Improving Analog Zero-Forcing Null Depth with N-bit Vector Modulators in Multi-beam Phased Array Systems

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***Abstract*—Multiantenna systems can increase the spatial reuse of the wireless spectrum by nulling the interfering directions. However, the efficiency of the spatial interference suppression is highly sensitive to errors in the progressive phase applied to the antenna elements. We examine the impact of one particular source of error resulting from the quantization of the analog beamforming weights. In particular, we focus on vector-modulator based RF beamforming system. To improve the quantization error, we propose a sliding reference approach for using a floating phase reference minimizing the quantization error of the RF beamformer. Monte-Carlo simulations are performed to analyze the performance of the zero-forcing with quantized coefficients. With small arrays, the simulation results showed almost 10 dB of improvement in the average null depth compared to the conventional round-off method.**

***Index Terms*—Beamforming, beam synthesis, interference cancellation, millimeter-wave, phased array, round-off method, quantization.**

I. Introduction

Multi-antenna systems play a key role in fifth generation (5G) and beyond communication systems targeting for millimeter-wave (mmW) frequencies. It is already well-known that the use of beamforming can improve spectral efficiency, reduce impact multi-path fading, improve bit-error rate, and mitigate co-channel interference. In addition, the mmW radio frequency (RF) electronics have a small form factor that implies inconspicuous integration on small mobile and vehicular platforms. In the practical mmW platforms, the phased antenna array equipped with RF phase shifters is the prevalent approach to electronically steer the beams and null interference. Efficient nulling requires that also amplitudes of the RF beamformers have to be controlled.

Several analog beamforming solutions have been proposed and used with active and passive phase shifters [1]–[3] and voltage controlled amplifiers (VGAs). Passive phase shifters can be used to implement the phase control with a good linearity and accuracy. However, the losses of the passive phase shifters degrade the overall performance of the system causing more need for high gain amplifiers in the transmitter and receiver. Some active solutions in e.g. [1], [4], [5] use a coupled oscillator array to control the relative phases by changing only the free-run frequencies in the array of all coupled oscillators. This strategy appears to be relatively complex to implement in practice, despite of being able to achieve a continuous phase change with theoretical relative maximum phase of $\pm$ 90 degrees.

In the RF integrated circuit (IC) community, the dominant active beamforming solution is to use vector modulator phase shifters (VMPSs) [6]–[9]. Beamforming by using VMPSs has many advantages such as notably improved signal-to-noise-ratio (SNR) during transmission and reception and improved transmitter output power utilization [10]. In addition to the controllable phases, VMPS can also control the amplitude, potentially removing the need of external voltage controlled amplifiers (VGAs) from each RF branch. The performance of the VMPS-based beamforming depends on the number of bits used to describe the control voltages. However, the cost of the VMPS increases excessively with the number of bits which makes high resolution VMPSs difficult to realize in practice.

In multi-user systems, beamforming techniques such as zero-forcing (ZF) [11] and inter-beam interference cancellation (IBIC) [12] can compute the beamforming coefficients according the steering directions to serve a user in the intended direction while minimizing the interference from/to the directions of the other users. However, the RF phase shifters have a finite number of different weights that can be used to realize the beams. Moreover, quantization of the analog beamforming cause small errors for the beamforming coefficients. The quantization errors can increase the sidelobe levels (SLLs), change the direction of the main beam [13], decrease the effective isotropic radiated power (EIRP), and reduce the depth of the nulls. Especially in nulling, even small errors in the coefficients may have significant impact on the ZF performance.

The ideal coefficients can be mapped to the phase shifters states by multiple ways. The reasonable choice of choosing the beamforming weights thus plays a crucial role in the realized beam pattern shape. Since

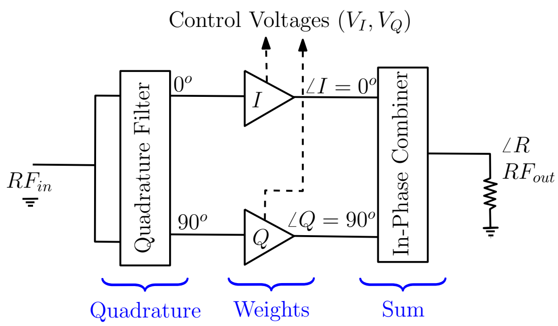


Fig. 1. Principle of a vector modulator based active phase shifter.

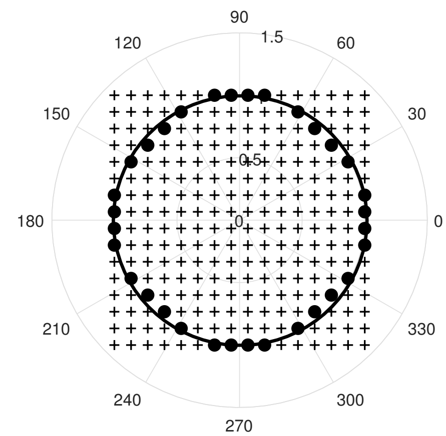


Fig. 2. IQ constellation of a 8-bit vector modulator.

the early days of research in phased arrays, the round-off method has been mostly used to simply map the coefficients to the nearest implementable beamforming weight. The coefficients are mapped by choosing the first antenna as a zero-phase reference and mapping the others according to that. However, rounding change of SLL, causes pointing deviation of the main beam, and decreases the depth of the nulls of the radiation pattern [14]. In fact, increased sidelobes and systematic pointing offset depend on the periodicity of errors due to round-off phase quantization. Thus, in [15]–[17] it is conceptualized that if the mapping of the coefficients is randomized, the periodicity of phase quantization errors would be disrupted and the sidelobe levels are reduced. Usually this is called as "quantization by random process" or simply "random phasing".

In the round-off method, the choice of the reference antenna/phase has impact on the quantization error. In this paper, we (1) study the impact of the quantization to the ZF performance and (2) propose a method to map the beamforming coefficient to the N-bit VMPS by finding the floating reference phase to minimize the Euclidian norm of the residual between the ideal and quantized beamforming weights. It is shown that this can significantly improve the performance especially in low-resolution VMPS-based ZF.

II. Quantization Error of VMPS and its Impact on the Interference Nulling Performance

A. Vector Modulator as a Phase Shifter

The simplified principle of the VMPS is shown in Fig. 1. The VMPS divides the signal to the in-phase (I) and quadrature-phase (Q) components, weight them individually by VGAs, and finally add together to provide a phase shifted version of the input. The resultant vector R can be presented as a phasor whose magnitude is

$$|R| = \sqrt{I^2 + Q^2}, \tag{1}$$

and phase

$$\underline{/R} = \arctan\left(\frac{Q}{I}\right). \tag{2}$$

The VGAs of I and Q paths have digital control with N bits. An example of the VMPS having four bits for both I and Q is depicted in Fig. 2. Thus the total number of control bits is 8. The outermost circle drawn for maximum phase resolution corresponds 32 phase values which makes 5 bits when used as a phase shifter. In this paper, we consider the VMPS as a N-bit vector modulator, where half of the control bits is used for I and half for Q. Thus, instead of using it as a phase shifter, we use it also for controlling the amplitude for shaping the beam pattern.

B. Beamformer Mapping for Quantized VMPS

In general, there are two main ways to think the quantization error in beamforming. One way is to consider the error as a random process and model the quantization as noise. However, in analogue beamforming with continuous wideband RF waveforms in each antenna, the quantization is not necessary behaving like noise. This holds especially with low number of antennas. In addition, considering the quantization error as noise rely on the averaging effect instead of using the achievable beamforming words effectively to serve the purpose. Another way is to consider the quantized beamforming coefficients as fixed weights and try to use them as effectively as possible to provide the desired beam shape. This approach does not consider the quantization as random error but tries to utilize it instead. The mapping can be calculated offline for different scenarios and implemented as a codebook, or the coefficients can be calculated by adaptive algorithms during the operation. In the following, we introduce two mapping methods used in this paper.

1) Round-off Method: The round-off method maps the ideal beamformer simply by rounding the beamformer to the nearest possible value. Usually, the first antenna is chosen to be the reference and the other antennas are mapped according to that. Thus, the quantized coefficients can be calculated as

$$\hat{w}_{qr,i} = \underset{w_{qr,i} \in \mathbb{W}_{\shortparallel}}{\arg\min} |cw_i - w_{qr,i}|, \tag{3}$$

where $\hat{w}_{qr,i}$ denotes the round-off quantized coefficients of antenna i, w_i denotes the ideal coefficient of antenna i, and $w_{qr,i} \in \mathbb{W}_{\shortparallel}$ are the discrete coefficients in the IQ constellation $\mathbb{W}_{\shortparallel}$ of the VMPS. In (3), $\arg()$ denotes the argument of the minimization problem. The normalization coefficient $c \in \mathbb{C}$ is common for all antennas and describes the reference value. Usually in round-off method, it is simply chosen as $c = (w_1)^{-1}$.

2) Modified Round-off with Sliding Reference: Especially with smaller arrays, choosing the reference c value in (3) has impact on the quantization error. In beamforming, the overall beam is generated by the differences over the antennas and thus the ideal beam shape remains the same for all beamformers $c\vec{w}$. Hence, the c can be chosen to reduce the overall quantization error by taking c as additional argument in (3). However, the reference has to be common for all antennas. The minimization of the Euclidian distance between the ideal and quantized beamformer with the sliding reference can be written as

$$\hat{c} = \underset{c \in \mathbb{C}}{\arg\min} \left\| c\vec{w}_i - \vec{w}_{qr} \right\|_2, \tag{4}$$

where $\left\| cw_i - w_{qr} \right\|_2$ denotes the Euclidean distance between the vectors. For each c, the quantized coeffients are calculated to satisfy (3).

III. Analog ZF with Quantized Vector Modulators

A. Analog Zero-Forcing

In this paper, we model the antenna arrays as simple uniform linear arrays (ULAs) of N_A elements. Each ULA is assumed to be the same length and the ULAs are stacked on top of each other in the vertical domain. The channel of user m towards a unique spatial direction θ_m (i.e. line-of-sight (LOS) channel) can be written as

$$\begin{aligned} \vec{H_m} =& e^{jk(m-1)d_y cos(\theta_m)} \\ & [1, e^{jkd_x cos(\theta_m)}, ..., e^{jk(N_A-1)d_x cos(\theta_m)}]^T, \end{aligned} \tag{5}$$

where $k = \frac{2\pi}{\lambda}$ denotes the wave number, d_x and d_y denotes the antenna spacing in horizontal and vertical directions, and θ_m is the beamforming direction. The overall channel can be stacked to a single matrix as

$$\mathbf{H} = [\vec{H_1}, \vec{H_2}, ..., \vec{H_{N_b}}], \tag{6}$$

where N_b denotes the number of beams. The ZF coefficients can be calculated as

$$\mathbf{W}_{zf} = \mathbf{H}^H (\mathbf{H}\mathbf{H}^H)^{-1}, \tag{7}$$

where $(\ )^{-1}$ denotes the inverse and $(\ )^H$ denotes conjugate transpose of the matrix. The mth column of $\mathbf{W}_{zf}$, corresponds to the ZF coeffients of user m.

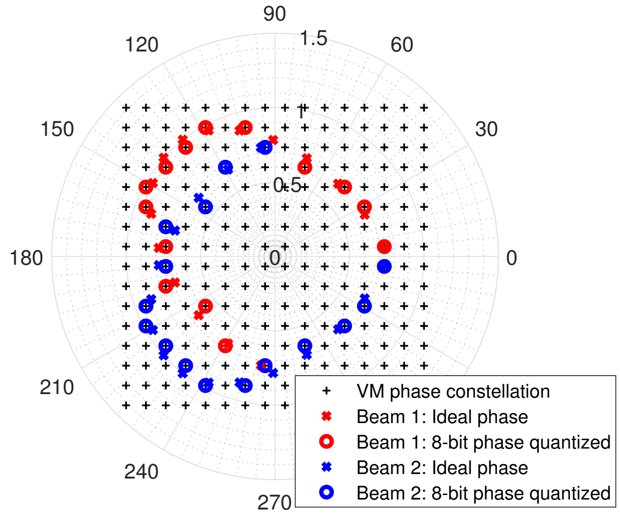


Fig. 3. Mapping of the ideal and 8-bit VMPS quantized ZF beamforming coefficients for 16 antenna elements.

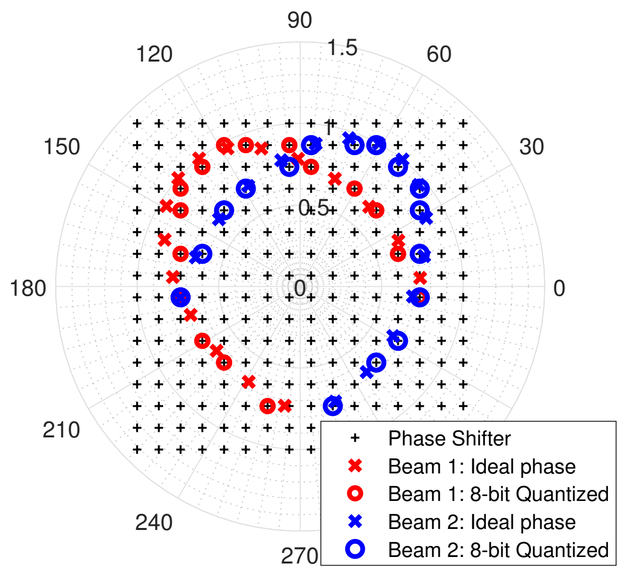


Fig. 4. Mapping of the ideal and 8-bit VMPS quantized ZF beamforming coefficients for 16 antenna elements with sliding reference.

B. ZF by Round-off Method

Position accuracy and depth of the null depends on the quantization of the beamforming weights. An example of the ZF coefficients mapped to the 8-bit vector modulator constellation by round-off method (3) is shown in Fig. 3. The example has two 16-element ULAs stacked on top of each other. For simplicity, the arrays have identical omnidirectional elements spaced with $\lambda/2$ at 28 GHz. The ZF coefficients are calculated according to (7). In the example, the arrays are steered to azimuth directions of $5°$ and $-5°$, respectively. Both the ideal and quantized coefficients are shown for both of the beams. The corresponding beams simulated over the $30°$ azimuth sector are plotted to Fig. 5. The beams are symmetric due to the

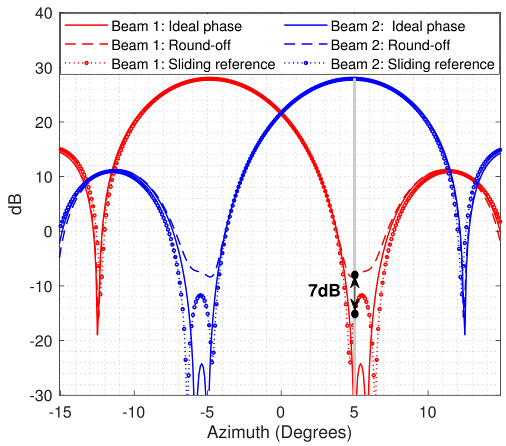


Fig. 5. Nulling Interference with quantized coefficients w/wo offset for CW signal.

symmetry of the chosen steering angles. As a result of the quantization, we see that the null depth is decreased. In the example scenario, the round-off method achieves around 36 dB of SIR while the ideal coefficients are totally nulling the interference.

C. Improved ZF with Sliding Reference

The same example presented in the previous section is used to demonstrate the coefficient mapping with the proposed method. The coefficients are obtained by finding the reference phase that gives the minimum quantization error according to (4). The used offset phase is found by exhaustive search by sweeping phase over $360°$ with $0.1°$ steps. The mapped coefficients are shown in Fig. 4 and corresponding beams are shown in Fig. 5. In the example scenario, the sliding reference mapping improves the SIR by almost 7 dB compared to the round-off method.

IV. Statistical Analysis in Multi-beam Scenario

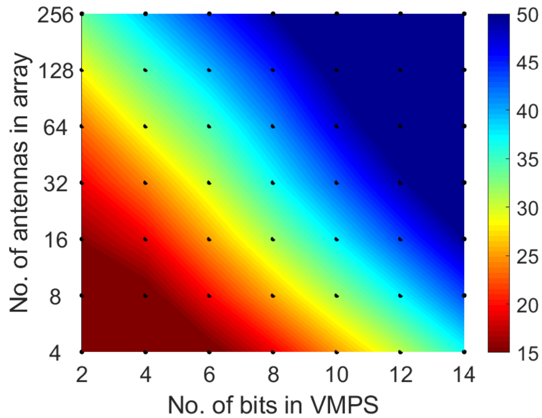
The examples shown in the previous sections were done in order to understand the physical meaning of the quantization in analog ZF. Here we extend the analysis to show the impact with random directions, different number of antennas and different amount of VMPS control bits. Statistical simulations with dynamic beam configuration are performed in order to analyze the interference reduction techniques in a more realistic scenario. Two directions of the beams are chosen randomly from uniform distribution within scan region from -20 to 20 degrees in azimuth. The beams are allocated to two identical vertically stacked ULAs. The simulations are performed for antenna configurations from 4 to 256 antennas with logarithmic steps and the number of VMPS bits is varied from 2 to 14. Note that 2 bits means that in VMPS there is only one bit reserved for I and one for Q, respectively. For each scenario, the ZF coefficients are calculated to null the beams from each other. The Monte-Carlo (MC) simulations are performed over 10^4 rounds and the SIR is recorded from the directions of both beams.

The mean SIRs with round-off method and sliding reference method over the MC runs are plotted to Figs. 6a and b, respectively. With round-off method, doubling the number of antennas seems to have similar impact than doubling the number of VMPS constellation points (increasing two bits). However, with the sliding reference method, the higher number of bits gives more benefits compared to the round-off method especially with smaller number of antennas. The impact is clearly seen in Fig. 6c which presents the improvement of the sliding reference method compared with the round-off method. With higher than 8 bits in the VMPS and less than 16 antennas, the improvement can be even 10 dB in the SIR. For example with 10 VMPS bits and 8 antennas, the round-off method have around 32 dB SIR on average while the sliding reference was giving more than 38 dB. This is due to the fact that with smaller number of antennas, all the points are potentially inside one circle of the VMPS constellation. With higher number of elements, quantization of the beamformer has less impact and hence the SIR performance can be decent with smaller number of bits. With higher number of elements, the initial SIR is also decreased even without the ZF due to the decreased beamwidth.

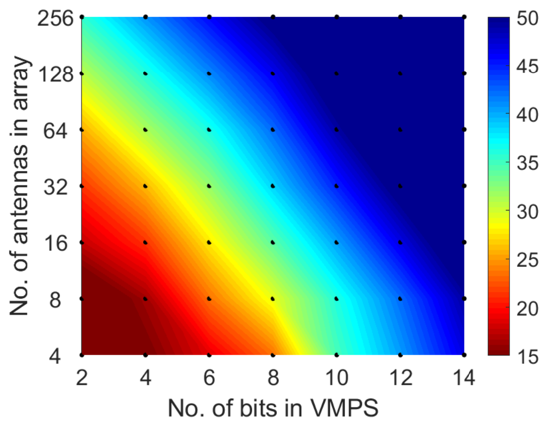
V. Conclusion

Vector modulators used as phase shifters in phased array systems have a finite number of possible phase and amplitude weights. The quantization of the weights do not significantly limit the beam steering resolution. However, in more advanced beamforming techniques, the phase and amplitude accuracy decreases the performance. We studied the ZF SIR reduction performance of analogue beamforming VMPSs having finite phase and amplitude resolution. To decrease the quantization error, we proposed a sliding reference technique, where the reference phase is varied to minimize the Euclidean distance between the ideal and quantized beamformer weights. The proposed technique is shown to increase the ZF performance compared to the round-off method. The impact was observed to be larger with small number of antenna elements.

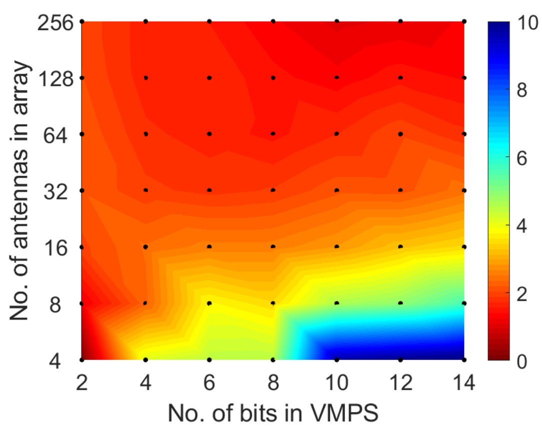
In addition to the quantization, phased arrays suffer also from the other sources of amplitude and phase errors. The errors set a need for internal calibration procedures for the array to increase the performance. The proposed sliding reference technique can be also utilized to calibrate the array for certain RF beamforming weights.



(a)



(b)



(c)

Fig. 6. Monte-Carlo simulated mean SIR [dB] with two random beam directions by using (a) round-off method and (b) sliding reference and (c) the SIR improvement of the sliding reference method compared to the reference method.

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