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The Beam Squint Effects in Antenna Arrays at Millimeter Bands

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Abstract
Beam squint phenomenon is considered one of the most drawbacks that limit the use of (mm-waves) array antennas; which causes significant degradation in the BER of the system. In this paper, a uniform linear array (ULA) system is exemplified at millimeter (mm-waves) frequency bands to realize the effects of beam squint phenomena from different directions on an equivalent gain response to represent the channel performance in terms of bit error rate (BER). A simple QPSK passband signal model is developed and tested according to the proposed antenna array with beam squint. The computed results show that increasing the passband bandwidth and the number of antenna elements, have a significant degradation in BER at the receiver when the magnitude and phase errors caused by the beam squint at 26 GHz with various spectrum bandwidths.

Keywords
Millimeter Waves, Passband, Baseband, QPSK, Bandwidth, Antenna Array, Array Gain Response.

I. INTRODUCTION

One of the best methods for 5G and the forthcoming 6G systems is millimeter wave (mm-wave) communication [1]. Most consumer wireless systems employ carrier frequencies below 6 GHz, while mm-wave uses the spectrum from 30 GHz to 300 GHz [2]. Using mm-wave carrier frequencies has the primary benefit of having access to wider spectral bands. Systems using the unlicensed 60 GHz mm-wave band often use channels with a bandwidth of 2 GHz, as an example. Higher data rates can be achieved through wider bandwidth channels [3]. However, the path-loss at such high frequencies is far worse than it is for sub-6 GHz systems [4]. Particles in the channel cause small-scale fading at these frequencies; oxygen or the rain fade and humidity can further attenuate signals [5]. These considerations motivate the adoption of narrow beams formed by antenna arrays as a solution for mm-wave systems to attain coverage comparable to that of sub 6GHz bands. One solution to this issue is the massive multiple-input multiple-output (m-MIMO) technology. With the use of this technology, a sizable number of antennas could offer enough gain to make up for the route loss [6]. Due to its simplicity, phased array is one of the most widely used options. Phased arrays, however, are only a good solution for narrowband systems because phase shifters can only be built up at the carrier frequency [7], however, beam squint is a phenomenon that happens when wideband waveforms' beam direction changes in relation to frequency [8]. Also notice that when the signal arrives at angle θ that is away from bore sight direction i.e 0 degree. the beam direction is frequency dependent [7]. Beam squint, also known as a variation in steering angle vs. frequency, is a well-known issue in mm-wave communication systems that can drastically reduce the performance of the communication system by lowering the antenna gain near the fringes of the frequency spectrum. [9].

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The beam squint phenomena have received a lot of attention, studies have been made to either overcome the beam squint or exploit it to improve system performance. Waleed A et al. analyzed the beam squint effect on serially fed antenna and proved that it was a significant problem [10]. Zhijun Liu et al. in 2013 solved the problem of beam squint in 60 GHz communication system by proposing new beamforming codebook design [11]. Mingjin Wang et al. in 2019 studied the effect of beam squint on channel estimation and proposed an uplink channel estimation algorithm that take into account the beam squint phenomena [12]. The preceding works illuminated the impact of beam squint on the system, particularly concerning antenna configurations. Nevertheless, these studies were limited in their scope, as they did not comprehensively analyze the totality of squint effects across all parameters inherent to a communication system.

In this paper the beam squint effect was investigated for mm-wave signals. The main contributions of this paper are: First, we find a relationship between the baseband bandwidth and passband bandwidth to correctly decide the bandwidth of mm-wave signal that will be multiplied with the array gain. Second, it provides a complete study on the relationship between the bandwidth of the passband signal and beam squint and how that will affect the bit error rate (BER). The rest of this paper is organized as follows. Section II. presents the beam squint modal. Section III. identifies the relationship between the baseband and passband bandwidth. Section IV. presents general system modal. Section V. presents the error rate results and conclusion respectively.

II. MM-WAVE BEAM SQUINT PHENOMENA

There is a time delay between array elements as a wavefront approaches them based on the wavefront angle θ with respect to boresight. It is possible to provide beam steering for a single frequency by substituting a frequency-specific phase shift for the time delay. This is true for narrow-band waveforms, but for wideband waveforms, when the bandwidth contains a variety of frequencies, the beam's direction can change depending on the frequency. This introduces beam squint. Beam squint is defined as the ratio of operating frequency f to the carrier frequency fc [13] We consider a uniform linear array (ULA) at the receiver with N elements, the distance between elements is d that is equal to $(\lambda/2)$ If we assume that f is the operating frequency which is equal to [fc-B/2 fc+B/2] where B is the bandwidth and fc is the carrier frequency, θ_i is the incident angle and θ_f is focus angle. Then we will have the incident vector as a function of f [14].

$$a(\theta_i,\phi_i,f)=\frac{1}{\sqrt{N}}\left[1,e^{-j2\pi\left(\frac{d}{c}f\right)\sin(\theta)},\dots\quad e^{-j(N-1)2\pi\left(\frac{d}{c}f\right)\sin(\theta)}\right]^T \tag{1}$$

And the steering vector in equation as function of f_c .

$$a(\Theta_s,\Phi_s,f_c)=\frac{1}{\sqrt{N}}\left[1,e^{-j2\pi\left(\frac{d}{c}f_c\right)\sin(\theta)},\dots,e^{-j(N-1)2\pi\left(\frac{d}{c}f_c\right)\sin(\theta)}\right]^T \tag{2}$$

To find the total array gain we find the dot product of these two vectors

$$g(f,\theta)=a(\Theta_i,\Phi_i,f)\cdot a(\Theta_s,\Phi_s,f_c) \tag{3}$$

The final gain of uniform ULA

$$g(f,\theta)=\frac{\sin\left(\frac{N\pi}{2}\sin(\theta)\left(\frac{f}{f_c}-1\right)\right)}{\sqrt{Nr}\cdot\sin\left(\frac{N\pi}{2}\sin(\theta)\left(\frac{f}{f_c}-1\right)\right)}\cdot e^{j0.5(N-1)\pi\sin(\theta)\left(\frac{f}{f_c}\right)} \tag{4}$$

III. SYSTEM MODEL

The depicted system diagram, illustrated in Fig 1, outlines a comprehensive communication framework encompassing a digital baseband transmitter, a digital baseband receiver featuring N individual elements within an antenna array configuration, and the utilization of an Additive White Gaussian Noise (AWGN) channel for signal transmission. The communication process involves the elevation of the baseband signal to a Radio Frequency (RF) carrier frequency, followed by its passage through the AWGN channel n(t). Subsequently, the received signal undergoes an array processing stage, which includes convolution by an array gain g(t), down-conversion to the original frequency domain, and finally demodulation to extract the transmitted information. Notably, the system's performance is rigorously evaluated in terms of Bit Error Rate (BER), specifically, to demonstrate the extent to which the array gain influences signal fidelity. The signal was modulated using QPSK modulation.

In the context of QPSK modulation, the symbol time (T_s) governs how quickly symbols are transmitted. It's determined

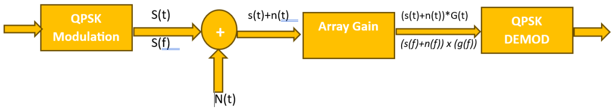


Fig. 1. Communication modal with beam squint.

TABLE I. n_c-TO-PASSBAND BANDWIDTH RELATION

Pass Bandwidth (GHz)	n_c
1	8×26
2	4×26
3	$8/3 \times 26$
4	2×26

by the product of an integer to satisfy the symbol time called n_c, and the duration of a carrier cycle (T_c), as expressed in Equation 5:

$$T_s = n_c \cdot T_c \tag{5}$$

For our discussion, let's assume a carrier frequency (fc) of 26 GHz, making Tc equal to 1/26 nanoseconds. To fit within a 2 GHz passband, which accommodates twice the baseband frequency [15], the symbol time T_s is set at 1 ns. With this, nc equals 26 for a single sample period. Given that QPSK employs 4 samples per symbol, nc increases to 4 times 26. This illustrates how modulation complexity influence the timing of the signal. Table I shows the relation between nc integer and passband bandwidth.

IV. BIT ERROR RATE RESULTS

This section focuses on assessing the Bit Error Rate (BER) across different scenarios. These scenarios involve transmitting QPSK passband signals over an AWGN channel, followed by signal amplification using array gain at the receiver. The key variable in each scenario is the incident angle, spanning from 0 to 50 degrees. BER, a crucial metric, quantifies the signal accuracy in the presence of noise and channel impairments. The analysis of BER variations reveals the effect of incident angles and array gain. providing crucial insights into the system's performance and its resilience against different operational conditions.

A. Number of antenna elements effect

In this section, the effect of increasing the number of antenna elements on the antenna gain at the receiver has been studied. Due to the fact that has been derived from equation 5 which state that increasing the number of antenna elements will increase the antenna gain at carrier frequency fc and reduce the gain for frequencies at the edges. The effect of beam squint has been studied for (32, 64) elements to show how increasing the number of elements at the receiver increases the distortion of the received signal. In Fig. 2 the magnitude and phase of the antenna gain of 32 elements has been plotted, it's clear that the center frequency has the highest magnitude while the edges frequencies have less magnitude

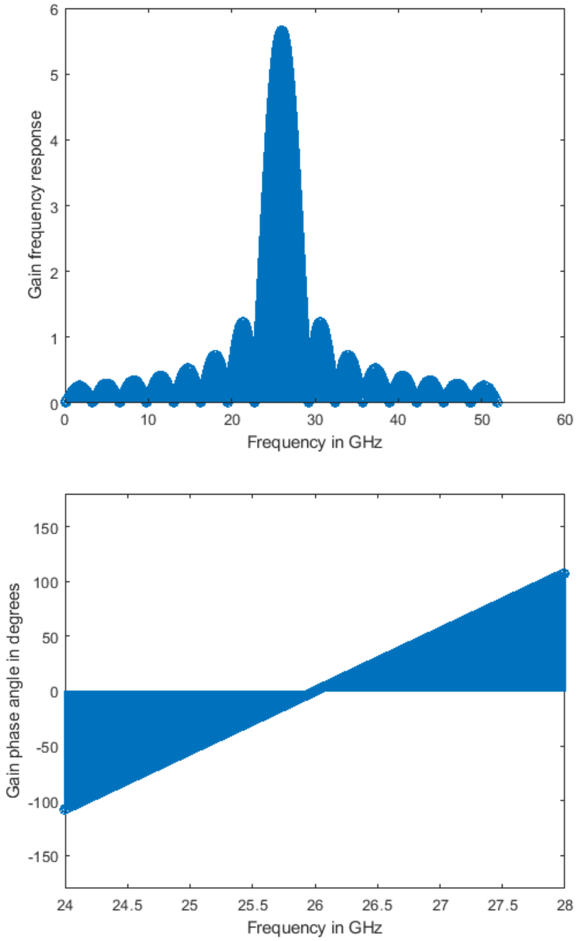


Fig. 2. Magnitude and phase of 32 elements.

The outcomes obtained by multiplying the gain magnitude, considering a scenario involving 32 elements without phase errors, with the incoming signal have revealed a notable elevation in error rates. These findings are effectively illustrated in Fig 3. It clear that increasing the incident angle from 0 to 50 degree increase the error rate.

Moving from a setup involving 32 antenna elements to an extended configuration of 64 elements yields distinct changes in both gain magnitude and phase. This transformation is visually captured in Fig, 4 which showcases the measured magnitude and phase characteristics of the 64-element Uniform Linear Array (ULA). The phase plotted assuming that the first element is the reference point.

Increasing the number of antenna elements leads to a significant rise in the Bit Error Rate (BER). This is due to the distortion

caused by the array gain applied to the received signal. which can be seen graphically in Fig. 5 which displays the

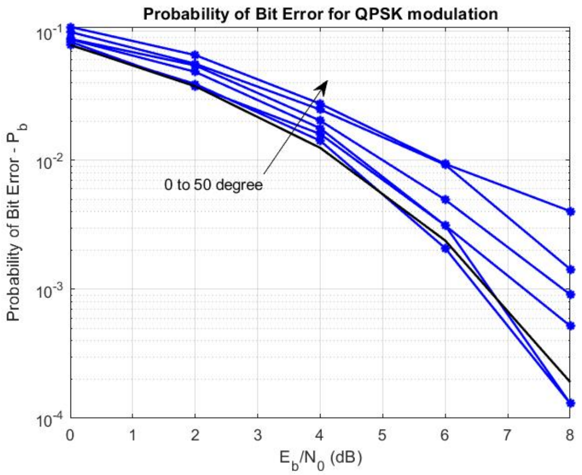


Fig. 3. BER of 32 elements without phase error.

BER results for a 64-element array. In this case, the signal is only multiplied by the gain magnitude, without considering the phase error. The incident angel moves from 0 to 50 degree.

B. *Effect of Bandwidth*

The bandwidth of the signal can be defined as the range of frequencies that the signal cover. In 5G mm-wave system the signal bandwidth become large. When the signal bandwidth become wider, and since the array gain is frequency dependent the beam squint problem become more visible. In this section the relationship between the bandwidth and beam squint will be discussed in term of BER. First, 1 GHz passband bandwidth has been taken (from 25.1 to 26.5) as shown in Fig. 6. The signal has been multiplied with the array gain in term of both magnitude and phase error and BER has been measured.

Second, the passband bandwidth increases to 2GHz from (25 to 27) as shown in Fig. 7. Again, the BER has been measured and the results has shown significant increase in the error rate.

Now the bandwidth increased to 4GHz from 24 GHz to 28 GHz as shown in Fig. 8 and the error rate has become more visible.

Our investigation has illuminated a crucial phenomenon tied to signal bandwidth and array size. Specifically, when the bandwidth is extended to 4 GHz and the array contains 64 elements or more, an alarming trend emerges: the error rate becomes uncontrollable. This problem arises from the complex relationship of increased bandwidth and a larger array. The response of the array becomes more susceptible to frequency variations as the bandwidth increases. Simultaneously, a larger array introduces greater complexity. Such uncontrolled error escalation has direct implications for Bit Error Rate (BER), making it unreliable and compromising the system's communication reliability. Effective strategies are required, including advanced array processing and bandwidth management, to navigate this challenge and maintain acceptable error rates in the face of expanded bandwidth and larger arrays. Fig. 9 shows the error rate for 1 GHz , 2 GHz and 4 GHz with 32 elements array without phase error. The incident angel moves from 0 to 50 in each case. Table II provide a numerical result that shows how the error rate increase with increasing the bandwidth.

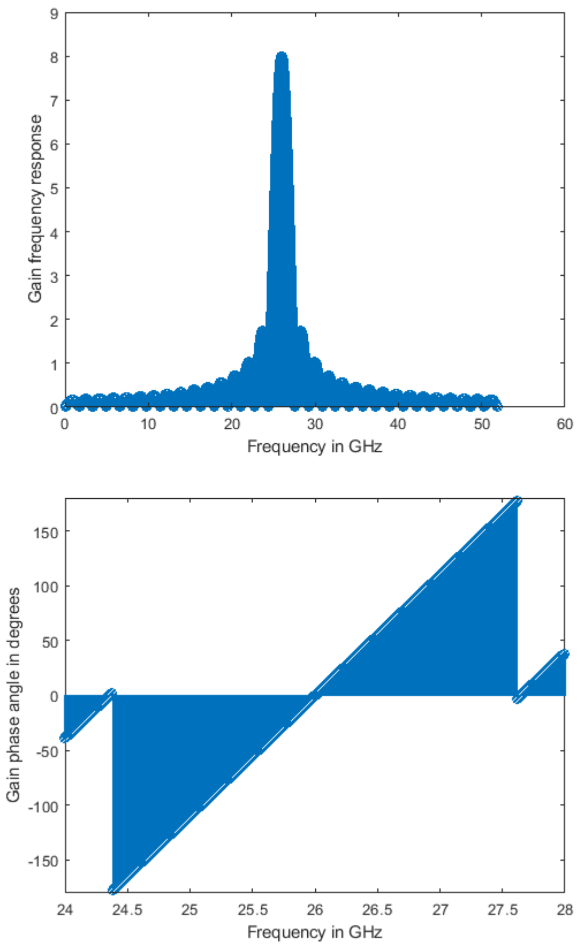


Fig. 4. BER of 32 elements without phase error.

V. CONCLUSION

In this paper, to analyze the beam squint problem in mm-wave communication system, we proposed a passband QPSK mm-wave communication system with different parameters. We first derive the array gain as function of frequency the array gain function consisted of two parts (magnitude and

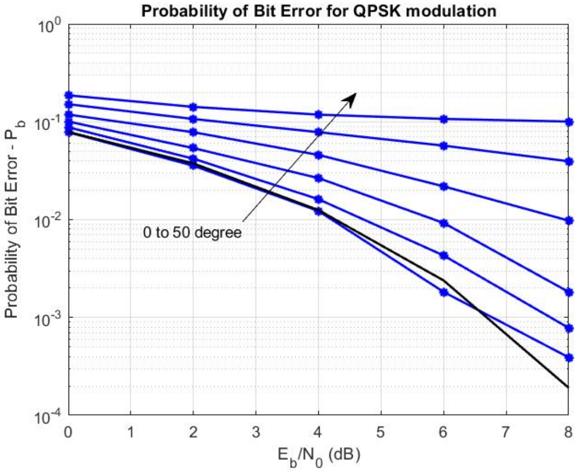


Fig. 5. BER of 64 elements.

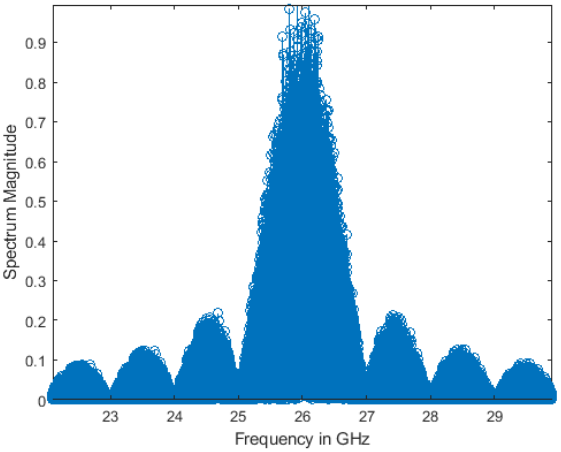


Fig. 7. Spectrum of 2 GHz QPSK.

phase), and in addition to frequency the array gain depends on the number of elements in the array and bandwidth. The baseband signal upconverted to 26 *GHz* carrier frequency the passband signal bandwidth was changed from 1 to 2 to 4 *GHz* respectively. Simulation begins with measuring the BER of QPSK passband signal received by ULA with 32 elements, then the number of elements increased to 64, the maximum error increased from 0.1070 to 0.1783 without the phase error and the incident angle was set to 50 degree, with SNR ranging from 0 to 8dB. Then the phase error was included for the same scenario the maximum error rate increased from 0.1070 for 32 elements to 0.2423 and from 0.1783 to 0.4010 for 64 elements. Then passband signal bandwidth was changed from 1 to 2 to 4 *GHz* with 32 elements, the resulting error rate changed from 0.0902 to 0.1034 to 0.1784 respectively. Then phase error was included and the maximum error rates increased to 0.1320 for 1 *GHz* and 0.2339 for 2 *GHz* and 0.4005 for 4 *GHz*. other types of modulations were also tested and the results showed same behavior. The simulation results show that the array gain varies with different factors, and that as each factor increases, so does the number of communication errors (BER). To improve the performance and reduce the number of errors in 5G communication systems, any correction methods such as filters, equalizers, or adaptive beamforming must consider these factors.

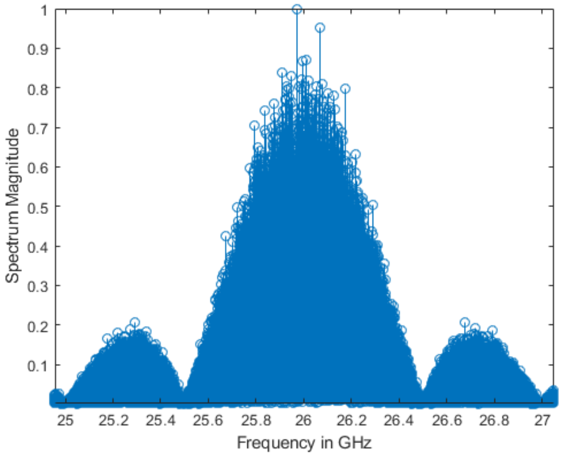


Fig. 6. Spectrum of 1 GHz QPSK.

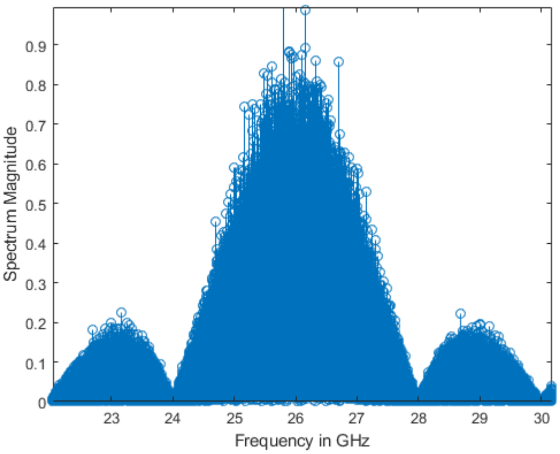
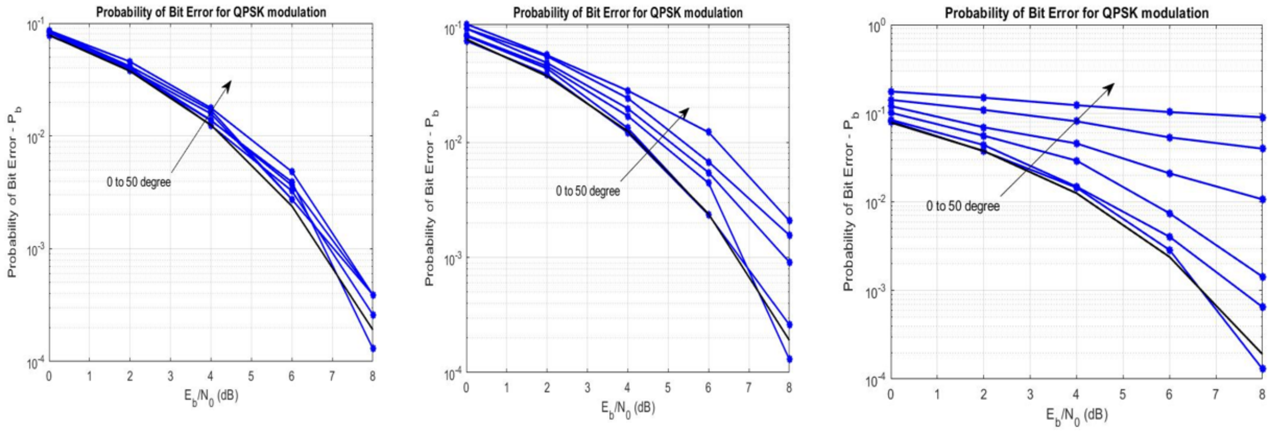


Fig. 8. Spectrum of 4 GHz QPSK.



BER of 1GHz BW (N=32) BER of 2GHz BW(N=32) BER of 4 GHz BW(N=32)

Fig. 9. BER of QPSK with different BW

TABLE II. BER -to-bandwidth results

Bandwidth (GHz)	Eb/No (dB)	Number of elements	Bit Error Rate Without Phase Error (incident angle 50 degree)	Bit Error Rate with Phase Error (incident angle 50 degree)
1	8	32	0.00039	0.0073
2	8	32	0.0022	0.1792
4	8	32	0.0943	0.397
1	8	64	0.0027	0.1918
2	8	64	0.0894	0.3979
4	8	64	0.2763	0.4204

CONFLICT OF INTEREST

The authors have no conflict of relevant interest to this article.

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