Progress In Electromagnetics Research B, Vol. 98, 147–164, 2023

Comparative Analysis of Smart Beam-Steering Antennas for mm-Wave Communication Systems & 5G

**Shafaq Kausar[1, *], Ahmed Kausar[2], Hani Mehrpouyan[1],
Muhammad U. Hadi[3], and Salahuddin Tariq[4]**

Abstract—The aim of the next-generation 5G wireless network is to provide high data rates, low latency, increased network capacity, and improved quality of surface (QoS) for wireless communication and internet of things (IoT). The millimetric wave communication is a promising technique with the capability of providing multi-gigabit transmission rate, network flexibility, and cost-effectiveness for 5G backhauling. Smart antennas are a critical requirement for the success of millimetric wave communication system, and these antennas have the capability to form a high gain beam in desired direction and a null towards interfering signal. Directional beam-forming mitigates the high path loss associated with millimetric communication & improve signal to interference noise ratio. This article presents comparative analysis, effectiveness, and current limitations of various beam steering techniques for 5G networks based on some figures of merit with the aim of highlighting areas of improvements for each beam steering technique.

1. INTRODUCTION

Fifth generation (5G) communication systems are designed to meet high data-rate requirements of wireless networks, and these systems are posed to solve challenges associated with network congestion and latency. With 5G, users would be able to download a high definition (HD) data within a second (a task that can take up to 10 minutes on 4G LTE). To be able to achieve such connectivity, high device density, low latency, and fast data rate must be achieved. Extending operating frequency towards higher frequency bands, advanced multi-antenna systems and wireless power transmission are some of the key technologies that are being developed for 5G systems. Fig. 1 shows expected performance improvements for 5G networks. 5G network is expected to have 10 to 100 times higher number of connected devices, 1000 times higher mobile data volume, 5 times reduced end to end latency, 100 times higher typical user data rate, and 10 times longer battery life. All these attributes make it a promising technology for next-generation communication networks [1, 2].

To employ 5G systems, large bandwidth is required. However, the radio spectrum is widely occupied by other services. Millimetric wave band is emerging as a good alternative to sub-6 GHz band for next generation wireless communication as sufficient bandwidth is available at millimetric frequency bands. Millimetric wave frequency communication will play a key role in next-generation 5G technology because of fast data rates and high aggregate capacity for handling multiple users at the same time. However, the use of millimetric frequencies has its own drawbacks. Key challenges associated with millimetric

---

Received 23 November 2022, Accepted 20 February 2023, Scheduled 3 March 2023

[*] Corresponding author: Shafaq Kausar (shafaq.omar@yahoo.com).

[1] Department of Electrical and Computer Engineering, Boise State University, Boise, Idaho 83725, USA. [2] Arts & Science Division at University of Toronto, Toronto, Ontario M5S 3G3, Canada. [3] School of Engineering, Ulster University, Newtownabbey BT37 0QB, UK. [4] Department of Electrical and Computer Engineering, University of Texas at Dallas, Richardson, Texas 75080, USA.

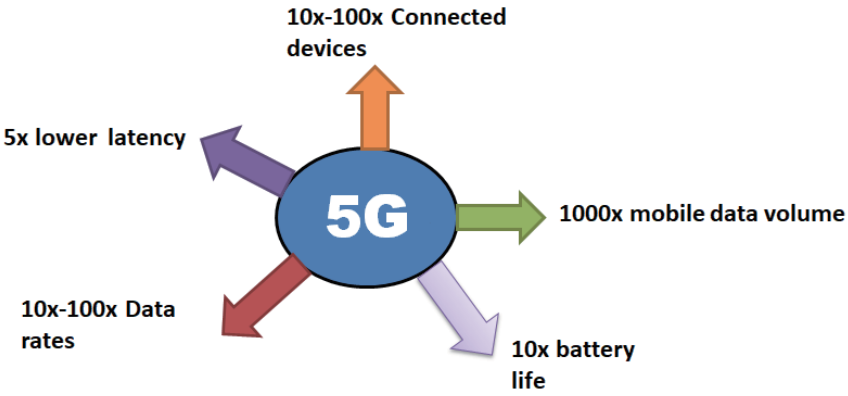


Figure 1. 5G performance objectives compared to existing network.

frequency bands are high path loss and atmospheric absorption due to rainfall and non-line of sight propagation [3, 4]. The free space path loss (FSPL) equation is given below [3].

$$\text{FSPL} = \left(\frac{4\pi R}{\lambda}\right)^2 \tag{1}$$

$$\text{FSPL(dB)} = 92.4 + 20\log(f) + 20\log(R) \tag{2}$$

where f is the frequency, and R is the distance between antennas (transmitting and receiving antennas). The link budget is affected by this loss and becomes a big challenge when transmitting over a large distance. High gain millimeter wave antennas are required to overcome the high path losses. Distances between respective nodes should be reduced to a few meters to decrease the losses. Beyond 60 GHz the absorption of energy from radio waves reaches its peak value due to atmospheric gases. At frequencies of this band size of raindrops, walls and other objects become significant as compared to the wavelength. Walls and objects become obstacles yielding high penetration losses at mm-wave frequencies. Hence, these issues become major concerns for using millimetric waves for 5G systems. The solution to such problems is reducing the transmission distances and employing highly directional antennas.

Effective deployment of 5G infrastructure requires the design of compact and efficient antennas. Antennas capable of beam steering can provide high gain and can suppress noise and interference by avoiding communication towards undesired direction. Beam steering antenna systems can improve the network performance and reduce cost by channeling the communication towards the desired direction.

2. BEAM STEERING TECHNIQUES

As mentioned previously, smart beam-steering antennas form a high gain directional beam towards the intended direction. In this paper we have analyzed multiple beam-steering techniques for next generation 5G communication systems. These beam-steering techniques include metasurface based beam-steering, switched array based beam-steering, parasitic array based beam-steering, mechanical beam-steering, electronic beam-steering, and rotatable phase selective surface based beam-steering. In this paper, we will also analyze figure of merit of the above mentioned beam-steering techniques and evolution of these techniques for implementation in 5G networks.

2.1. Mechanical Steering

In mechanical beam-steering the antenna radiation pattern is steered by mechanical movement of the antenna aperture. Typically, mechanical beam-steering antennas have high scan range and do not suffer from scan loss as well as skew loss. However, mechanical beam-steering antennas are slow in steering antenna beam, and these antennas are prone to mechanical wear & tear. Due to slow response time and mechanical issues, electronic beam-steering antennas are preferred for high end applications.

2.2. Beam-Forming

Beam-forming refers to forming a directive beam by using multiple elements arranged in an array. Phases of array elements are adjusted to form a highly directive beam. This can be done by adding a time delay to each element. These techniques can be classified as analog beam-forming, digital beam-forming, or hybrid beam-forming. In general, the radiation pattern for an n element array is given as:

$$A(k) = a_0 e^{jkd0} + a_1 e^{jkd1} \ldots + a_{n-1} e^{jkd(n-1)} \tag{3}$$

where a_n corresponds to the magnitude and phase of the weight applied to the n_{th} antenna element; k equals 2π; and d_n represents the distance of the element from the point of reference. The applied weights help underline energy in a particular direction, thereby producing a high Signal to Noise Ratio (SNR) over an omnidirectional pattern in the desired direction contributing to enhanced gain and directivity. Beam-forming can be analog, digital, and hybrid.

2.2.1. Analog Beam-Forming

In analog beam-forming, each antenna element has its individual phase shifter, and beam-steering is achieved by controlling phased shift of the RF signal at each antenna element. Fig. 2 depicts the typical implementation of an analog beam-forming antenna. In [5], the design of a planar array antenna for Wi-Fi applications is discussed, and the proposed antenna is capable of steering its radiation pattern. Analog beam-forming antenna systems can produce multiple beams simultaneously to perform multi-function operations; however, there are some challenges which need to be considered. At high frequencies, the bandwidth of phase shifter puts some limitations on the operation of the antenna. Phase shifters have losses, and insertion loss becomes high when the number of shifters increases. Insertion losses also increase with an increase of frequency, and at high frequencies insertion loss becomes high. Moreover, such antennas have large sizes, and it becomes difficult to employ them in compact configurations.

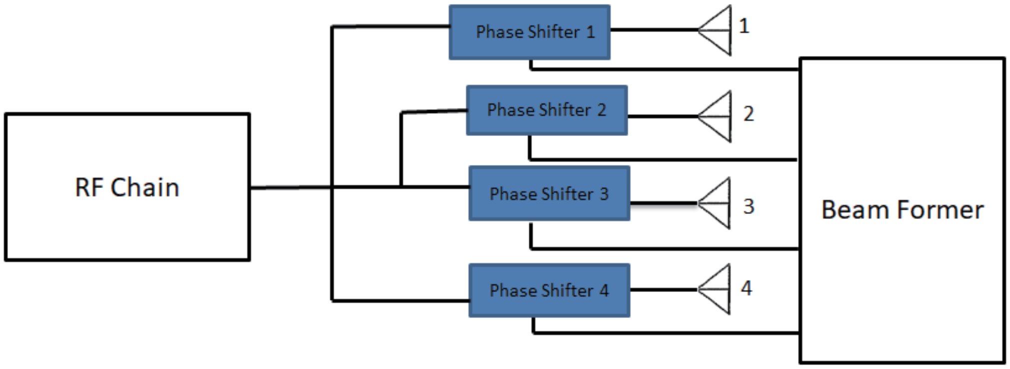


Figure 2. Analog beam-forming.

2.2.2. Digital Beam-Forming

In digital beam-forming phase shift (time delay) is added to the RF signal of each antenna element in the digital domain using advance digital signal processing techniques. In this technique, each antenna element has its own RF chain and analog to digital (A/D) or digital to analog (D/A) converters. The A/D and D/A converters convert analog signal to digital domain and vice versa.

Digital beam-forming is one of the most efficient beam-forming technique, and it is possible to form multiple beams using this technique. However, digital beam-forming involves A/D and D/A converters which increases cost as well as power consumption of the antennas. Fig. 3 shows the typical implementation of a digital beam-steering antenna.

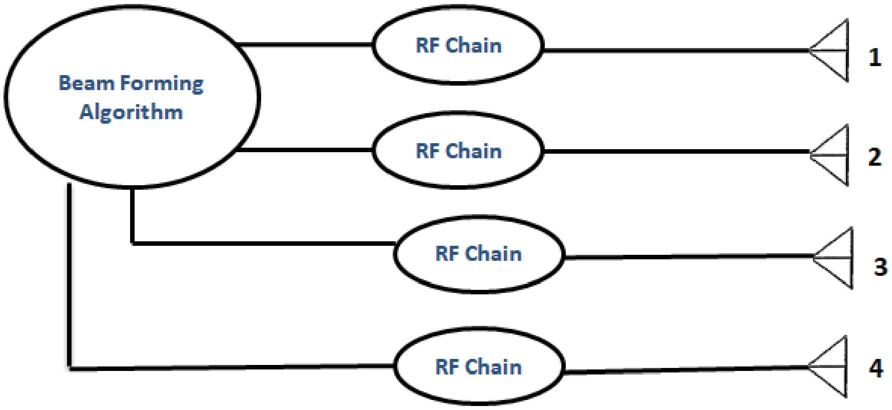


Figure 3. Digital beam-forming.

2.2.3. Hybrid Beam-Forming

Hybrid beam-steering is a hybrid between analog beam-steering and digital beam-steering. Fig. 4 shows implementation of a hybrid beam-forming antenna. This technique reduces the number of digital phase shifters that are required for steering antenna.

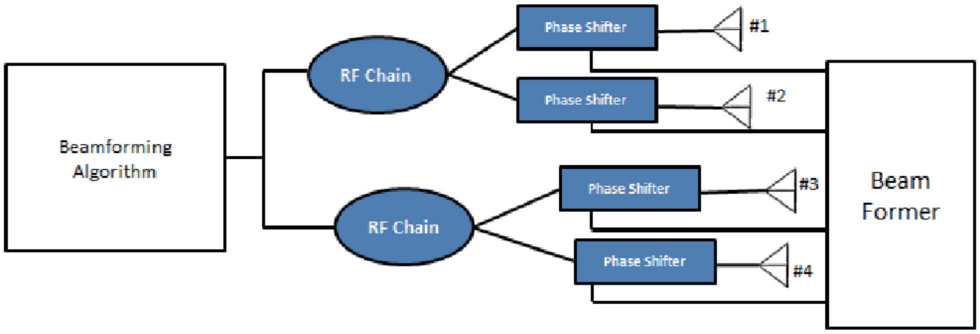


Figure 4. Hybrid beam forming.

2.3. Passive Electrically Steerable Antenna

In passive antennas there is an active antenna feed, and the active antenna excites the passive elements through mutual coupling. The term parasitic is used for the element which gets energy through mutual coupling from active element. Yagi-Uda antenna is an example of a basic parasitic array antenna, shown in Fig. 5. It consists of directors, reflectors, and the driven element made up of half wave dipoles [6, 7]. Directors absorb the radiations from driven elements and redirect them with a different phase. Waves from multiple elements superpose to enhance the radiation pattern. In this manner, antenna gain increases substantially as compared to the gain of a simple dipole. This type of configuration can radiate in a specific direction. This design has been transformed into different configurations to achieve steerable patterns. Circular monopole array (CMA) is another configuration of parasitic steerable antennas [8, 9]. In such antennas, driven element is placed at the center, and parasitic elements surround the driven element. Parasitic elements are energized from driven central element via mutual coupling.

Electronically Steerable Parasitic Array Radiator Antenna (ESPAR) is an example of parasitic circular monopole array. It consists of a central monopole surrounded by six parasitic monopoles as shown in Fig. 6 [10–12]. ESPAR antenna is simple and cheap to construct and can be used for directional communication and active tracking of dynamic targets [13]. In such kind of antennas distances between

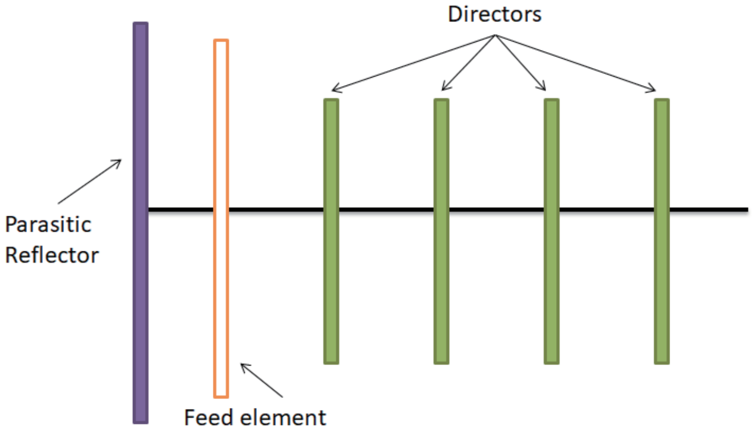


Figure 5. Yagi-Uda antenna.

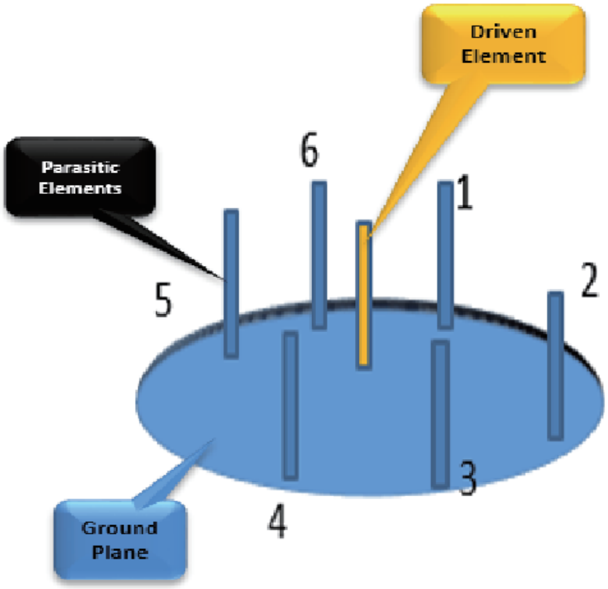


Figure 6. ESPAR antenna schematics.

parasitic elements and the central element should be between 0.1 and 0.5λ. This separation has a great effect on antenna performance. If the spacing is too short, the mutual coupling distorts the antenna performance. Similarly, the distance between parasitic elements should be appropriate to avoid excessive coupling between them [14].

Beam steering in ESPAR antenna is controlled by loading the array elements with varactors. Varactors provide variable reactance dependent on the applied voltage and control the overall radiation pattern formed by elements. Apart from cylindrical monopoles printed parasitic antennas have also been designed. By appropriately setting the thickness of patches and their mutual distances beam steering in two planes can be done. Fig. 7 shows an example of such an antenna; it consists of four printed parasitic elements and one driven element. A lot of techniques have been introduced to improve the steering angle and resolution of such designs. In [15], the design of a shell-in-shell (sis) resonator based antenna is proposed. In this case, active element excites the sis resonator.

Parasitic antenna designs do not involve phase shifters. Such antennas are easy to fabricate and extremely low cost. Mutual coupling reduces power consumption of antenna systems and saves cost.

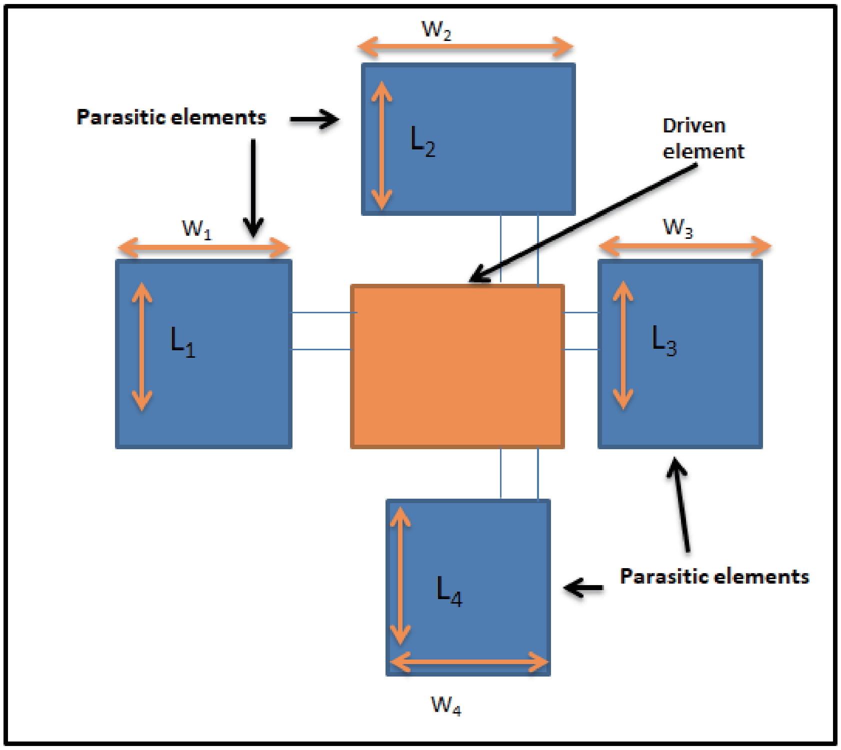


Figure 7. Parasitic patch antenna.

Insertion loss is also lower because of the absence of phase shifters. Parasitic steering only supports predefined angles. For 5G communication highly directional antennas are required, and parasitic steering has moderate gain, so to employ such antennas for 5G configuration gain enhancement needs to be done. Gain enhancement can be done using the following techniques:

- The magnitude of electric field of an antenna is proportional to its length. Gain can be increased by increasing the effective length of the antenna. This is because of the increase in the radiation aperture.
- Gain of an antenna can be enhanced by partially cutting slots in the substrate and using multiple layer dielectric substrates.
- A reflector can be integrated in antenna system. Electromagnetic waves after striking the reflector form a unidirectional beam thus increases the antenna gain.
- Increasing the number of array elements.
- Using planar configuration instead of linear or circular one.

2.4. Metamaterial Based Antennas

Metamaterial based antennas use meta-surfaces for converging electromagnetic (EM) signals. Metamaterials are materials engineered to have unique properties, and they do not occur naturally [16]. Metamaterials develop their properties because of the unique arrangement of sub-wavelength structures. The specific geometry and orientation of sub-wavelength structures enable metamaterials to manipulate electromagnetic waves (EM waves) by blocking, bending, or absorbing the RF signal [17–19].

Metamaterials have unique characteristics in a way that their relative permeability and permittivity can be turned negative and positive [20]. Using this property their refractive index can be controlled via diodes, varactors, or RF switches. Hence, metamaterials can be used to steer the antenna radiation pattern without using complex structures or phase shifters. Because of novel properties and design simplicity, metamaterials are gaining lots of popularity these days.

Metamaterial based antennas consist of periodic metallic cells printed on a substrate and placed above the radiating surface. They act like frequency selective surface (FSS). To achieve beam steering, cells are connected to varactors. By tuning each cell with different capacitance, permittivity and permeability can be changed thus change the refractive index of the material. Fig. 8 shows a metamaterial based antenna configuration. In this design, an FSS unit is placed in front of the horn antenna. The FSS unit is made up of a rectangular metallic ring and a patch. Varactor diodes are placed along incident electric field polarization direction. By tuning the varactors, the transmission phase of the emitted wave can be varied to achieve beam steering [20].

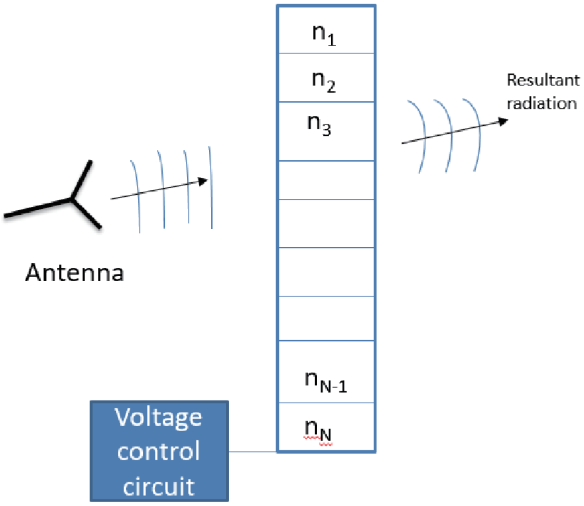


Figure 8. Metamaterial based antenna surface.

Metamaterial based lens has also been designed for beam steering. In such antennas, metamaterials act like a lens. Layers of metamaterials are placed over radiating elements. Beam steering in integrated lens antennas is achieved by offset of the radiating array elements placed at the back focal plane of the lens. In the case of a metamaterial lens, the refractive index of the lens can be changed by tuning the active device in the metamaterial [21].

Metamaterials can also be used to increase beam scanning range and gain of conventional antennas. Using metamaterials in antenna design leads to size reduction and side lobe suppression. Metamaterial antenna systems can also be used to support communication links, navigation systems, and surveillance sensors. However, there are some challenges associated with metamaterials which antenna designers need to consider. Since they act as frequency selective surfaces, antenna behavior changes with frequency, and it may not be convenient to use metamaterial antennas for narrow band applications.

2.5. Steerable Lens Antenna

Steerable lens antennas (SLAs) have gained popularity after 1990. They were introduced with the aim of providing high directionality and enhancing the efficiency of printed microstrip antennas at millimetric wave frequencies. Steerable Lens antennas consist of single or multiple lenses and antenna array. Lens antennas are typically designed using geometrical optics or physical optics. Antenna array elements are placed at the focal length of the lens, and switch is used to energize each antenna element individually. SLA does not use multiple elements at a time, and instead they use a single element at a time, so the gain is achieved by a combination of single element and lens. Fig. 9 shows schematics of a steerable lens antenna.

The use of lens in place of phase shifter reduces the cost and complexity of the architecture. The lens acts as a passive phase shifter and focuses the radiations towards the particular region. Lens plays two major roles; it focuses the electromagnetic radiations at the front end to improve gain and

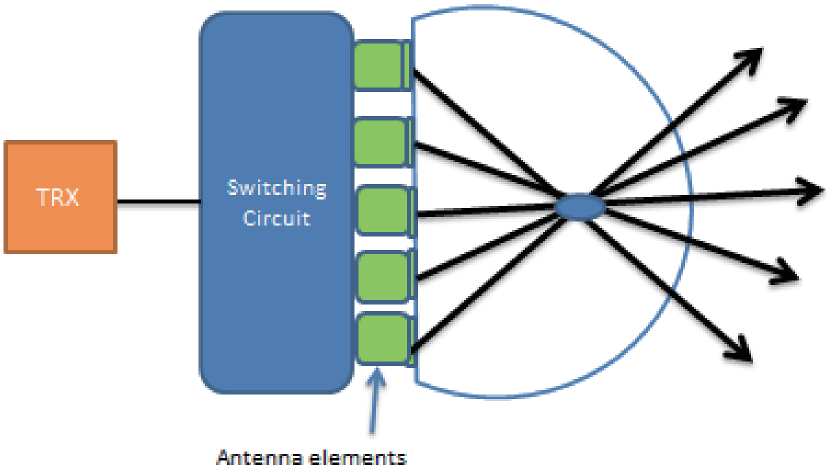


Figure 9. Integrated lens antenna schematics.

directivity and provides concentrated signal power. These properties make it a good tool for RF front in beam-forming architecture.

A lot of research is being done to configure the lens antenna for 5G networks. In [22], the authors discuss measurement results for integrated lens antenna system for 5G E-band having two dimensional (2D) beam steering capability. Continuous beam switching range for specified range is demonstrated with the lens having the maximum measured directivity of 36.7 dB. The article in [23] presents another antenna prototype for 5G systems. Operating frequency is 28 GHz. The prototype used is hybrid beam-forming where lens acts as a passive phase shifter. Two different types of lens prototypes are discussed, one for static usage and the other for mobile usage. The maximum directivity and gain achieved were approximately 36 dBi and 15 dBi. In [24], a 60 GHz integrated Lens antenna is proposed. Gain and directivity measured are approximately 19 dBi and 19.9 dBi. Measurement results show antenna performances to be very stable over 55 GHz to 65 GHz band.

Integrated lens antennas use lesser number of elements to achieve high gain as compared to parasitic steerable antennas (discussed in the previous section). Moreover, RF switches can be used instead of phase shifters to control the array elements for beam steering which makes the system simple and low cost as compared to phase shifter antennas. Integrated lens antennas have high gain, low sidelobes, narrow beamwidth, and low noise temperature. The lenses designed with quasi-optical characteristics have low losses, particularly at millimetric wavelengths. They have greater design tolerance and can handle a large number of signals at a time.

To accommodate the steering in two planes elements can be arranged in two dimensions, but this configuration will still have one active element at a time. The offset between elements has to increase in order to get large steering angles, and this increases the gain scan loss. Studies are being done to use reconfigurable materials in the lens such as metamaterials to enhance the antenna properties [21].

2.6. Switched Beam Antennas

In switched beam antennas, elements are arranged such that they cover a specific range of interest. Each individual element covers a predefined specific range of interest. Elements are turned on when there is a need to radiate in a particular direction. Elements are usually arranged in a semicircular arrangement. This configuration is similar to steerable lens antennas (SLAs), but in SLAs, elements are arranged in a straight line. Fig. 10 shows schematics of switched beams antenna. Eight antennas are arranged in circular geometry, and each antenna covers a specific range. Switched beam antenna can be single beam or multibeams. Multibeam antenna can accommodate multiple users at the same time as shown in Fig. 11, and the antenna communicates with user 1, user 2, and user 3 simultaneously. This technique is based on a basic switching function and chooses the beam which gives the strongest

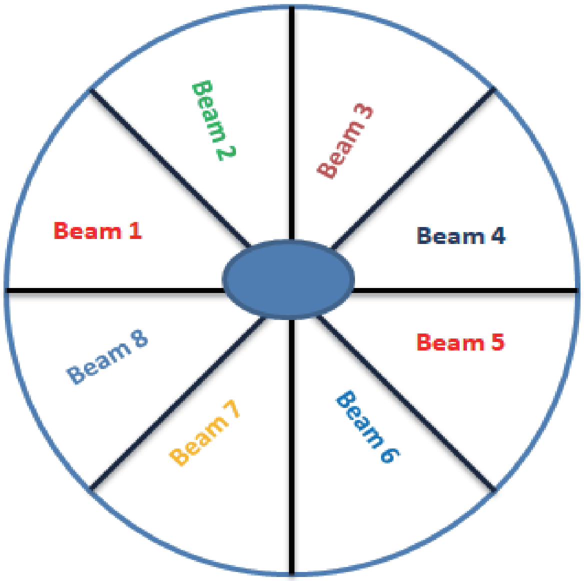
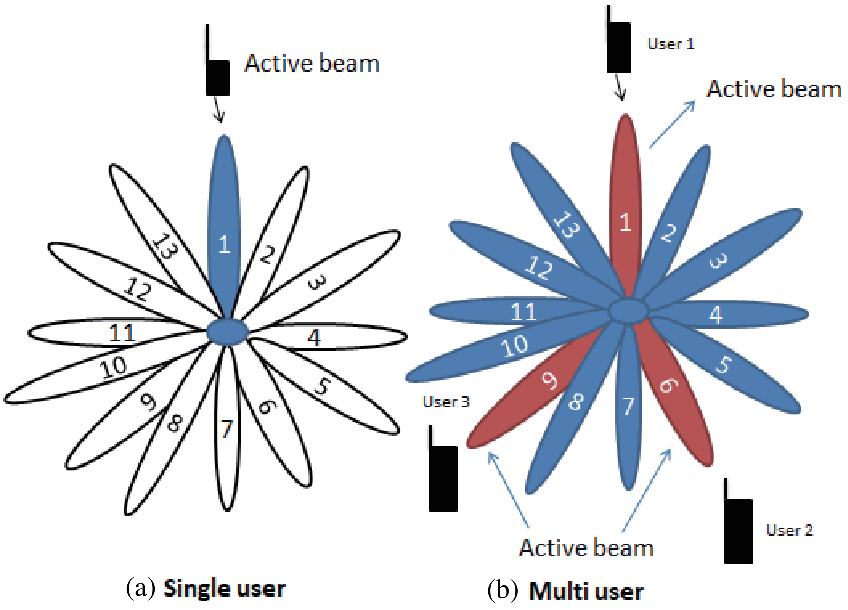


Figure 10. Schematics of switched beam antennas.



(a) **Single user** (b) **Multi user**

Figure 11. Coverage pattern.

received signal. When the incoming signal is detected, it determines the beam which is best aligned with the user and switches that beam to communicate with the user. RF switches and radio logic are used to select the particular beam with the greatest strength and received power. This technique is simple to implement and offers the advantages of more elaborate smart antenna systems at fraction of cost and complexity.

Switch beam antennas for next-generation 5G systems have also been proposed. The letter in [25] presents a 28 GHz switched beam antenna system based on a rectangular waveguide and reconfigurable semiconductor circuit (RSC) with slots. Surface PIN diodes are used to open/close slots to achieve the required configuration of an aperture. Antenna system provides three beams directed toward 0°, 30°, and 45°. Beam switching is done by a reconfigurable arrangement of a set of slots. The article in [26] presents a 28 GHz millimeter wave beam forming network based on the Butler matrix. The Butler matrix is a beam forming network through which N inputs are accessed, and a beam is steered towards the desired direction. 8×8 Butler matrix is integrated with a 1×8 switch. In [27], a Yagi-Udha antenna has been proposed for millimetric wave switched beam systems. Antenna results show the gain of 11.5–13 dB at 22–25 GHz. The designed antenna exhibits high radiation efficiency ($> 90\%$) and is well suited for mm-wave radars and high data rate communication systems. In [28], the design of a switched array antenna for Wi-Fi applications is discussed, and the proposed antenna steers beam between predefined discrete points.

In switch beam antennas, the overall goal is to increase gain in the desired direction. However, beams are fixed/predefined, and the intended user may not be in the center of the beam. Shortcomings of these antennas are increased size and redundancy, and interference and mutual coupling can occur between antennas which can affect network efficiency. This technique is complicated to use for areas where interference is high. Fig. 12 compares the interference rejection comparison of switched beam antenna and adaptive antenna. We can observe that the switch beam antenna can catch the interference and may lower the quality of reception for areas where interference is considerably high. Moreover, they are not capable of nulling the interference and have less coverage than adaptive antennas. Despite all the disadvantages, this technique is less complicated than completely adaptive systems and also increases the network range [29]. When the desired user is in the center of beam, it considerably rejects the interference and increases the network capacity.

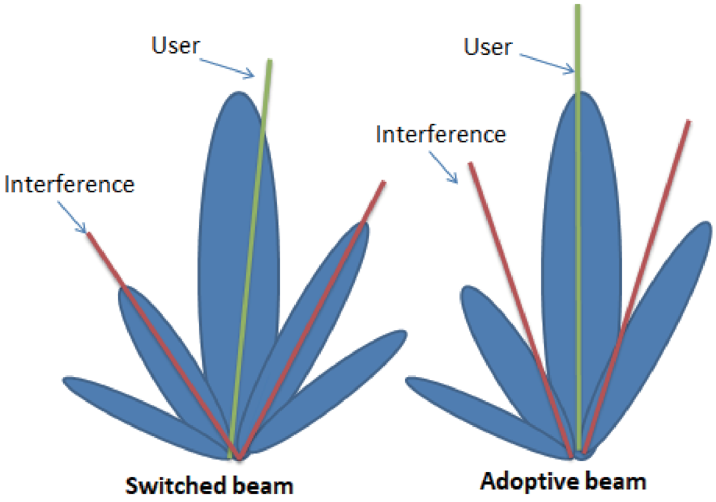


Figure 12. Interference rejection comparison.

2.7. Steerable Reflectarray Antenna

Steerable reflectarray antennas are a hybrid of classic parabolic antennas and phased array antennas. In these antennas, a reconfigurable reflectarray surface focuses EM signals that are radiated by the feed horn. In reflectarray antennas, several elements are mounted to form an array structure as shown in Fig. 13. The array elements can be parasitic or driven depending upon the particular geometry of the antenna. Each element in the array is excited by the incident wave coming from the feed antenna. To attain constructive interference in the required direction, every element of the array needs to provide the particular phase compensation. Using array theory, the phase shifts desired on the element with coordinates (a, b) is given as follows.

$$\phi_d(a,b) = k_0 d_a b - k_0(a \cdot \sin\theta_c \cos\phi_c + b \cdot \sin\theta_c \sin\phi_c) \tag{4}$$

To achieve the phase delay, several configurations have been proposed. Array elements can be made with patches having variable length stubs. Incident wave received by the patch enters the open-ended stub and reflects back. The reflected signal reenters the patch and is reradiated with

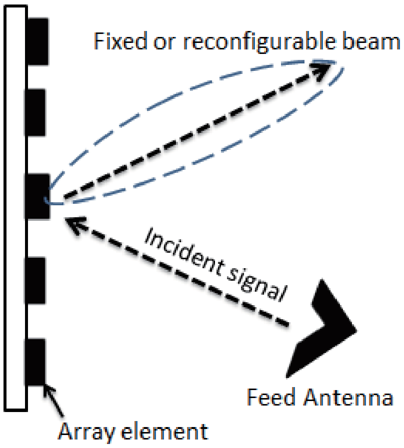


Figure 13. Reflectarray antenna schematics.

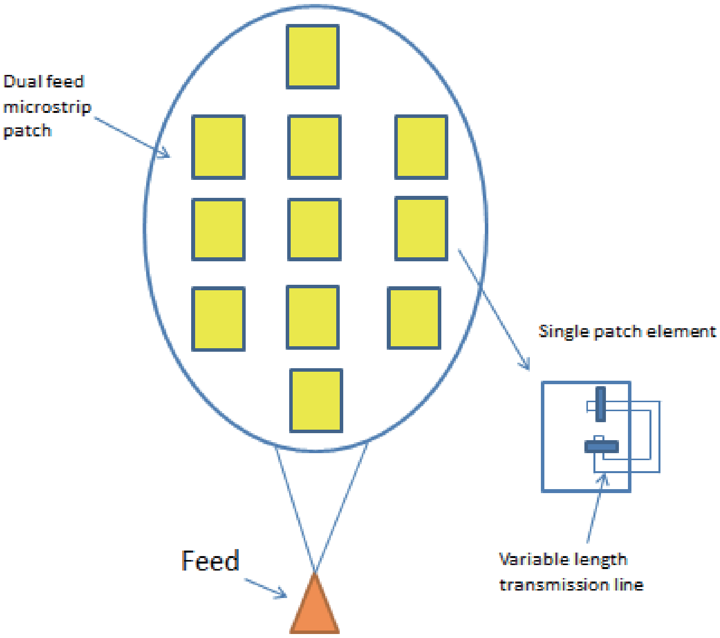


Figure 14. Reflectarray antenna with variable length patch elements.

the accumulated phase shift depending upon stub length [30]. Another technique of achieving the phase delay is using aperture coupled patches with variable length transmission lines as shown in Fig. 14. By varying the length of the transmission line, the desired phase ranges from 0° to 360° can be achieved [31]. Reflectarray antenna combines the advantages of parabolic reflectors and planar structure of antenna arrays. Similar to parabolic reflectors, reflectarray antennas can achieve very high efficiencies. Being flat and compact in form reflectarray enables an inexpensive fabrication procedure with reasonably moderate installation costs. Reflectarray elements with active phase adjustment capability can provide beam steerable capabilities. High gain, easy fabrication, compact form, and beam scanning capabilities make reflectarrays potential candidates for telecommunications, spacecraft, radars, and wireless applications. Researchers are working to extend reflectarray antennas for 5G networks. Various antenna configurations are introduced including wideband reflectarray antenna [32], millimetric wave circular reflectarray antenna [33], and 38 GHz folded reflectarray antenna [34].

2.8. Phase Shifting Surfaces (PSSs)

We have discussed mechanical and electrical beam steering in previous sections, and each technique has its strength and weaknesses. To utilize the advantages of both electrical and mechanical beam steering hybrid beam steering was introduced. Hybrid solutions utilize electrical steering in one axis and mechanical scanning in the second axis.

In this technique rotate-able dielectric wedges (lenses) are placed in front of the feed horn [35, 36]. Typically, a pair of dielectric wedges is required for steering beam in elevation as well as azimuth plane. They provide relatively compact beam steering configuration which can cover a significant portion of a hemisphere. The mechanism used for beam steering is considerably simpler and less bulky than the typical azimuth and elevation positioner used for reflector antennas. However, there are some shortcomings of Risley prisms. Risley prisms are bulky and heavy dielectric wedges, particularly at lower frequencies, and have high reflections at the interfaces, which significantly deteriorates the antenna radiation characteristics.

In past years, the phase-shifting surface (PSS) technique has been proposed as low cost, compact, and lightweight alternative to dielectric lenses [37–39]. This technique can be used to utilize spatial phase shifters with linear phase progression similar to dielectric wedges, but phase shifting surfaces have very small wedge thickness. In PSS based antenna, PSS surface is placed over radiating elements, and surfaces are rotated. PSS acts like a passive lens and steers the beam of feed antenna. Fig. 15 shows the basic configuration of PSS based antenna. PSSs are made up of the lattice of cells. Each cell has conducting shapes of different sizes. Conducting shape can be conducting discs, patches, or strips which are etched over dielectric sheets. Cells consist of a repetitive structure made up of the perfect magnetic conductor (PMC) etched over perfect electric conductor (PEC). Fig. 16 shows the implementation of a PSS based antenna. The multi-layered PSS is placed in-front of feed antenna. Square unit cells are used in this configuration. Square unit cells are polarization independent due to their symmetrical geometry, thus they do not incur losses due to polarization mismatch. By appropriately varying the sizes of conducting shapes, the thickness of the surfaces changes from layer to layer, and this difference of thickness plays a role in changing the phase of the incident wavefront. Consider the phase shifting surface with the x-axis and y-axis parallel to the plane of the surface and z-axis normal to it. Electromagnetic waves entering the front of the surface at some point (x, y) would experience a phase shift as they propagate through the surface (because of varying design geometry). To translate the incident wave into a desired output transmission phase of the surface would in general need to be a function of (x, y).

In conventional transmitting array antennas, significant spacing is needed between elements or layers of transmitting arrays in order to avoid undesired mutual coupling, which may otherwise deteriorate the performance. In PSS, unlike conventional arrays, layers are closely spaced, and they

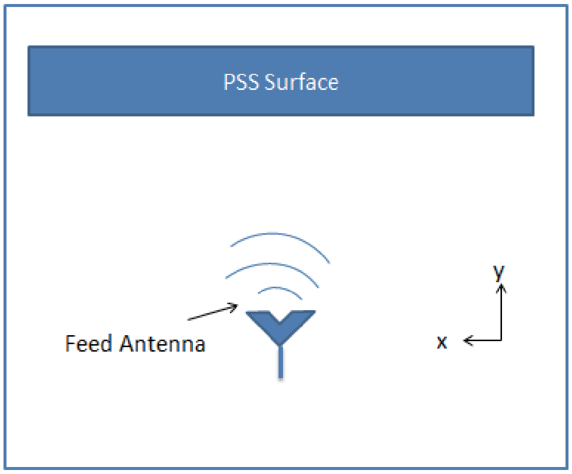


Figure 15. Configuration of PSS based antenna.

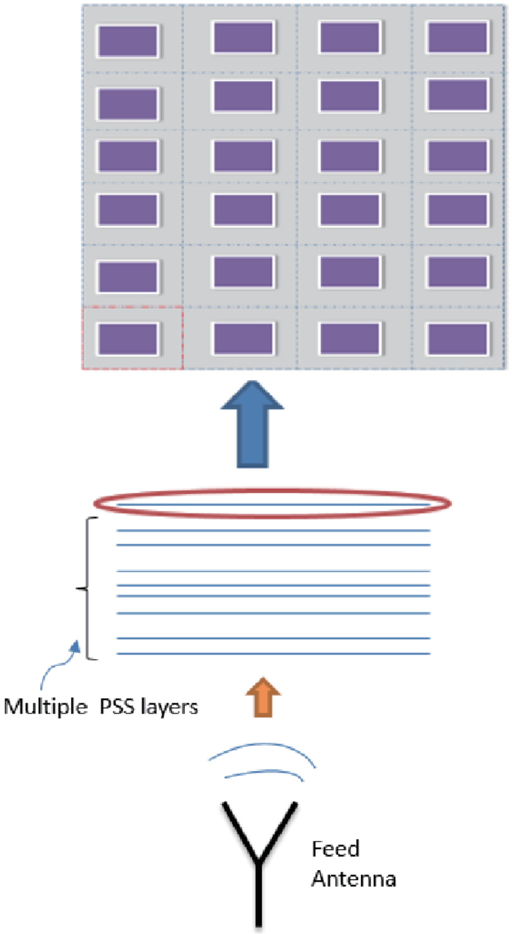


Figure 16. PSS based antenna with square unit cells.

are considered as an entire structure. The coupling between layers is used to achieve a reasonable phase shifting range. This property of PSSs helps to achieve high gain. Metamaterial-based antennas may look to have a similar configuration to PSS, but they are quite different actually. PSS is majorly concerned with transmission and reflection behavior, whereas metamaterial antennas work by realizing effective permittivity and permeability of the material (thus changing the refractive index).

PSS antennas have high gain and a considerably simple configuration. To improve the aperture efficiency fewer layers should be used, as each layer adds additional scattering and reflections. They are easy and cheap to fabricate. Moreover, they follow hybrid beam steering thus maximize the advantages of electrical and mechanical beam steering. These all attributes make PSS a good candidate for satellite communication and 5G networks.

2.9. Artificial Impedance Surfaces

Artificial impedance surfaces are surfaces which are designed to produce specific impedance [40]. The high-impedance surfaces are made up of a flat metal sheet covered with resonant cavities. Cavity sizes are much less than a wavelength. The surface can be designed by etching metallic patches on printed circuit board [41, 42]. The surfaces impedance can be varied by altering the spacing between the metallic patches. Gap spacing creates the capacitance across the unit cells and produces impedance across the layer. Fig. 17 shows the unit cell configuration of an artificial impedance surface.

Adaptive impedance surfaces have also been designed for 2D beam steering. In such surfaces, varactors are used to vary the capacitance of cell, which in turn changes the impedance, hence

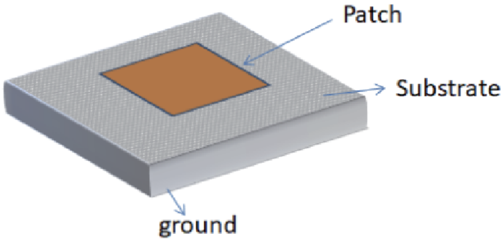


Figure 17. Unit cell impedance surface.

reconfigurable radiation characteristics can be achieved. Since voltage can be altered with time, the impedance characteristics can be varied, and thus the beam reconfiguration can be realized. These surfaces have several other advantages. Artificial impedance surfaces can be used as a ground plane for monopole based antennas, which would considerably reduce the antenna size, thus making the antenna compact and thin. They can also be employed to reduce surface waves and to realize holographic-based antennas, reflectarray antennas, and transmitarray antennas. We have discussed phase shifting surfaces (PSSs) in the previous section. Artificial magnetic surfaces and PSSs may look similar, but they are quite different in nature. In PSSs, unit cell is typically subwavelength in size. In artificial impedance surfaces, unit cell is quite small, typically one-tenth of free space wavelength. Artificial magnetic surfaces are reflective surfaces whereas PSSs are transmissive surfaces. PSS can be used to transform the amplitude of incident signal, thus can also be used for beam focusing. Artificial magnetic surfaces are reflective surfaces, hence they do not perform amplitude transformation. Artificial impedance surface controls the phase of the incident signal and reflects back.

3. ANALYSIS OF TECHNIQUES

Mechanical steering can be a good option for beam steering since it does not experience insertion losses, but its shortcoming has slow speed and relatively more wear and tear than electronic ways. Phased array antennas offer fast scanning speed, but they introduce insertion losses due to elements used to achieve group delay. Phased array antennas are expensive, consume more power, and have relatively larger sizes than other electronic steerable antennas. To implement a phased array technique for 5G, we need to work on cutting down the design cost for phased array antennas. With the exception of mechanical steering, all other steering techniques suffer from limited steering resolution. Working at millimetric wave frequency band, fine steering is required for meshing networks and small cell backhauls since antennas can be easily misaligned due to wind loads.

Parasitic steering relies on switches to achieve steering. It is relatively less complicated and low cost. It has a predefined resolution. Such antennas have moderate gain, but for 5G communication through mm-wave links we need very high gain. Parasitic steerable antennas have typically narrow bandwidth. Antenna size is determined by operating frequency, and a lot of factors need to be tailored to make the antennas broadband. Reflectarray antennas may provide a good solution at 5G; however, feed blockages, bandwidth phase deviation, angle of incidence (reflectarray antennas are sensitive to incident angle) need to be taken into account. Integrated lens antennas work by switching between various antenna elements to achieve beam steering. Only one element is switched on at a time which introduces redundancy in the network. They offer predefined steering resolutions, and system performance may deteriorate while it tries to achieve wider steering angles.

Switched beam antennas also introduce redundancies in the system which leads to high cost and increased sizes. There is no bandwidth phase deviation as the performance of the antenna is maintained over the range of steering. Like parasitic antennas, mutual coupling is a factor that needs to be taken into account for switch beam antennas. Metamaterial based antennas with exotic properties can offer beam steering with reduced antenna sizes. These materials have gained a lot of attention from researches because of their unique properties. To boost the rollout of the 5G wireless systems, a research project at the University of Exeter aims to develop new metamaterials. The new materials aim to make the antenna systems lighter, smaller, and cheaper to construct and install. Rotatable planar phase shifting surface antennas offer robust beam steering. They are well suited for slow changing environment. They are low cost, thin, and lightweight alternative to dielectric lenses. They offer high gain and employ electrical and mechanical means for beam steering. The comparative analysis of steering techniques is given in Table 1.

Table 1. Comparative analysis.

PSS & Predefined steering, low insertion losses (ILs), moderate size/cost
Metamaterial & Predefined steering, high ILs, moderate size/cost
Mechanical & Continuous steering, no ILs, moderate cost, large sizes
Analogue BF & Predefined steering, high ILs, high cost, moderate size
Digital BF & High steering resolution, high complexity/cost, moderate size
Parasitic Steering & Predefined steering, low losses, small size, low cost
Reflectarrays &Predefined steering, moderate size/cost, low ILs
SBA & Predefined steering, medium ILs large sizes, high cost
SLA & Predefined steering, medium cost, medium ILs

4. COMPARISON WITH REVIEW ARTICLES

In this paper, we have provided a comprehensive overview of beam-steering antennas. To the best of authors knowledge this is the first time when a comparative analysis among mechanical beam-steering, passive steering array, meta-material based antennas, switched beam antennas, steerable reflectarray antennas, phase shifting surfaces, and artificial impedance surfaces antennas is published in one article. Table 2 shows the comparison between our paper and [43–48].

Table 2. Comparison with review papers.

A review of design and integration technologies for D-band antennas [43]	This review paper does not cover mechanically steerable antennas, reflectarray antennas, switchable antennas, parasitic antennas and artificial impedance surfaces antennas
A review on antenna technologies for ambient RF energy harvesting and wireless power transfer [44]	This review paper does not cover mechanically steerable antennas, digital beam-forming antenna, hybrid beam-forming antennas, reflectarray antennas and artificial impedance surface antennas
A review on the history and current literature of metamaterials and its applications to antennas and radio frequency identification (RFID) devices [45]	This review paper does not cover analog beam-forming, mechanically steerable antennas, digital beam-forming antenna, hybrid beam-forming antennas and artifical impedance surface antennas
Carbon-based thz micro-strip antenna design: A review [46]	This review paper only covers micro-strip antennas and does not cover mechanically steerable array as well as artificial impedance surface antennas
Electronically steerable antennas for future heterogeneous communication networks: Review and prospective [47]	This review paper does not cover mechanically steerable antennas and impedance surface antennas
Multiband reconfigurable antennas for 5G wireless cubesat applications: A review [48]	This paper only covers broadband patch antennas and does not cover mechanically steerable antennas, impedance surface antennas, switchable array antennas and meta-surface antennas

5. CONCLUSION

In this paper, we shed light on various beam steering techniques and compared them using mm-wave 5G system benchmarks. The paper highlights limitations and challenges which need to be resolved in order to use millimetre wave frequencies for next-generation 5G networks. 5G networks need regularly placed, highly directional microwave antennas to fulfil high data rates and network capacity requirements. Using highly directional antennas, it becomes practical to deal with heavy traffic demands and attenuation caused by mm-wave frequency bands. The figure of merit and key parameters of design of 5G antennas are steering angle resolution, antenna insertion losses, antenna bandwidth, cost of antenna design, and complexity. Effectiveness, current limitations, and required future research areas of different beam-steering techniques are also presented in this paper.

REFERENCES

1. Albreem, M. A. M., "5G wireless communication systems: Vision and challenges," *2015 International Conference on Computer, Communications, and Control Technology (I4CT)*, 493–497, Apr. 2015.
2. Gohil, A., H. Modi, and S. K. Patel, "5G technology of mobile communication: A survey," *2013 International Conference on Intelligent Systems and Signal Processing (ISSP)*, 288–292, Mar. 2013,
3. Zhang, J., X. Ge, Q. Li, M. Guizani, and Y. Zhang, "5G millimeter-wave antenna array: Design and challenges," *IEEE Wireless Communications*, Vol. 24, No. 2, 106–112, Apr. 2017.
4. Al-Ogaili, F. and R. M. Shubair, "Millimeter-wave mobile communications for 5G: Challenges and opportunities," *2016 IEEE International Symposium on Antennas and Propagation (APSURSI)*, 1003–1004, Jun. 2016.
5. Donelli, M. and P. Febvre, "An inexpensive reconfigurable planar array for Wi-Fi applications," *Progress In Electromagnetics Research C*, Vol. 28, 71–81, 2012.
6. Venkatarayalu, N. V. and T. Ray, "Optimum design of Yagi-Uda antennas using computational intelligence," *IEEE Transactions on Antennas and Propagation*, Vol. 52, No. 7, 1811–1818, Jul. 2004.
7. Arceo, D. and C. A. Balanis, "A compact Yagi-Uda antenna with enhanced bandwidth," *IEEE Antennas and Wireless Propagation Letters*, Vol. 10, 442–445, 2011.
8. Sharma, S. K. and L. Shafai, "Beam focusing properties of circular monopole array antenna on a finite ground plane," *IEEE Transactions on Antennas and Propagation*, Vol. 53, No. 10, 3406–3409, Oct. 2005.
9. Simpson, T. and J. Tillman, "Parasitic excitation of circular antenna arrays," *IRE Transactions on Antennas and Propagation*, Vol. 9, No. 3, 263–267, May 1961.
10. Kausar, S., H. U. Rahman, A. Kausar, and T. Hassan, "Espar antenna system for dynamic tracking of active targets," *2013 European Modelling Symposium*, 533–535, Nov. 2013,
11. Kausar, A., H. Mehrpouyan, M. Sellathurai, R. Qian, and S. Kausar, "Energy efficient switched parasitic array antenna for 5G networks and IOT," *2016 Loughborough Antennas Propagation Conference (LAPC)*, 1–5, Nov. 2016.
12. Kausar, S., H. U. Rahman, T. Hassan, and A. Kausar, "Miniaturization of espar antenna using folded monopoles and conical central element," *2015 International Conference on Radar, Antenna, Microwave, Electronics and Telecommunications (ICRAMET)*, 87–91, Oct. 2015.
13. Hou, Y., R. Ferdian, S. Denno, and M. Okada, "Low-complexity implementation of channel estimation for ESPAR-OFDM receiver," *IEEE Transactions on Broadcasting*, Vol. 67, No. 1, 238–252, 2021.
14. Hou, Y. F., "Low-complexity implementation of channel estimation for ESPAR-OFDM receiver," *IEEE Transactions on Broadcasting*, Vol. 67, No. 1, 238–252, 2021.
15. Menon, S. K., G. Marchi, M. Donelli, M. Manekiya, and V. Mulloni, "Design of an ultra wide band antenna based on a SIS resonator," *Progress In Electromagnetics Research C*, Vol. 103, 187–193, 2020.

16. Kshetrimayum, R. S., “A brief intro to metamaterials,” *IEEE Potentials*, Vol. 23, No. 5, 44–46, Dec. 2005.
17. Dong, Y. and T. Itoh, “Metamaterial-based antennas,” *Proceedings of the IEEE*, Vol. 100, No. 7, 2271–2285, Jul. 2012.
18. Giovampaola, C. D. and S. Maci, “Historical overview of EM metamaterials,” *2016 IEEE International Symposium on Antennas and Propagation (APSURSI)*, 693–694, Jun. 2016,
19. Caloz, C., “Ten applications of metamaterials,” *2016 IEEE International Symposium on Antennas and Propagation (APSURSI)*, 1299–1300, Jun. 2016.
20. Engheta, N. and R. W. Ziolkowski, “A positive future for double-negative metamaterials,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 53, No. 4, 1535–1556, Apr. 2005.
21. Jiang, M., Z. N. Chen, Y. Zhang, W. Hong, and X. Xuan, “Metamaterial-based thin planar lens antenna for spatial beamforming and multibeam massive MIMO,” *IEEE Transactions on Antennas and Propagation*, Vol. 65, No. 2, 464–472, Feb. 2017.
22. Ala-Laurinaho, J., J. Aurinsalo, A. Karttunen, M. Kaunisto, A. Lamminen, J. Nurmiharju, A. V. Räisänen, J. Säily, and P. Wainio, “2-D beam-steerable integrated lens antenna system for 5GE-band access and backhaul,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 64, No. 7, 2244–2255, Jul. 2016.
23. Cho, Y. J., G. Suk, B. Kim, D. K. Kim, and C. Chae, “RF lens-embedded antenna array for MMwave MIMO: Design and performance,” *IEEE Communications Magazine*, Vol. 56, No. 7, 42–48, Jul. 2018.
24. Nguyen, N. T., N. Delhote, M. Ettorre, D. Baillargeat, L. L. Coq, and R. Sauleau, “Design and characterization of 60-GHz integrated lens antennas fabricated through ceramic stereolithography,” *IEEE Transactions on Antennas and Propagation*, Vol. 58, No. 8, 2757–2762, Aug. 2010.
25. Yashchyshyn, Y., K. Derzakowski, G. Bogdan, K. Godziszewski, D. Nyzovets, C. H. Kim, and B. Park, “28 GHz switched-beam antenna based on S-pin diodes for 5G mobile communications,” *IEEE Antennas and Wireless Propagation Letters*, Vol. 17, No. 2, 225–228, Feb. 2018.
26. Huang, F., W. Chen, and M. Rao, “Switched-beam antenna array based on butler matrix for 5G wireless communication,” *2016 IEEE International Workshop on Electromagnetics: Applications and Student Innovation Competition (iWEM)*, 1–3, May 2016.
27. Alhalabi, R. A. and G. M. Rebeiz, “High-gain Yagi-Uda antennas for millimeter-wave switchedbeam systems,” *IEEE Transactions on Antennas and Propagation*, Vol. 57, No. 11, 3672–3676, Nov. 2009.
28. Moriyama, T., M. Manekiya, and M. Donelli, “A compact switched-beam planar antenna array for wireless sensors operating at Wi-Fi band,” *Progress In Electromagnetics Research C*, Vol. 83, 137–145, 2018.
29. Alreshaid, A. T., O. Hammi, M. S. Sharawi, and K. Sarabandi, “A millimeter wave switched beam planar antenna array,” *2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*, 2117–2118, 2015.
30. Pozar, D. M. and T. A. Metzler, “Analysis of a reflectarray antenna using microstrip patches of variable size,” *Electronics Letters*, Vol. 29, No. 8, 657–658, Apr. 1993.
31. Robinson, A. W., M. E. Bialkowski, and H. J. Song, “An X-band passive reflect-array using dualfeed aperture-coupled patch antennas,” *1999 Asia Pacific Microwave Conference. APMC’99. Microwaves Enter the 21st Century. Conference Proceedings (Cat. No. 99TH8473)*, Vol. 3, 906–909, Nov. 1999.
32. Dahri, M. H., M. H. Jamaluddin, M. I. Abbasi, and M. R. Kamarudin, “A review of wideband reflectarray antennas for 5G communication systems,” *IEEE Access*, Vol. 5, 17803–17815, 2017.
33. Haraz, O. M. and M. M. M. Ali, “A millimeter-wave circular reflectarray antenna for future 5G cellular networks,” *2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*, 1534–1535, 2015.
34. Shen, Y., S. Hu, and W. Dou, “38 GHz folded reflectarray antenna for point-to-point 5G communications,” *2016 IEEE 5th Asia-Pacific Conference on Antennas and Propagation (APCAP)*, 369–370, Jul. 2016.

35. Yang, Y., "Analytic solution of free space optical beam steering using risley prisms," *Journal of Lightwave Technology*, Vol. 26, No. 21, 3576–3583, Nov. 2008.
36. Tame, B. J. and N. A. Stutzke, "Steerable risley prism antennas with low side lobes in the Ka band," *2010 IEEE International Conference on Wireless Information Technology and Systems*, 1–4, Aug. 2010.
37. Gagnon, N., A. Petosa, and D. A. McNamara, "Research and development on phase-shifting surfaces (PSSS)," *IEEE Antennas and Propagation Magazine*, Vol. 55, No. 2, 29–48, Apr. 2013.
38. Gagnon, N. and A. Petosa, "Using rotatable planar phase shifting surfaces to steer a high-gain beam," *IEEE Transactions on Antennas and Propagation*, Vol. 61, No. 6, 3086–3092, Jun. 2013.
39. Gagnon, N., A. Petosa, and D. A. McNamara, "Thin microwave quasi-transparent phase-shifting surface (PSS)," *IEEE Transactions on Antennas and Propagation*, Vol. 58, No. 4, 1193–1201, Apr. 2010.
40. Sievenpiper, D. F., *Artificial Impedance Surfaces for Antennas*, Ch. 15, 737–777, John Wiley & Sons, Ltd., 2008, [Online], Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/9780470294154.ch15.
41. Colburn, J. S., A. Lai, D. F. Sievenpiper, A. Bekaryan, B. H. Fong, J. J. Ottusch, and P. Tulythan, "Adaptive artificial impedance surface conformal antennas," *2009 IEEE Antennas and Propagation Society International Symposium*, 1–4, Jun. 2009.
42. Sievenpiper, D., J. Colburn, B. Fong, J. Ottusch, and J. Visher, "Holographic artificial impedance surfaces for conformal antennas," *2005 IEEE Antennas and Propagation Society International Symposium*, Vol. 1B, 256–259, Jul. 2005.
43. De Kok, M., A. B. Smolders, and U. Johannsen, "A review of design and integration technologies for D-band antennas," *IEEE Open Journal of Antennas and Propagation*, Vol. 2, 746–758, 2021.
44. Ullah, M. A., R. Keshavarz, M. Abolhasan, J. Lipman, K. P. Esselle, and N. Shariati, "A review on antenna technologies for ambient rf energy harvesting and wireless power transfer: Designs, challenges and applications," *IEEE Access*, Vol. 10, 17231–17267, 2022.
45. Abdullah, S., G. Xiao, and R. E. Amaya, "A review on the history and current literature of metamaterials and its applications to antennas and radio frequency identification (RFID) devices," *IEEE Journal of Radio Frequency Identification*, Vol. 5, No. 4, 427–445, 2021.
46. Lu, G., J. Wang, Z. Xie, and J. T. W. Yeow, "Carbon-based thz microstrip antenna design: A review," *IEEE Open Journal of Nanotechnology*, Vol. 3, 15–23, 2022.
47. Chaloun, T., L. Boccia, E. Arnieri, M. Fischer, V. Valenta, N. J. G. Fonseca, and C. Waldschmidt, "Electronically steerable antennas for future heterogeneous communication networks: Review and perspectives," *IEEE Journal of Microwaves*, Vol. 2, No. 4, 545–581, 2022.
48. Ramahatla, K., M. Mosalaosi, A. Yahya, and B. Basutli, "Multiband reconfigurable antennas for 5G wireless and cubesat applications: A review," *IEEE Access*, Vol. 10, 40910–40931, 2022.