Evaluation of RF Device Error Factors on the Beam Directivity of an Uniform Linear Array Antenna

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Abstract: This paper reports the error effects of actual mmWave RF devices on beam pattern by monte carlo simulation. A mmWave beamforming by array antenna is one of the most promising technique to realize access methods which meet requirements of URLLC, mMTC, and eMBB communication simultaneously. The accuracy of analog beam forming is necessary to be increased to realize 5G or beyond 5G access. Our simulation shows individual effects of frequency, phase, and gain non-linearity characteristics on beamforming accuracy. We conclude that a proper calibration on the phase difference between array antenna elements improve the beamforming accuracy effectively and guarantee providing sufficient beam gain required in the entire communication area.

Keywords: mmWave, beamforming, 5G, quantization error, beam squint

Classification: Antennas and propagation

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1 Introduction

The mmWave bands bring GHz of spectrum in 5G cellular communication. A mmWave beamforming is one of the most promising techniques to realize access methods which meet 5G system requirements of URLLC, mMTC, and eMBB communication simultaneously [1]. However, the signals at mmWave frequencies suffer significantly higher path loss than the signals below 6 GHz [2]. Thus, it is necessary to compensate the attenuation using beamforming technique by a phased array with a large number of antenna elements for supporting mmWave mobile applications [3]. In addition, more beamforming control accuracy is required with increasing the number of elements since the sharp beam generated by multiple antenna elements may cause significant reduction in received power by a slight error in radiation direction due to the phase error distribution [4]. This paper discusses analog beamforming directivity accuracy with an uniform linear array (ULA) antenna by considering the properties of the RF devices for a base station.

2 System model

We evaluated beamforming accuracy of 28 GHz by computer simulation. In this study, we consider an ULA consists of $N$ identical isotropic antenna elements so that we can focus on the error effects of analog beamformer device. Let $d$ be the distance between two adjacent antenna elements. The angle of departure (AoD) $\theta_{\text{AoD}}$ is defined as the angle of the signal relative to the array boresight, increasing counterclockwise. The steering vector $\mathbf{w}$ and the response vector $\mathbf{s}$ are denoted as

$$
\mathbf{w} = (A_1 e^{j\beta}, A_2 e^{j2\beta}, \ldots, A_N e^{j(N-1)\beta})^T
$$

$$
\mathbf{s} = (e^{j\xi}, e^{j2\xi}, \ldots, e^{j(N-1)\xi})^T,
$$

where $(\cdot)^T$ represents the transpose operation, $A_n$ is the excitation amplitude controlled by $n$-th attenuator, $\beta = 2\pi d\lambda^{-1} \sin \theta_{\text{AoD}}$ is the progressive excitation phase shift between adjacent antenna elements, $\theta$ is an observation angle, and let $\xi = 2\pi d\lambda^{-1} \sin \theta$. Given that $A_n$ is uniform over the entire array, the array factor is

$$
AF(\theta_{\text{AoD}}, \theta) = w^*(\theta_{\text{AoD}})s(\theta) = A_0 \sum_{n=1}^{N} e^{j(n-1)\psi(\theta_{\text{AoD}}, \theta)},
$$

where $(\cdot)^*$ is the Hermitian transpose operation and $\psi \equiv \xi - \beta = 2\pi d\lambda^{-1}(\sin \theta - \sin \theta_{\text{AoD}})$. Here, a half wavelength is adopted as element spacing $d = 0.5\lambda$. 

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A digital phase shifter controls the excitation phase electronically and replaces each real number with an approximation from a finite set of discrete values. Assuming that the number of phase shifter bits is $q$, i.e. the phase resolution is $\Delta \psi = 2\pi/2^q$, and the required input phase value is $\psi_{\text{in}}$, the quantized phase set value by the phase shifter is denoted as

$$\psi_{\text{set}} = \left\lfloor \frac{\psi_{\text{in}}}{\Delta \psi} \right\rfloor \cdot \Delta \psi,$$

where $\lfloor \cdot \rfloor$ means the Gauss symbol. Therefore, the quantization phase error of $n$-th element is bound to $|\delta \psi_n| \leq \pi/2^q$. This error causes not only a decrease in beam gain but also beam granularity in which beam scanning step is discrete.

The excitation amplitude can also be electronically controlled by the step of 0.5 dB. The actual gain set for each element antenna is quantized. The effect of the quantization gain error can be neglected in the case of uniform excitation distribution, while it affects the case where excitation amplitudes are controlled between antenna elements.

The excitation phase is electronically controlled by a phase shifter for each element. Gain errors and phase errors caused by phase control are assumed to follow the normal distribution of standard deviation $\Delta_{\text{ph}}$ and $\delta_{\text{ph}}$, respectively. Gain errors and phase errors caused by amplitude control are also assumed to follow the normal distribution of standard deviation $\Delta_{\text{amp}}$ and $\delta_{\text{amp}}$, respectively.

In addition, an error can also occur in the initial phase between element antennas. The main factor for the gain error is considered to be the difference in the performance of the active RF components, and the phase error is considered to be the line length difference. The gain error and the phase error added to all the elements follow the normal distribution of standard deviation $\Delta_{\text{ch}}$ and $\delta_{\text{ch}}$.

Moreover, the beam directivity shows the beam squinting effect on frequency changes [5]. In a beamformer circuit, gain and phase of each element show a ripple-like behavior with respect to a change in transmission frequency due to unavoidable impedance mismatch. The evaluation results of the frequency characteristics with respect to the gain and phase of the manufactured beamformer show periodicity of about 1.3 GHz, which is wider than the maximum transmission bandwidth of 400 MHz used in 5G system. Considering a situation in which the error has the worst effect on beamforming, it is reasonable to assume that both gain and phase change linearly as a function of frequency within the transmission bandwidth, respectively. The change rate of each channel is set to the maximum absolute values $\Delta_{\text{freq}}$ and $\delta_{\text{freq}}$ of the respective derivatives of the vibration components of the measured frequency characteristic, and a random value according to a normal distribution using $\Delta_{\text{freq}}$ and $\delta_{\text{freq}}$ as standard deviations is set.

### 3 Simulation results and discussion

In order to simulate the directivity error with respect to the number of bits of the phase shifter and the phase resolution, the detected directivity $\theta_{\text{peak}}$ of the 8-element linear array antenna with isotropic antenna elements is compared to the
desired radiation angle $\theta_{\text{AOD}}$. Figure 1(a) shows the deviation angle $\delta\theta_{\text{peak}} \equiv \theta_{\text{peak}} - \theta_{\text{AOD}}$ caused by quantization phase error neglecting the device random errors in the 8-element linear array antenna. In general, a scanning angle range is limited to avoid generation of grating lobes. The inset summarizes $\delta\theta_{\text{RMS}}$, the root mean squared value of $\delta\theta_{\text{peak}}$, for scanning range $|\theta_{\text{AOD}}| < 60^\circ$ and $|\theta_{\text{AOD}}| < 45^\circ$ with respect to the phase shifter bit number. Regarding only on the quantization error using a 28 GHz 8×1 array antenna with a 6-bit phase shifter, $\delta\theta_{\text{RMS}}$ is less than 0.05°, indicating the radiation angle control accuracy is in units of 0.1°, while if the digital 12-bit phase shifter is used, the unit is less than 0.01°. This fact suggests that the quantization error by a 6-bit phase shifter is sufficiently small compared to the random error caused by RF devices as described later and, moreover, the one in digital beamformer is virtually negligible.

In addition to the quantization error, the influence of random error originated from RF semi-conductor devices is considered. All the random errors in gain and phase is assumed to follow a normal distribution. In order to investigate the relationship among the distribution of the absolute error values, the gain accuracy, and the radiation angle control accuracy, five sets of parameters are used as shown in Table I. The standard deviation values of Case 4 are obtained from experimental

![Fig. 1](image)

**Fig. 1.** (a) Beam directivity error of 8-element linear array antenna using isotropic antenna caused by quantization error. The inset shows $\delta\theta_{\text{RMS}}$ for $|\theta_{\text{AOD}}| < 60^\circ$ and $|\theta_{\text{AOD}}| < 45^\circ$. (b) $\delta\theta_{\text{RMS}}$ considering random error caused by 6-bit phase shifter for each case in Table I.

### Table I. Standard deviation set values of various random errors

| Case   | Phase shifter | Attenuator | Inter-channel |
|--------|---------------|------------|---------------|
|        | $\Delta_{\text{ph}}$[dB] | $\delta_{\text{ph}}$[deg] | $\Delta_{\text{amp}}$[dB] | $\delta_{\text{amp}}$[deg] | $\Delta_{\text{ch}}$[dB] | $\delta_{\text{ch}}$[deg] |
| 1      | Best          | 0.2/3      | 1.5/3         | 0.25/3         | 1.0/3         | 0.7/3         | 5.625/2        |
| 2      | Calibrated    | 0.2/2      | 1.5/2         | 0.25/2         | 1.0/2         | 0.7/2         | 5.625/2        |
| 3      | Most-likely   | 0.2/2      | 1.5/2         | 0.25/2         | 1.0/2         | 0.7/2         | 10/2           |
| 4      | Measured      | 0.2        | 1.5           | 0.25           | 1.0           | 0.7           | 10             |
| 5      | Worst         | 2*0.2      | 2*1.5         | 2*0.25         | 2*1.0         | 2*0.7         | 20             |
results of our prototype TX/RX beamformer prepared for practical use. Case 4 assumes a pessimistic situation in which all the measured data are within the range of 1σ of the error probability density distribution of each index. Case 3 is the most-likely parameter set in which measured data is distributed within the range of 2σ. Case 2 is a situation where the initial phase errors between the elements are calibrated in units of phase resolution $\Delta\psi$. Here, we adopt $\Delta\psi = 5.625^\circ$ based on 6-bit phase shifter of our beamformer and the calibration method is, for example, rotating element electric field vector (REV) method [6]. Case 1 assumes an optimistic situation where all the experimental data are within the range of 3σ. Case 5 assumes a worst situation where all the data are within the range of 0.5σ. For each case, monte carlo simulation is iterated 1000 times with pseudo-random number generator and the root mean squared (RMS) values of $\delta\theta_{\text{peak}}$ are calculated for evaluation. The results of $\delta\theta_{\text{RMS}}$ in the scan range $0^\circ \leq \theta_{\text{AOD}} \leq 60^\circ$ is shown in Figure 1(b). Comparing between Case 2 and Case 3, it is found that the phase error $\delta_{\text{ch}}$ between the element antennas significantly affect $\delta\theta_{\text{RMS}}$ since the value of $\delta_{\text{ch}}$ is 2 - 10 times as large as the other phase values in the parameter set. Thus, reducing the inter-channel phase difference is the most effective way to improve accuracy of the radiation angle in our beamformer.

Next, the effect of calibration is estimated by changing the value of $\delta_{\text{ch}}$. Here, the setting values of errors other than $\delta_{\text{ch}}$ are fixed to the most-likely Case 3 values in Table I. As shown in the simulation result Fig. 2(a), $\delta\theta_{\text{RMS}}$ monotonically decreases by suppressing $\delta_{\text{ch}}$ down to $\sim2.8^\circ$. The straight lines are guides to the eye indicating linear relationship between $\delta_{\text{ch}}$ and $\delta\theta_{\text{RMS}}$ in $\delta_{\text{ch}} \geq 2.8^\circ$ where the inter-channel phase difference is dominant compared to the other error factors. This indicates that the beam directivity error $\delta\theta_{\text{RMS}}$ can be effectively suppressed down to $\sim0.3^\circ$ by calibrating inter-channel phase error. Since the number of bits of the phase shifter is 6, the calibrated value of $\delta_{\text{ch}}$ is $\sim2.8^\circ$ at best.

In 5G NR, broadband transmission using up to 400 MHz is assumed. Specifically,
given that the subcarrier spacing is 120 kHz and the center frequency is 28 GHz, the maximum and minimum subcarrier frequencies are 28.1901 GHz and 27.8099 GHz, respectively. Even if the desired radiation angle of 45° and the detected radiation angles of the maximum and minimum subcarrier frequencies deviate the most during 10000 times monte carlo simulation of Case 2 error set, the difference between them is about 1.5° and the RMS value of angular difference is 0.8° (see Fig. 2(b) in detail). It is sufficiently small value for a beam width of ~16°. Furthermore, the gain did not change in the resolution at which the simulation is performed. These results show that the gain and phase frequency characteristics of the beamformer in this study do not have a serious effect on the bandwidth used in 5G. On the other hand, when performing high-precision null steering, it would be necessary to consider the beam squinting effect.

4 Conclusion

We simulated the effects of quantization error and random error caused by mmWave semi-conductor devices on beamforming accuracy. Regarding only on the quantization error using a 28 GHz 8×1 array antenna with a 6-bit phase shifter, the radiation angle control accuracy is found to be in units of 0.1°, while the digital 12-bit phase shifter improves the accuracy to the order of 0.01°, suggesting that a digital beamformer remains unaffected by the quantization error. Taking the random error factors of our prototype beamformer into consideration, the effect of the initial phase error between the element antenna channels is the largest among several error factors and the total error effect is calculated to be \( \delta \theta_{\text{RMS}} \sim 2.0° \) at most by the monte carlo simulation in the worst case. This error is expected to be reduced to \( \delta \theta_{\text{RMS}} \sim 0.3° \) by calibrating the phase difference between antenna elements using the REV method. Furthermore, even when the transmission bandwidth is 400 MHz, the simulation suggests that the in-band radiation angle error is within ~1.5°. This indicates that the beam squint effect has relatively small impact on beamforming accuracy in mmWave band compared to random errors of RF devices. From these results, we conclude that a proper correction to the inter-channel phase difference improve the beamforming accuracy effectively and guarantee providing sufficient beam gain required in the entire communication area.

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