Investigation the Beam Squint Effect on the Performance of Patch Antenna in mm-Waves Wireless Communication

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Abstract. 5G cellular networks require higher system capacity and user data rates. The demand for new frequency spectrum is increased by this potential expansion and the current spectrum deficit. A promising candidate with a lot of accessible capacity is the new millimeter wave spectrum (around 60 GHz). A new requirement for single element antenna and array design is imposed by the new spectrum. This paper addresses the issues of mm-wave antenna design and the problems that designer may face during the designing process. The proposed antenna has a resonating frequency of 26 GHz with 2 GHz bandwidth. The problem of beam squint is analyzed in this paper. The results showed that the gain of the mm-wave antenna array becomes a function of frequency which significantly reduces the performance of mm-wave communication system.

Keywords: MM-waves, MIMO, patch antenna, Antenna array, Beam Squint

1. Introduction

With more than five billion devices requiring wireless connections to run voice, data, and other applications available in today's wireless networks, there have been active research activities in recent years all over the world to advance the next-generation 5G wireless networks [1]. Due to the availability of smart portable devices that offer broadband wireless applications like multimedia and interactive gaming, the volume of mobile data has drastically expanded over time [2]. The current cellular networks are exceeding their technical limits due to the rising demand for bigger data rates, wider coverage, low latency, high dependability, and quicker speeds [3]. Therefore, a change to the most recent cellular technology is required. Effective low-profile antennas are needed for high-performance millimeter-wave devices in order to provide dependable and interference-free communications [4].

Mm-wave antennas have drawn a lot of interest from both the academic community and business community for use in wireless transmission systems. In order to increase the bandwidth

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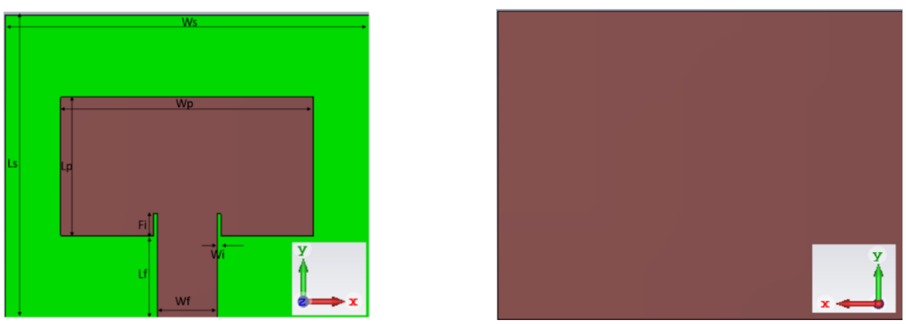
coverage and allow the antenna to operate in the UWB frequency range, various antenna designs with various techniques were utilized [5].

There are a number of problems with mm-wave antennas that may restrict their use. One of these issues is extreme attenuation, however because higher frequency antennas are smaller in size and can be crammed into smaller spaces, this can be leveraged to produce significant beamforming improvements to make up for the severe attenuation [6]. However, there are a number of significant difficulties with mm-wave massive MIMO wireless systems that must be resolved. Beam squint [7] is one of these difficulties. The term "beam squint" refers to how a beam's spatial direction varies with frequency and causes dramatic variances in the path phases at various frequencies [8].

In this paper a simple single element design of square patch antenna operating in mm-wave is presented, then a study of beam squint is presented showing how the gain is changing with frequencies. The remainder of the paper is structured as follows: The design process for the antenna is presented in section 2. Section 3 present beam squint phenomena., and conclusion in Section 4.

2. Antenna design and results

The proposed inset fed patch antenna is designed based on a traditional square patch printed on a substrate of a square geometry as shown in Fig. 1.



(a) (b)

Fig.1. Geometry of the Proposed inset fed patch antenna (a) front view and (b) back view.

The antenna is designed to operate at Mm-wave at 26GHz. The substrate martial is chosen as the Rogers RT Duroid 5880, with dielectric constant ε_r of 2.2 and thickness of 0.508mm. The ground plane made of copper with height 0.035mm. An inset feeding technique is used in this design with length f_i and width w_i to increase the impedance matching. The antenna dimensions are calculated by equation (1):

$$W_p = \frac{C}{2f_o}\sqrt{\frac{2}{\varepsilon_r+1}} \quad . \tag{1}$$

where *Wp* is the patch width, *C* is the speed of light = 3×10^8m/sec, f_o is the resonant frequency and ε_r is the substrate dielectric constant. and the patch length was calculated using equation (2).

$$L_p = L_{eff} + \Delta L \tag{2}$$

where Lp is the patch length, *Leff* is the effective patch length and ΔL is the extension length. Effective Length can be calculated using equation (3).

$$L_{eff} = \frac{c}{2f_o\sqrt{\varepsilon_{reff}}} \ . \tag{3}$$

Effective Dielectric Constant can be calculated using (4).

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12\frac{h}{Wp}}} \quad . \tag{4}$$

Equation (5) used to calculate Extension in length

$$\Delta L = 0.412h\left[\frac{(\varepsilon_{reff}+0.3)\left(\frac{Wp}{h}+0.264\right)}{(\varepsilon_{reff}+0.258)\left(\frac{Wp}{h}+0.8\right)}\right]. \tag{5}$$

where h is the height of substrate. Length and width of substrate is calculated using equation (6) and (7)

$$Ls = 6h + Lp \tag{6}$$
$$Ws = 6h + Wp \tag{7}$$

Table (1) lists of the parameters of the proposed inset fed patch antenna and their values.

Table. 1 Parameters of the Proposed patch antenna

Parameters	**Description**	**Value(mm)**
Ls	Substrate length	7.7
Ws	Substrate width	9.5
t	Thickness of substrate	0.508
Wp	Patch width	6.6
Lp	Patch Length	3.53
Wf	Feedline width	1.55
h	thickness of ground	0.035
Fi	Inset length	0.55
Wi	Inset width	0.1

The design of the proposed inset fed patch antenna was carried out using CST microwave studio version 2020 and the parameter values were adjusted to give best results.

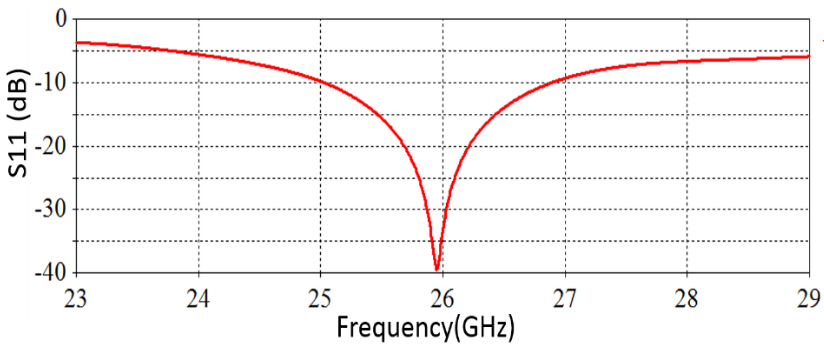


Fig.2. S11 versus Frequency plot

2.1 Antenna return loss

The antenna return loss is a measure of the power that is reflected from the antenna back to the source [9]. It provides a general notion of the reflection coefficient's size. To increase the transmitted power, the antenna must have as little reflection coefficient as possible. Given is the return loss in equation (8):

$$R_l = 10 \log \frac{Pincedint}{Preflected} \quad (8)$$

The bandwidth is computed based on the range of frequencies for which |S11| 10dB [10]. The S11 plot for the proposed antenna is shown in Fig. 2. It can be seen that the proposed antenna bandwidth can reach to up to 2 GHz (from 25 GHz to 27 GHz). Increasing the width of the inset will reduce the match as will as shift the resonance frequency to lower frequencies.

Gain vs frequency plot: Figure (3) shows the curve of the realized gain vs frequency of the proposed inset fed patch antenna. It can be seen from this figure that the gain varies across the 2 GHz bandwidth which is one of the challenges of wide band communications.

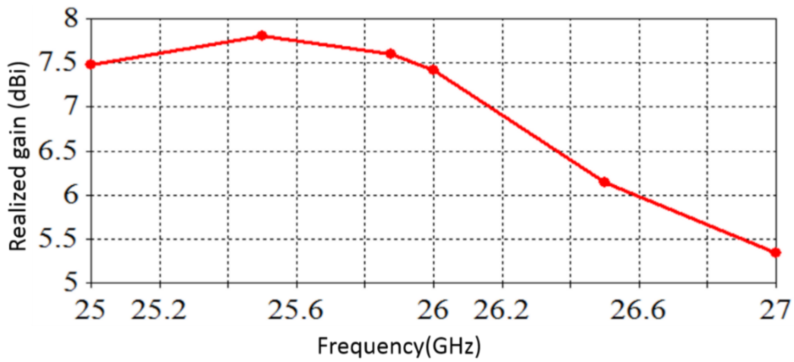
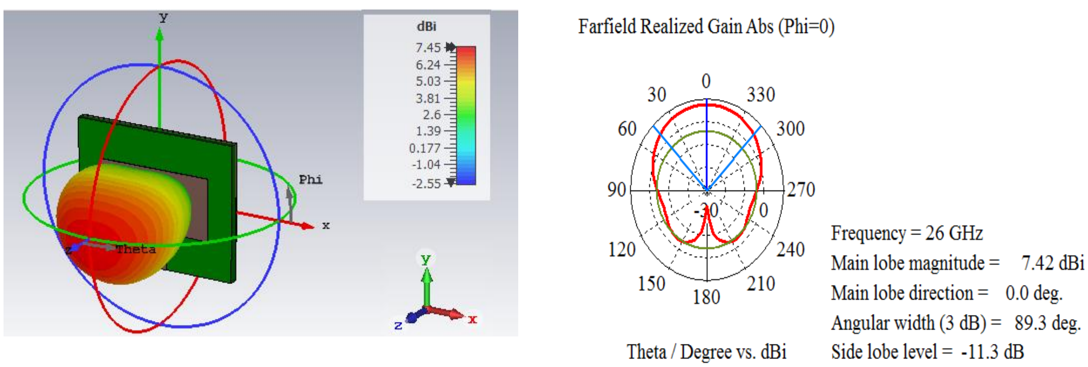


Fig.3. Realized gain vs frequency plot of the proposed inset fed patch antenna.

2.2 Far field and Gain 3D plot

Figure (4a) and figure (4b) show the 2D and 3D far field radiation pattern of the proposed antenna at (26 GHz) respectively. It can be seen that the antenna has gain of (7.42 dBi) at boresight direction.



(a) (b)

Fig. 4. Far field of the proposed inset fed patch antenna (a) 2D and (b) 3D

3. Beam squint

Designing antenna that works on Mm-waves frequency ranges has become the interest of researchers. the high frequencies require small size antenna which make it difficult to add slots and shapes, also the fabrication process can be complicated [11]. However, the short wave length of mm-waves makes it possible for the signals to pass through walls with ease, which causes some attenuation if line of sight connection is not offered [12].

To overcome mm-waves issues massive MIMO transmitters and receivers are used, however maintaining antenna array that works on these frequency ranges also comes with

problems. One of the main problems that come with using high frequency ranges is beam squint. Beam squint, which limits the usage of the antenna for wide band applications, is defined as the main lobe of the array being orientated at various angles for different microwave signal frequencies [8].If we assumed that f is the operating frequency and fc is the carrier frequency, Θ is the incident angle and Θ_f is focus angle.
If we have the incident wave vector in equation (9).

$$a(\Theta i, \phi i, f) = \frac{1}{\sqrt{Nt}}\left[1, e^{-j2\pi(\frac{d}{c}f)\sin(\theta)}, \ldots\ldots, e^{-j(Nt-1)2\pi(\frac{d}{c}f)\sin(\theta)}\right]^T \quad (9)$$

And the steering vector in equation (10).

$$a(\Theta s, \phi s, fc) = \frac{1}{\sqrt{Nt}}\left[1, e^{-j2\pi(\frac{d}{c}fc)\sin(\theta)}, \ldots\ldots, e^{-j(N-1)2\pi(\frac{d}{c}fc)\sin(\theta)}\right]^T \quad (10)$$

By taking the dot product of the two vectors the result is in equation (11)

$$a(\Theta, \phi, f) \,.\, a(\Theta, \phi, fc) = g(\varepsilon\varphi - \varphi f) \quad (11)$$

which is the gain of ULA and can be written as in equation (12).

$$g(\varepsilon\varphi - \varphi f) = \frac{\sin\left(\frac{N\pi}{2}(\varepsilon\varphi - \varphi_f)\right)}{\sqrt{Nr}\sin\left(\frac{N\pi}{2}(\varepsilon\varphi - \varphi_f)\right)} e^{j\frac{(N-1)\pi}{2}(\varepsilon\varphi - \varphi_f)} \quad (12)$$

we have $\varphi = \sin(\theta)$ if we assumed that $\varphi = \varphi_f$ and $\varepsilon = \frac{f}{fc}$ then we will get the equation (13)

$$g(f, \theta) = \frac{\sin\left(\frac{N\pi}{2}\sin(\theta)(f/fc - 1)\right)}{\sqrt{Nr}\sin\left(\frac{N\pi}{2}\sin(\theta)(f/fc - 1)\right)} e^{j0.5(N-1)\pi\sin(\theta)(\frac{f}{fc})} \quad (13)$$

If (Θ) is known then the equation will be function of f only. And from this equation we can say that the gain of ULA is function of frequency, and its value change with frequency changing and this will cause beam squint. Figure (5) plot the gain with elevation angle at Θ =10 degree the blue beampattern is when $f=f_c$, the red pattern is when $f > f_c$, and the yellow beam pattern is when $f < f_c$.

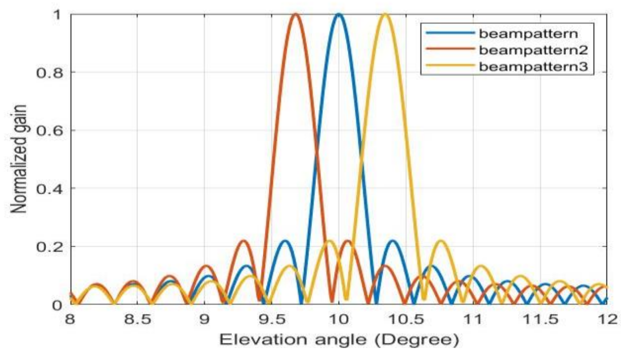


Fig.5. Normalized gain vs elevation angle.

Figure (6) shows the plots of both magnitude and phase of the gain function with frequency assuming that carrier frequency (f_c=26 GHz) at different incident angle.

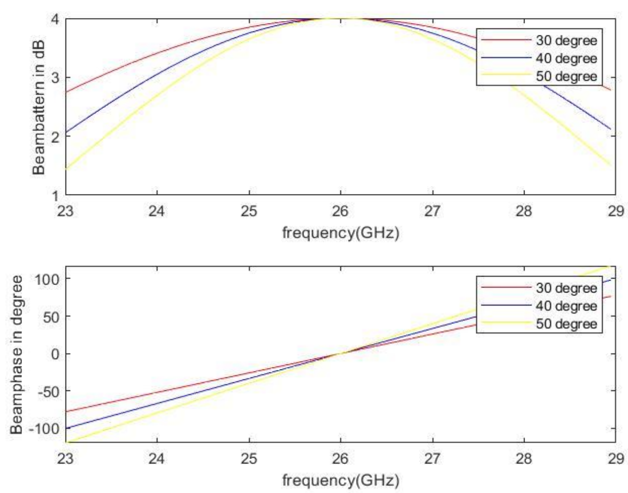
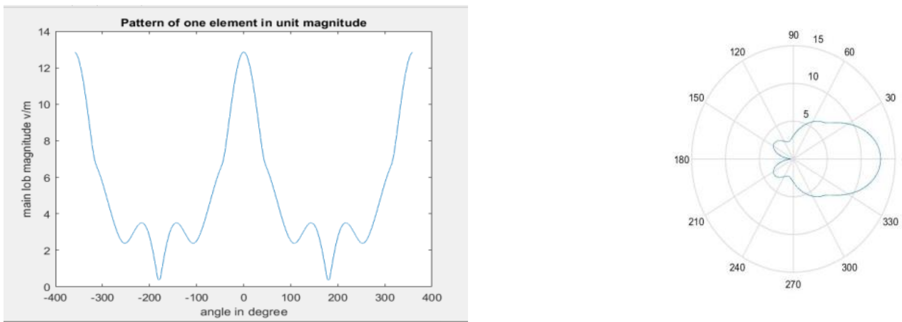


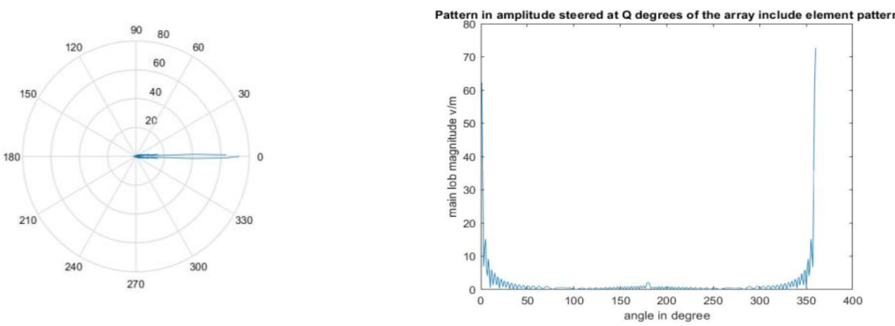
Fig.6. Magnitude and phase of the gain function with frequency at different incident angles.

To more visualize this problem first we call the pattern of the proposed antenna element from CST simulator to MATLAB and plot it. Fig (7) shows the pattern of one element. Then we multiply the single element radiation pattern with the array factor to get the pattern of uniform linear array. Fig (8) shows the resulting pattern of 16 elements uniform linear array at boresight direction (0 degree) and f_c=f=26 GHz.



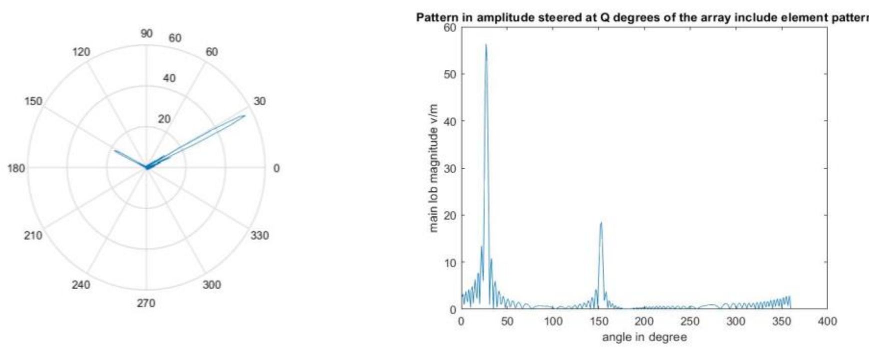
(a) (b)

Fig. 7. Radiation pattern of one element antenna (a) 1D polar plot(b) 1D cartesian plot.



(a) (b)

Fig. 8. Radiation pattern of ULA array (16 elements at 0 degree and $f = f_c$) (a) 1D polar (b) 1D cartesian



(a) (b)

Fig. 9. Radiation pattern of ULA array (16 elements at 30 degree and $f/f_c = 0.09$) (a) 1D polar (b) 1D cartesian plot.

Now if we change the incident angle to 30 degree and (f/f_c=0.09) we get the following response in Fig. 9. We can see that the main beam squinted from 30 degree to 27 degree. The degree of beam squint increase when the incident angel drift away from boresight direction. Or when the ratio of frequency of the incoming signal (f) to the carrier frequency (f_c) increased. All these effects motivated the authors to consider the basic antenna bandwidth accordingly. Therefore, it is a significant criterion in any mm-wave communication systems.

The principal objective of this study revolves around the investigation of the beam squint effect, particularly in the context of employing a straightforward antenna design within the millimeter-wave (mm-Wave) frequency spectrum. Notably, our design has demonstrated commendable bandwidth characteristics, exhibiting compact dimensions and a straightforward geometry conducive to cost-effective manufacturing. The ensuing discussion provides a comparative analysis, primarily focusing on other research endeavors pertaining to patch antenna designs.

Table 2 Comparision with other works

Reference	**Bandwidth (GHz)**	**Gain (dB)**	**Size of antenna (mm)**	**Efficiency**	**squint**	**Geometery**
Khattak et. al. [13]	1.30	7.60	6 x 6	85	Not taken into account	Complicated
Kaeib et. al. [14]	2.48	6.37	7 x 7	86	Not taken into account	Complicated
Jandi et. al. [15]	dual band (1 GHz each)	7.50	21 x 21	62	Not taken into account	simple
Proposed work	2 GHz	7.45	7.7 x 9.5	90	Taken into account	simple

4. Conclusion

MM-wave broadband inset fed patch antenna, that are suitable for future 5G mobile networks applications has been proposed in this paper and the effect of beam squint on its properties was studied. The patch is printed over Rogers RT Duroid 5880 substrate with size of 7.7mm x 9.5mm x 0.508mm. Inset with size 0.55 x 0.1 mm is added to increase the impedance matching. The results of the proposed antenna demonstrate a promising performance enhancement in term of gain, bandwidth, return losses. Beam squint problem is presented in this paper by calling the pattern of the proposed patch element from CST studio to MATLAB and multiply it by the array factor to give the resulted pattern of 16 element ULA. The results demonstrated that the array gain in MM-wave has become function of frequency and that will reduce the performance of the communication system if the traditional narrow band phase shifters is used in wide band communication. Therefore, we believe that choosing the basic antenna element is a critical issue in mm Wave 5G communication system. In future research we will try to find a method to compensate beam squinting phenomena that take into account complexity and cost.

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