International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-10 Issue-4, November, 2021

Reducing Subcarriers Beam-Squinting of Ultra-Wideband Mobile Communication Systems using Phased Array Antennas

K. Rama Devi, M. Nani

***Abstract:** There has been increasing demand for accessible radio spectrum with the rapid development of mobile wireless devices and applications. For example, a GHz of spectrum is needed for fifth-generation (5G) cellular communication, but the avail- able spectrum below 6 GHz cannot meet such requirements. Fortunately, spectrum at higher frequencies, in particular, millimeter-wave bands, can be utilized through phased-array analog beamforming to provide access to large amounts of spectrum. However, the gain provided by a phased array is frequency dependent in the wideband system, an effect called beam squint. We examine the nature of beam squint and develop convenient models with a uniform linear array. To further simplify the evaluation of the system performance, an approximated closed-form expression for the array gain is derived. Furthermore, to evaluate the performance of the proposed design, rigorous numerical results concerning different system parameters are provided in this paper.*

***Index Terms:** Beam-squinting, Analog architecture, Millimeter wave, Wideband, Array gain, Capacity.*

I.INTRODUCTION

Applications of wireless technologies and the number of wireless devices have been growing significantly in the past decade. For example, the global mobile data traffic grew 63 percent in 2016, and it is expected to grow at a compound annual growth rate of 47 percent over the next five years. There are increasing demands for radio spectrum to meet the requirements of higher data rates for an increasing number of mobile devices. As noted in a report from the President's Council of Advisors on Science and Technology (PCAST), access to spectrum will be an increasingly important foundation for economic growth and technological leadership in the coming years. However, the current process of long-term, static frequency allocation below 6 GHz cannot meet these demands for mobile spectrum. Two major directions are being explored for enhancing spectrum access, namely, reusing currently under-utilized spectrum through dynamic spectrum access (DSA), or spectrum sharing, and enabling access to spectrum at higher frequencies, e.g., millimeter-wave (millimeter-wave) bands .

Manuscript received on November 16, 2021.
Revised Manuscript received on November 22, 2021.
Manuscript published on November 30, 2021.
* Correspondence Author
Dr. K. Rama Devi*, Assistant Professor, Department of Electronics and Communication Engineering, Jawaharlal Nehru Technological University, Kakinada, (Andhra Pradesh). India.
M. Nani, Student, M. Tech, Jawaharlal Nehru Technological University, Kakinada, (Andhra Pradesh). India.

Although both directions require progress on interesting technical issues, this dissertation focuses on enabling spectrum access in millimeter-wave bands based upon, on the one hand, its potential for wide bandwidths and less congested airwaves and, on the other hand, DSA's on going regulatory and market uncertainties despite over a decade of significant research effort. There are several key features of millimeter wave bands that make them very attractive as the next frontier in wireless technology development. First, the millimeter-wave band ranges from 30 GHz to 300 GHz, with spectrum opportunities on the order of tens of GHz wide. In a loose sense, the 20-30 GHz band is also considered part of the millimeter wave band, further increasing the amount of available spectrum. By contrast, the total amount of spectrum available for sharing below 6 GHz is limited, on the order of hundreds of MHz. Second, signals at millimeter wave frequencies experience higher path loss and atmospheric absorption, typically 20 dB or more attention, than those below 6 GHz. Therefore, millimeter wave systems often require higher antenna directionality and have comparatively smaller range or coverage than systems operating below 6 GHz. Third, relatively sparse deployments currently in millimeter-wave bands leave much of the spectrum open to new entrants and simpler interference avoidance mechanisms, whereas the more congested spectrum below 6 GHz presents many technical challenges for deployment of spectrum sharing such as spectrum sustainability and hidden nodes . Fourth, commercially viable radio hardware for millimeter wave access is less mature than radio hardware operating below 6 GHz, and the device cost is usually higher. As development of device technologies for millimeter wave accelerates, the cost gap should close rapidly. A promising method to compensate for the higher attenuation in millimeter wave bands is beamforming. To achieve high directional gain, either a large physical aperture or a phased-array antenna is employed. The energy from the aperture or multiple antennas is focused on one direction or a small set of directions. The cost of a large physical aperture is relatively high, especially in terms of installation and maintenance. Fortunately, the short wavelengths of millimeter wave frequencies in principle allows for integration of a large number of antennas into a small phased array, which would be suitable for application in commercial mobile devices. In millimeter wave beamforming, a phased array with a large number of antennas can compensate for the higher attenuation.

In this dissertation, we consider practical implementations of millimeter wave analog beamforming with one radio frequency (RF) chain and a phased array employing phase shifters. Traditionally, in a communication system with analog beamforming, the set of phase shifter values in a phased array are designed at a specific frequency, usually the carrier frequency, but applied to all frequencies within the transmission band- width due to practical hardware constraints. Phase shifters are relatively good ap- proximations to the ideal time shifters for narrowband transmission; however, this approximation breaks down for wideband transmission if the angle of arrival (AoA) or angle of departure (AoD) is far from the broadside because the required phase shifts are frequency-dependent. The net result is that beams for frequencies other than the carrier “squint” as a function of frequency in a wide signal bandwidth [1]. This phenomenon is called beam squint [2]. As we will see, beam squint translates

In this paper, a novel analog architecture design to mitigate the impact of BS is proposed. The main idea behind the proposed design is to divide a wideband or ultra-wideaband signal into chunks of comparatively narrowband signals using a bank of bandpass filters, followed by an additional phase shift with respect to the centre frequency of each filter. The advantage of our proposed design is that it does not rely on any compensation in the digital domain or use any specialized components such as a Rotmanlens. It is therefore suitable for computational power constrained or delay-sensitive applications [3], [4], which do not have the liberty to calculate large compensation matrices in the digital domain. Table I provides a brief summary along with comments on the key design features of the aforementioned existing approaches to mitigate beam-squinting. The previously proposed methods are either specifically intended for a system employing hybrid precoding or require multiple radio frequency (RF) chains in the transceiver design. In comparison, our proposed design does not have such constraints and can be tailored for the aforementioned scenarios. Therefore to show a fair comparison and following the literature [5], [6], [7],[8],the performance of the proposed design is compared against an ideal system with no BS and a practical system with BS. Hence, this letter addresses the question in ultra-wideband mmW-enabled massive MIMO systems: “how to provide an order of magnitude capacity improvement without adding any computational complexity?”

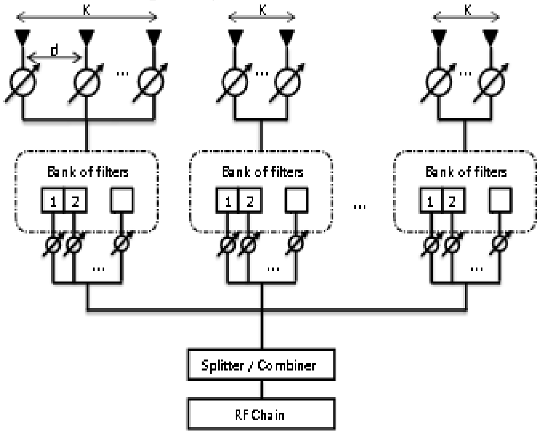

Fig. 1: System Model

II.SYSTEM MODEL OF THE RECEIVER ARRAY

Suppose the signal arriving at the array is s(t), then the received signal vector y(t) at N antenna elements before the phase shifters is

$$\mathbf{y}(t)=\left[s(t),...,s\left(t-\frac{(n-1)d\sin\theta}{c}\right),\right.\\ \left....,s\left(t-\frac{(N-1)d\sin\theta}{c}\right)\right]^T. \quad (1)$$

Similarly, its frequency response can be written as

$$\mathbf{y}(f,\theta)=s(f)\,[1,\exp j(2\pi c^{-1}fd\sin\theta),\\ ...,\exp j(2\pi c^{-1}f(n-1)d\sin\theta),\\ ...,\exp j(2\pi c^{-1}f(N-1)d\sin\theta)]^T \quad (2)$$

where y(f, θ) is a function of the AOA θ, and

θ ∈{−π,π }.Define the ULA response vector as

$$\mathbf{a}(\theta,f)=[1,\exp j(2\pi c^{-1}fd\sin\theta),\\ ...,\exp j(2\pi c^{-1}f(n-1)d\sin\theta),\\ ...,\exp j(2\pi c^{-1}f(N-1)d\sin\theta)]^T. \quad (3)$$

The optimal combiner or steering vector for the received signal y(f, θ) should be a filter matched to a(θ, f) denoted as

$$\mathbf{w}=\mathbf{a}^H(\theta,f).$$

Since elements in the matched filter are true time delay devices and they have their own implementation issues, we use phase shifters instead. A phase shifter is typically modeled as a constant phase shift for the whole frequency range it is designed for. Hence, the phase shifter based steering vector with phase shift βn for the nth antenna element is written as

wˆ= [exp j(β1), ..., exp j(βn), ..., exp j(βN)] .(5)

Following [9], the array gain of phased array at angle of arrival θ can be formulated as

$$g(\hat{\mathbf{w}},\theta,f)=\frac{1}{\sqrt{N}}\hat{\mathbf{w}}^H\mathbf{a}(\theta,f)\\ =\frac{1}{\sqrt{N}}\sum_{n=1}^{N}\exp j(2\pi c^{-1}f(n-1)d\sin\theta-\beta_n). \quad (6)$$

Typically we choose βn with respect to the centre frequency i.e., f_c in our case

$$\beta_n(\psi)=2\pi c^{-1}f_c(n-1)d\sin\psi. \quad (7)$$

Here ψ is the angle of desired beam and inter-antenna element distance $d=\frac{\lambda_c}{2}$. Putting (7) into (6), we get

$$g(\psi,\theta,\xi_{n_f})=\frac{1}{\sqrt{N}}\sum_{n=1}^{N}\exp j(\pi(n-1)(\xi_{n_f}\sin\theta-\sin\psi)). \quad (8)$$

Retrieval Number: 100.1/ijrte.D66191110421
DOI: 10.35940/ijrte.D6619.1110421
Journal Website: www.ijrte.org

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)

Here, ε_{n_f} is the ratio of subcarrier frequency to the carrier frequency fc for subcarrier n_f.

$$\xi_{n_f} = 1 + \frac{(2n_f - N_f + 1)b_{frac}}{2N_f}. \quad (9)$$

Here $b_{frac} = \frac{B}{fc}$ is the fractional bandwidth, $n_f \in \{0, 1, ..., N_f - 1\}$, and N_f is the total number of subcarriers

Lemma 1. *Following the proposed analog architecture, the array gain with the PC factor $\pi\emptyset k(n_f)$ is obtained as[9]*

$$g_{pc}(\psi, \theta, n_f) = \frac{1}{\sqrt{N}} \sum_{k=1}^{\frac{N}{K}} \sum_{n=(k-1)K+1}^{Kk} \exp\left(j\pi\left((n-1)x_{n_f} + \phi_k(n_f)\right)\right), \quad (10)$$

where

$$x_{n_f} = (\xi_{n_f} \sin\theta - \sin\psi),$$

and

$$\phi_k(n_f) = (K(k-1) + c_k)x_{c,n_f}.$$

Here the variable ck represents the index of antenna element which drives the subsequent layer of phase shifters within its antenna group of size K, and .

$$x_{c,n_f} = (\xi_{c,n_f} \sin\theta - \sin\psi)$$

$\forall \varepsilon_{C}, n_f$ represents the ratio of the centre subcarrier frequency of each bandpass filter to the carrier frequency fc. Hence, the value of x_{c,n_f} remains constant for all the subcarriers of each filter.

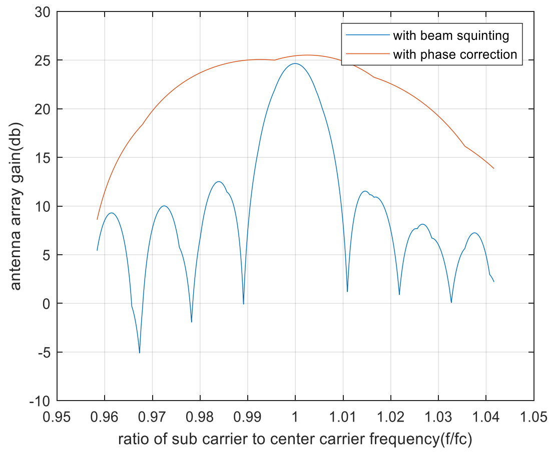

Fig. 2: Array gain for $f_c = 60$GHz, $N_f = 2048$, $N = 256$, $B = 5$GHz, $\psi = \theta = 0.8$ $K = 64$, $b = 16$, and $L = 3$. The plotted array gain is averaged over the set $\{\theta - 0.1, \theta, \theta + 0.1\}$.

This section illustrates the effects of beam squint on channel capacity for a ULA, with the understanding that there are similar effects in the case of a UPA. Although in general the effect of beam squint on capacity depends upon the AoD, the transmitter beam focus angle, the AoA, and the receiver beam focus angle, we consider for simplicity the case of no beam squint at the transmitter and study the beam squint of a single array at the receiver. Therefore, only the AoA and the receiver beam focus angle are examined here.

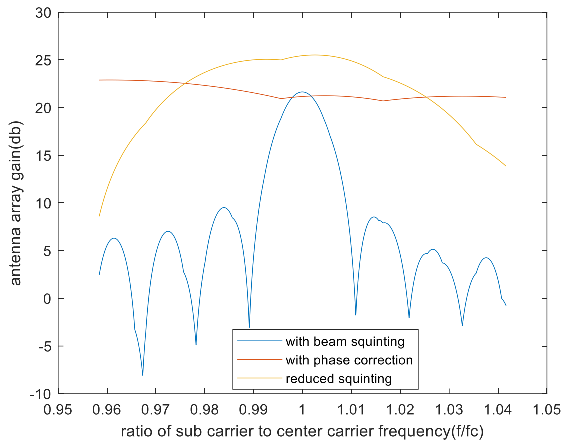

Fig2

Array gain for $f_c = 60$GHz, $N_f = 2048$, N=128 $B = 5$GHz, $\psi = \theta = 0.8$ $K = 64$, $b = 16$, and $L = 3$. The plotted array gain is averaged over the set $\{\theta - 0.1, \theta, \theta + 0.1\}$.

Consider a continuous-time AWGN channel with bandwidth W Hz, power constraint P Watts, and additive white Gaussian noise with power spectral density N0/2. Following the passband-baseband conversion and sampling at rate 1/W, this can be represented by a discrete-time complex baseband channel [10]
y[m] = x[m] + w[m],

where w[m] is CN (0, N0) and is i.i.d. over time. Note that since the noise is independent in the I and Q components, each use of the complex channel can be thought of as two independent uses of a real AWGN channel. The noise variance and the power constraint per real symbol is N0/2 and P / (2W) respectively. Hence, the capacity of the channel is $\frac{1}{2}\log\left(1 + \frac{P}{N_0 W}\right)$
bits per real dimension, This is the capacity in bits per complex dimension or degree of freedom. Since there are W complex samples per second, the capacity of the continuous-time AWGN channel is

$$C = B\log_2\left(1 + \frac{S}{N}\right)$$

Corollary 1. *Assuming Gaussian signalling [11] and following [12], the achievable capacity for the derived array gain in Lemma 1 can be expressed as*

$$C_{pc} = B\frac{1}{N_f}\sum_{n_f=0}^{N_f} \log\left(1 + \frac{P|g_{pc}(\psi, \theta, n_f)|^2}{B\sigma^2}\right) \quad (11)$$

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

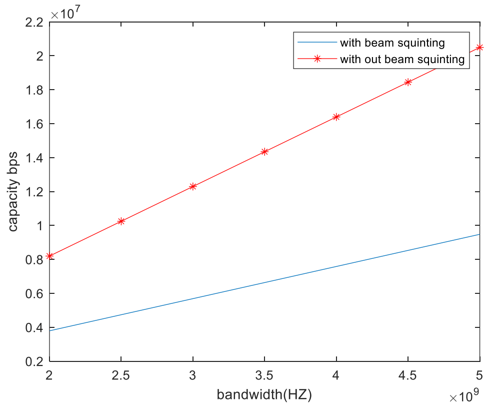

Fig. 3: Capacity with and without PC for fc = 60GHz, Nf = 2048, N = 256, ψ = θ = 0.8 K = 64, b = 16, and L = 3.The plotted capacity is averaged over the set {θ − 0.1, θ, θ + 0.1}.

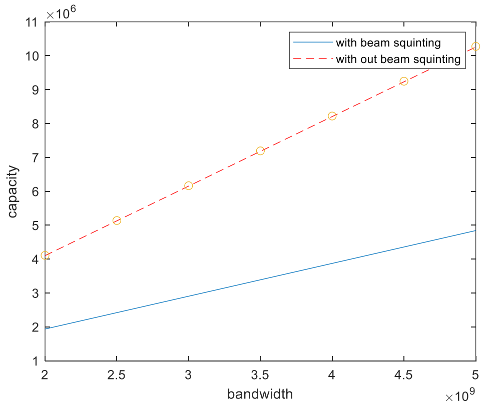

Fig. 4: Capacity with and without PC for fc = 60GHz, Nf = 2048, N = 128, ψ = θ = 0.8 K = 64, b = 16, and L = 3.The plotted capacity is averaged over the set {θ − 0.1, θ, θ + 0.1}.

III.NUMERICAL RESULTS

In this section, we analyze the performance of the novel proposed architecture. Fig. 2 shows the comparison between the array gain of the proposed model with PC (Lemma 1) and the array gain of a typical system with BS. It is observed that the proposed design improves the array gain of the subcarriers on the left and right of the main lobe. For example the ξnf =1.03and ξnf =0.97 improvement in array gain is approximately 10dB. Hence, in applications where the reliability of the information on all subcarriers are of equal importance or in scenarios where we do not have the liberty to calculate large compensation matrices in the digital domain, the proposed design can provide significant improvement in the array gain that will consequently improve the achievable rate. This improvement in the array gain is a direct result of those additional antenna driving elements, i.e., the bank of bandpass filters and the additional phase shifters. In addition to that, Fig. 2 also shows the impact of linear approximation of ck on the array gain by comparing the array gain curves of Lemma 1 and Theorem 1. It can be observed that the linear approximation of ck provided in theorem 1 is very tight for a wide range of subcarriers. The effect of this approximation on capacity is illustrated in Fig. 3.Fig. 3 compares the capacity of an ideal system with no BS, with BS, and with PC based on the proposed design (Corollary 1). All the relevant parameters are listed in the caption. Although gain of the proposed design, approximately 20% at B = 5GHz, is evident from the figure, it is worth mentioning that this capacity gain does not increase linearly with the bandwidth B. For example, we notice that the trend of the capacity with PC curve, at around B = 4GHz, starts to flatten and as we move further, it even shows a slightly decreasing trend, at around B = 4.6GHz. The rationale behind this nonlinear gain in capacity is the use of bank of filters of fixed size for all bandwidths (i.e., L = 3 used in Fig. 4). Moreover, capacity curves of Corollary 1 show that the approximation of ck to a linear function of b is very tight for a reasonable range of bandwidths and it can be even tighter for larger bandwidths if we optimize b for a given signal bandwidth. For example, the gap between the capacity curves of Corollary 1 and Corollary 2 at B = 5GHz can be further reduced if we optimize the value of b for B=5GHz,this point is further elaborated in the discussion of Fig. 5.Here, the capacity curve of Corollary 1 is generated using an exhaustive search on ck.

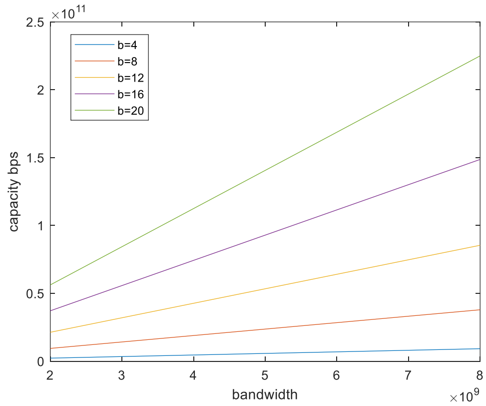

Fig. 5: Capacity with PC for fc = 60GHz, Nf = 2048, N = 256, ψ = θ = 0.8 K = 64, and L = 3. The plotted capacity (Corollary 2) is averaged over the set {θ − 0.1, θ, θ + 0.1}.

Fig. 4 shows the impact of the size of bank of band pass filters on to the capacity of the proposed design. It is noticed that the increase in the size of bank of filters doesn't directly translate into an increase in the capacity. Interestingly, if we look at the capacity curves around B = 4.5GHz, we notice that the increase in the size of bank of filters can even reduce the capacity. The rationale behind this non-trivial behavior is that each bandpass filter and its following phase shifter perform the PC with respect to the centre frequency of that bandpass filter. Hence, that constant PC can work negatively for the other subcarriers that lie within that bandpass filter. Therefore, increasing the size of a bank of bandpass filters does not always result in a linear increase in capacity and it should be optimized for a given signal bandwidth. Fig. 5 shows the impact of the parameter b on the capacity. It is evident from the results that its impact is nonlinear for ultra-wide bandwidths. Therefore, just like the size of a bank of filters L, it should also be optimized for a given signal bandwidth and desired beam angle to achieve maximum capacity.

Retrieval Number: 100.1/ijrte.D66191110421
DOI: 10.35940/ijrte.D6619.1110421
Journal Website: www.ijrte.org

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)

IV.CONCLUSIONS AND FUTURE WORKS

Beam squint is a concern for millimeter wave beam forming .In this paper, an analog architecture design to mitigate the issue of beam-squinting in wideband and ultra-wideband communication systems is proposed. We provided a detailed analytical model of the proposed design and illustrated its performance using numerical results. The results show that the significant gain in capacity can be achieved by the proposed design, for a range of signal bandwidths. Moreover, since the proposed design does not require any computation of large compensation matrices in the digital domain, it can be a promising solution for the delay sensitive applications. It is worth mentioning that this work can be extended to find the optimal values of the size of the bank of filters Land C_K, which represents the index of antenna element which drives the subsequent layer of phase shifters, for a given signal bandwidth. Also, parameter b which approximates the C_K to a linear function $(k-1)b$ can be optimized for a given signal bandwidth to maximize the array gain and consequently the achievable capacity.

REFERENCES

1. R. J. Mailloux. Phased array antenna handbook. Artech House, Norwood, MA, second edition, 2005.
2. S. K. Garakoui, E. Klumperink, B. Nauta, and F. E. van Vliet. Phased-array antenna beam squinting related to frequency dependence of delay circuits. In 41th European Microwave Conference, Manchester, UK, Oct. 2011.
3. M. Alsenwi, N. H. Tran, M. Bennis, A. Kumar Bairagi, and C. S. Hong, "eMBB-URLLC resource slicing: A risk-sensitive approach," IEEE Commun. Lett., vol. 23, no. 4, pp. 740–743, April 2019.
4. T. K. Vu, C. Liu, M. Bennis, M. Debbah, M. Latva-aho, and C. S. Hong"Ultra-reliable and low latency communication in mmWave-Enabled massive MIMO networks," IEEE Commun. Lett., vol. 21, no. 9, pp. 2041–2044, Sep. 2017.
5. K.Rama Devi "MicroStrip Planar Array Antenna for 5G baseband Communications" Journalof Emerging Technologies and Innovative Research UGC 2019
6. G. Li, H. Zhao, and H. Hui, "Beam squint compensation for hybrid pre- coding in millimetre-wave communication systems," Electronics Letters, vol. 54, no. 14, pp. 905–907, 2018
7. X. Liu and D. Qiao, "Space-time block coding-based beamforming for beam squint compensation," IEEE Wireless Commun. Lett., vol. 8, no. 1, pp. 241–244, 2019
8. K.Rama Devi "Design and analysis of microstrip antenna for 5G Applications" International research journal of engineering and technology 2019
9. C. A. Balanis, Antenna theory: analysis and design. John wiley &sons,2016
10. T.S. Rappaport. Wireless communications: principles and practice. Prentice Hall, Upper Saddle River, New Jersey, second edition, 2002.
11. T. M. Cover and J. A. Thomas, Elements of information theory. John Wiley & Sons, 2012.
12. D. Tse and P. Viswanath, Fundamentals of wireless communication. Cambridge university press, 2005.

AUTHORS PROFILE

Dr. K. Rama Devi, has completed Diploma in Electronics and Communication Engineering in 1995 and AMIETE in 2000. She obtained M.Tech degree in Microwave and Radar Engineering from Osmania University College of Engineering, Hyderabad in 2003. She started her career as teaching profession from 2003 onwards and working as Assistant Professor in department of ECE, JNTUK, Kakinada, Andhra Pradesh. She is received Doctoral degree from J.N.T.U. Kakinada in June 2017 in the area of Antenna Designing. She published more than 40 research papers in various national, international journals under UGC-CARE List Categorization-A and more than 20 papers presented in international conferences and published in IEEE-xplore, springer etc . She guided 28 PG projects as Supervisor and 7 Ph.D scholars as Supervisor and Co-Supervisor. She published 1 (one) text book on RFID Tag Antenna Designing. Her research interests in the area of Communications, image processing, signal processing, MicroStrip Patch Antennas, slot antennas simulated in MATLAB and HFSS, 4Nec etc. She is life member in IETE and ISTE

Nani, completed bachelor of technology in 2019, now he is a final year student set to complete his Masters in technology (m.tech) degree in 2021 from JNTU KAKINADA