holds for even small number of transmit antennas at Alice although it is derived under the condition that the number of antennas at Alice tends to large-scale. In our view, this expression can be directly applied in the hybrid analog-digital structure to evaluate the SINR loss.

V. Conclusion

In this paper, we have made an investigation of the influence of QE caused by finite-quantized phase shifters of AB structure on performance in DM systems. In the presence of QE, the expression of SINR performance loss is derived to be inversely proportional to the square of sinc function by making use of the law of large numbers in probability theory. From analysis and simulation, we find that our proposed expression is approximately close to the corresponding simulated result even when the number of antennas at Alice is small-scale. The SINR performance loss is lower than 0.3dB when the number of quantization bits is larger than or equal to 3. As for SR, we can obtain the same result. In other words, when the number of quantization bits is larger than or equal to 3, the SR difference between NQE and QE is less than 0.1 bits/s/Hz. Additionally, the BER performance is also shown to be intimately related to the number of quantization bits. A large $L$ means a good BER performance along the desired direction. Otherwise, a small $L$ means a poor BER performance along the desired direction. Considering the derived SINR performance loss holds for small-scale number of antennas at Alice in AB structure, it is very natural to extend it to a HAD beamforming structure with finite-quantized phase shifters in diverse scenarios for future wireless communications.

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