International Journal of Research and Development in Applied Science and Engineering (IJRDASE)
ISSN: 2454-6844

Modern 4G, 4G/5G, and 5G Antenna Electrical Reconfigurability: A Critical Analysis of Polarization and Frequency Reconfigurable Designs

Pradeep Kumar, Parimal Tiwari
Department of Electronics and Communication
Institute of Engineering and Technology, DRMLAU, Ayodhya, U.P., India
mailtojtopk@gmail.com

Abstract: This paper presents a critical review of modern 4G, 4G/5G, and 5G antennas, which employ PIN diodes and Varactors for polarization or frequency reconfiguration. For the reviewed 4G and 5G polarization reconfigurable antennas, a new parameter named spectrum utilization "AR/S11 B.W." is defined for the first time to predict the shared spectrum between the impedance bandwidth and the axial ratio bandwidth for circularly polarized antennas. The calculated spectrum utilization for many designs revealed that the majority of implementations failed to achieve full utilization of the available bandwidth. Besides, employing multiple PIN diodes is shown useful in improving the spectrum utilization and in supporting multiple polarization states. For the reviewed 4G, 4G/5G and 5G frequency reconfigurable antennas, the focus is mainly on comparing the available tuning range, fractional bandwidth and the Fractional Bandwidth Change (FBWC) upon tuning. The latter parameter, is defined and calculated in this work to measure the change in the FBW upon tuning. Utilizing multiple Varactors is shown promising in improving a 4G antenna's fractional bandwidth, while combining Multiple PINs and Varactors in one design is found efficient in improving the FBWC and the tuning range in the 5G spectrum.

Keywords: Frequency reconfigurability, Polarization reconfigurability, Axial ratio bandwidth, Tuning range.

1. Introduction

Wireless communication systems have been rapidly growing over the recent years. The new wireless technology, like the emerge of 4G and 5G communication systems, has set modern requirements to facilitate the user's experience such as enhanced bit rate, multi-standard applications and the electrical infrastructure to support it [1]. From a designer's point of view, a demand for creative antenna designs has unfolded to enable diverse communication schemes and bands with minimum cost [2]. These creative antennas need to be of a small footprint while covering several frequency bands (services) and can offer efficient bandwidth utilization as well as can communicate with diversely polarized antennas at once. This generally can not be electrically realized without reconfiguring an antenna design parameters. Antennas reconfigurability can refer to the ability to modulate and adjust the characteristics of an antenna such as its polarization, operating frequency and radiation pattern [3]. Antennas reconfigurability can be achieved by altering an antenna's electrical size and/or shape to control its operational characteristics such as frequency bands, polarization sense and radiation pattern. Frequency reconfiguration is crucial for a multi-standard supporting antenna, it overcomes the need of utilizing multiple antennas that resonate at different frequencies to transmit or receive a signal, which is area and cost efficient [4], [5], [6], [7].

An antenna polarization can also be reconfigured to allow for frequency reuse and mitigation of multipath effects [8], [9]. An antenna's polarization usually depends on its physical layout as the direction of the surface current on its radiating parts is directly affected by the antenna shape and how it is excited. A reconfigurable polarization can capitalize an antenna's ability to change the polarization sense into different types (i.e., Linear (LP) to Circular (CP), Right -Hand Circular (RHCP) to Left Hand Circular (LHCP), etc.). This improves the ability to send and receive information from a greater number of diversely polarized antennas [10].

Implementing the aforementioned types of reconfigurability using electronic switches like PIN and Varactor diodes is one of the most commonly used techniques, which referred to as "electrical reconfigurability" [3], [11]. Due to the appealing features of electrical reconfigurability, like the low cost and the ease of implementation, it has attracted the attention of researchers over the past years. PINs and Varactors can be utilized to reconfigure single or multiple antenna parameters and can enable reconfgiruation at RF frequencies [3]. Other reconfiguration techniques have also been used to reconfigure antennas [27]. They highlights the advantages and disadvantages of different antennas reconfigurability methods reported in the open literature. Optical reconfiguration utilizes photo-conductive switches, formed by laser light incident on some semiconductor material [27]. Embedding this type of switches eliminates the need for metallic connections and biasing while providing fast switching speed [27], however, high optical power level is consumed through the laser light activation, especially in highly resistive Si [28]. Physically / Mechanically reconfigurable antennas is implemented by manually altering the structure of an antenna to enable reconfigurability [30], [31]. This technique does not utilize switches, rather than it implements motor, actuators and other mechanical ways to shift parts of the structure or change its electrical properties [32]. A common example would be a motor - based steerable reflectarry, such as the ones used in radars [36]. This mechanism is associated with low cost [31] but the implementation of actuators and other tools requires the use of high voltage and causes slow switching speed while occupying a large area [32], [37], [38]. Smart antennas is a fairly new mechanism that implements the reconfigurability using smart materials such as liquid metals [33], water [34] and oil [35]. The characteristics of an antenna can be controlled by pumping a fluid into a hollow behind the design to alter the substrate's characteristics such as magnetic permeability and electric permittivity [39], [40]. While it allows for a high power handling [40], this type of reconfigurability has limited applications due to the high cost of the materials used [41], such as Galinstan [35], while some other materials such as Mercury are known to be severely toxic [35].

2. Overview on the use of Pin and Varactor Diodes to Reconfigure Antennas

A. Varactors

A Varactor diode, also called as a Variable Capacitor, is an electronic device that is structured from a normal PN junction which behaves as a variable capacitor under varying reverse bias voltages [58]. The structure of varactors is built from an N type material and a P type material layered together. The width of the depletion region of a varactor grows with the square root of the reverse voltage applied in a nonlinear fashion, which decreases the junction's capacitance. This allows it to be used for tuning applications [6], [7], [59], [60]. To visualize the employment of a Varactor diode in tuning "reconfiguring" the frequency of an antenna, the configuration shown in Fig. 1 is considered. The structure was first reported in [61]. However, the parameters of the structure are altered here and the antenna is redesigned for enhanced performance. The new design parameters are listed. The outline of the antenna shown in Fig. 1 includes two patches, one fed through an SMA connector, which is called "main antenna", while a second one "tuning patch" was added to tune the main antenna's resonant frequency via a Varactor diode integrated between the two. A Rogers Duroid 5880 is utilized as a substrate material with $\epsilon = 2.2$ and thickness of hs = 1.575 mm. A SMV2019-040LF varactor model was considered, with a capacitance range of [0.23, 1.43] pF, capacitance ratio of [Cmax/Cmin = 2.1] and Q factor of 500 [62], [63].

B. Pin Diodes

A PIN diode is a semiconductor element which functions as a variable resistor at RF and microwave frequencies under forward biasing conditions [66]. It is constructed from a P-type material and an N-type material with an intrinsic semiconductor I-region in between [67]. The I-region material affects the performance of the diode as it increases it0073

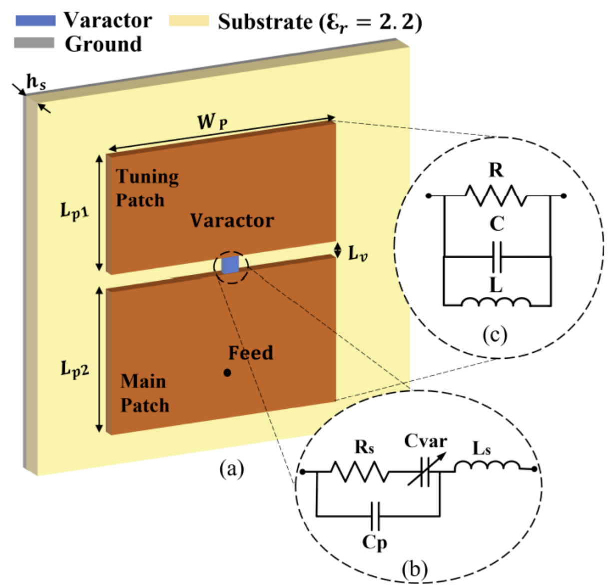

Fig. 1. (a) Proposed illustrative structure on the frequency reconfigurability of an antenna using a Varactor. (b) equivalent circuit of the Varactor diode, (c) equivalent circuit of a microstrip patch.

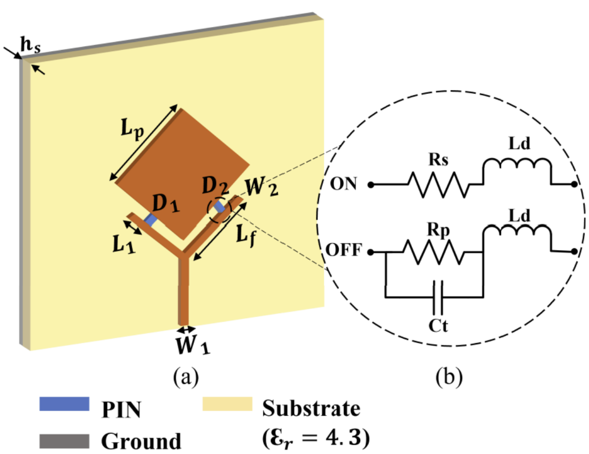

Fig 2. (a) Proposed illustrative structure on the polarization reconfigurability of an antenna using PINs (b) Equivalent circuit model of a PIN diode.

was redesigned, to elevate the operation from 4G in [7] to Sub-6 GHz (5G). The structure consists of a rhombus shaped patch antenna, fed by a Y-shaped feedline through two PIN diodes [52], built on FR-4 substrate with $\epsilon r = 4.3$ and substrate thickness of hs = 1.4 mm. The outline provides RHCP and LHCP diversity, depending on the states of the implemented PIN diodes, which are D1 and D2 shown in Fig.3). The geometry was simulated using CST Microwave Studio [53] to radiate at a center frequency of 3.5 GHz. The dimensions of the

ISSN: 2454-6844

antenna are given. The equivalent circuit model of a PIN diode is illustrated in Fig.3 (b) for both ON and OFF states. When D1 is ON (D2 is OFF), the patch antenna and the left branch line of the Y-shaped feedline are electrically connected. This aids the antenna to produce an electrically asymmetrical structure and this excites two orthogonal modes (TM10 and TM01) [51], which have an equal amplitude and a 90◦ phase difference. The excited TM10 and TM01 modes,, when D1 is ON and D2 is off, are shown in Fig.4 (e) and (f), respectively. The slots are added to these figures to show that the TM10 mode is electrically longer than TM01 along the y-axis (the current curls around the right slot), hence, the current rotates in the clockwise direction. Consequently, the antenna presents a LHCP state. Fig. 4 (a), (b), (c), and (d) exhibit the surface current distribution extracted from the CST antenna model at 3.5 GHz, when D1 is ON and D2 is off, for four samples of the current at different phase values to illustrate the progressive current rotation with reference to the positive y-axis. This curling current in the clockwise direction produces an electric field that follows same behavior leading to the generation of LHCP wave. Similarly, when D2 is ON (D1 is OFF), the antenna provides a counterclockwise current rotation, therefore generating a RHCP state.

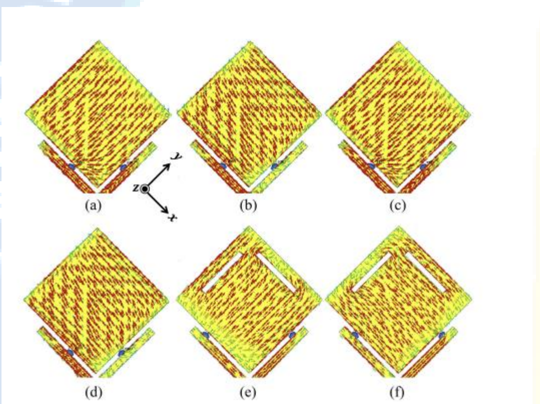

Fig 3. Surface current distribution predicted on the proposed antenna structure characterizing the LHCP state generation (a) 0◦ (b) 90◦ (c) 180◦ (d) 270◦ (e) TM10 mode (f) TM01 mode.

In addition to polarization diversity, PIN diodes are also used for frequency and pattern reconfigurability. For frequency reconfigurability, PIN diodes can be used as a bridge to connect/ disconnect metallic radiators to each other which can alter the effective length of the antenna, leading to frequency reconfiguration [15].

can alter the effective length of the antenna, leading to frequency reconfiguration [15]. To compare the simulated AR results to measured ones, the polarization reconfigurability example reported in [71], which uses a PIN diode for polarization reconfigurability at 2.45 GHz, is simulated using CST for the AR of the LHCP. The simulated results are compared to the measured ones extracted from Fig. 8 (b) in [71]. The simulated AR values are in good agreement with the measured ones. This establishes the validity of the simulated results obtained using CST for the examples included in the paper.

3. Polarization Reconfigurable Antennas

Polarization reconfigurability have been proposed in the early 1980s by Schaubert et al.. The design proposed in [46] is a square patch fed from the corner with four pairs of microwave diodes which operate as switchable shorting posts located along the center lines to achieve slant polarization, Horizontal Polarization (HP),Vertical Polarization (VP), Right Hand Circular Polarization (RHCP) and Left Hand Circular Polarization (LHCP).

Similar designs or they have further enhanced the performance of this type of configuration to satisfy modern demands. Generally, two approaches are used to implement a polarization reconfigurable antenna by either using a reconfigurable radiator [47] or a reconfigurable feeding network [48], [49], [50], [51]. The latter is more desirable, and hence more utilized by researchers, as it is more convenient for achieving full polarization diversity, in which both Linear Polarization (LP) and Circular Polarization (CP) are implemented. This approach also results in a lower cross polarization level [32]. There are many diverse implementations of this type of reconfigurability in both the 4G and the 5G spectrum [31], [37], [39] illustrate modern implementations of polarization reconfigurability in the 4G and 5G spectrum taking into account the main figures of merit related to polarization reconfigurability. The Axial Ratio bandwidth (AR B.W.) in the tables symbolizes the spectrum over which the CP polarization is within the acceptable range for CP antennas (below 3 dB). While the impedance bandwidth (S11 B.W.) is another important figure of merit for any antenna design, an antenna designer should carefully tune both the AR B.W. and the S11 B.W. with respect to the resonant frequency. Consequently, a considerable overlapping between AR B.W. and the S11 B.W. must be obtained to support the practicality (functionality) within the same spectrum. If an acceptable axial ratio bandwidth was obtained at frequencies with poor S11 matching, the design would not be of a practical value. This was not given enough consideration in many of the reported works in the literature, therefore, a new parameter is presented in this paper to calculate the percentage of overlapping between the AR B.W. and the S11 B.W. for all works included. This will allow for a real critical review for the state of the art. Fig.7 shows how the new parameter, which is called the spectrum utilization “AR/S11 B.W.” and indicates the percentage of overlapping, is calculated. The AR/S11 B.W. therefore symbolizes the utilization of the accepted bandwidth for polarization reconfigurability. According to Fig., f1 and f2 mark the 10 dB impedance bandwidth (S11 B.W.) limits whereas fa and fb define the 3 dB limit for the AR (AR B.W.). For the work done in [46], which is included, the S11 B.W. is 2.43 GHz - 2.72 GHz and the AR B.W. spans in 2.165 GHz - 2.67 GHz, therefore $AR\ S11 = 2.67-2.615\ 2.72-2.43 \times (100) = 19\%$. This means only within 19% of the S11 B.W., the antenna is reconfigured for circular polarization. This shows the importance of this newly defined figure of merit in this paper as designs that

ISSN: 2454-6844

achieve higher AR/S11 have better spectrum utilization. It is important to note that the calculation presented in Fig. 7 is valid as far as the AR B.W. is within the S11 B.W. or vice versa. Although the newly defined spectrum utilization (AR/S11 B.W.) figure of merit can be considered as an effective parameter to highlight the practically available bandwdith for the polarization reconfigurability for a given design, and hence how much that design can be improved, AR/S11 B.W. can also be used to compare between different designs, to measure the percentage of the obtained S11 B.W. than can be utilized for Circular Polarization as any remaining portion of the S11 B.W., that does not overlap with the AR B.W., will be useless as far as the polarization reconfigurability is concerned. Another figure of merit, that is listed in the tables is the number of achieved polarization states. This important parameter reflects the flexibility a design can offer to communicate with a broad number of antennas. Finally, the number of diodes employed is used as an indication for the complexity of the structure and listed as a figure of merit, where designs employing three PIN diodes and more are commonly considered complex. Other design facets are taken into consideration as well when classifying the designs, such as the antenna's structure, biasing circuitry and number of layers, which highlight the design's complexity and cost.

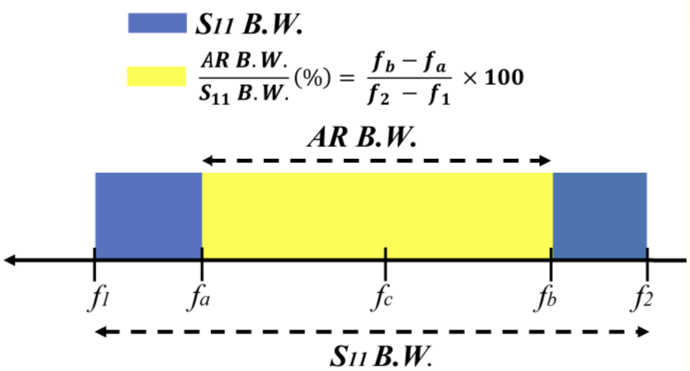

Fig 4. Illustration of the spectrum utilization (AR/S11 B.W.) calculation for CP antennas.

A. Polarization Reconfigurability In The 4g Spectrum

Many authors have presented designs which utilize two PIN diodes to implement polarization reconfigurability in the 4G spectrum [21], [27], [29]. Khidre et al. has proposed a simple design comprised of an E - shaped patch antenna printed on a single-layer substrate with a single feeding probe to excite the structure as shown in Fig.5. The antenna supports both Linear (LP) and Circular (CP) polarization states. As shown, two PIN diodes were inserted across the slots to control the polarization sense through changing the electrical length of the slots for a symmetrical or asymmetrical excitation. The design demonstrates an excellent AR/S11 B.W. of 100 % (spectrum utilization), which means a complete overlapping between AR B.W. and S11 B.W., with a fractional impedance and AR B.W. of 7% and 8.8%, respectively. The utilization of a single layer fabrication, as well as the use of small number of diodes, made the 2design simple while rendering very competitive performance. The works reported in [21], [26], [27] also utilized simple designs with two PIN diodes to achieve polarization diversity. All mentioned works were designed to serve applications in the 4G spectrum within the 2.4 GHz bands including WLAN, WiFi and Bluetooth. The design proposed in [51] offers only two polarization states, RHCP and LHCP, in contrast to the remaining mentioned designs which offer an additional LP state as well. Among these simple designs, the works in [30] and [32] offer the highest AR B.W. of 8.8 % and 8.1%, respectively. When taking the works done in [71], [86], [87], [91], and [93] into consideration, an important notion is highlighted on the use of simple structures with small number of PINs for polarization reconfigurability in the 4G spectrum, a very limited and impractical AR B.W. is obtained. This is noted from [43], where the AR B.W. achieved was 1.6%, 2.3%, 4.06%, 4.5% and 0.83%, respectively.

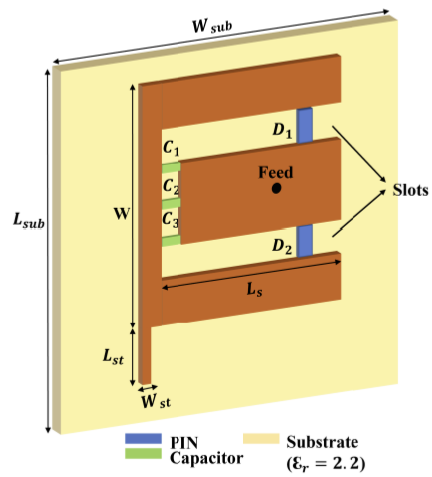

Fig 5. Polarization reconfigurability using a simple design with only two PIN diodes. Adapted from [90].

The calculated spectrum utilization (AR/S11 B.W) is listed for the designs. When considering the works done in [21], [17], [26], and [31] where the calculated AR/S11 B.W. is 28.57%, 19%, 22% and 14.81%, respectively, it becomes clear that simple designs with small number of PINs offer humble spectrum utilization (AR/S11 B.W.) in the 4G spectrum. In this regard, the reported narrow S11B.W. in [11] and [13] produce reasonable spectrum utilization yet, the usable frequency band is very narrow. This underlines the question of what is required by the targeted application to say if these figures are satisfactory. The polarization reconfigurability has been also implemented using diverse designs, which utilize more PIN diodes than the ones discussed thus far [23]. As described, these appear to utilize more complicated antenna structures and more PIN diodes to realize the targeted polarization states. For instance, Wang and Wong [80] presented a patch antenna fed through a cross feeding probe at 2.45 GHz, as shown in Fig.6, offering CP and LP reconfiguration. The structure was built from three multi-layered substrates and four probes that support the cross feed built from three strips. Three PIN diodes were

International Journal of Research and Development in Applied Science and Engineering (IJRDASE)
ISSN: 2454-6844

implemented between the strips to allow control over the polarization. When D1, shown in Fig.9 is ON, the current flows through Stub 1 and Stub 2, creating two orthogonal electric fields on the patch with a similar magnitude and 90◦ phase difference, resulting in a RHCP state. Similarly, when D2 is ON while D1 and D3 are OFF, the current flows through Stub 1 and Stub 3, leading to a LHCP state. For the LP state, D3 is ON while the rest are OFF, and the current is conveyed solely through Stub 1. This shows that the implementation of multiple PIN diodes offers a better control over the surface current, which facilitates reconfiguring multiple polarization states. The DC biasing circuit was embedded at the bottom substrate which was backed by the ground plane. The design achieved a 19.2 % AR B.W. and 16.32 % S11 B.W.. The AR/S11 B.W. is 100% which indicates the excellent spectrum utilization provided by the antenna. The outline of the antenna is characterized with multiple layers and PINs, which increase the overall cost and complexity. Designs reported in [79] and [82], [94], which employ six and eight diodes, respectively, targeted a different frequency band of 1.559 - 1.61 GHz which serves applications including GPS and CNNs [96]. Both [79], [94] have offered only CP diversity, with AR/S11 B.W. of 66.67% and 35.4%, respectively, while [82] offered four polarization states with full spectrum utilization, where AR/S11 B.W. is 100%. Although Varactors are scarcely used for polarization reconfigurability, an antenna design based on two Varactors with figures of merits that are of interest was proposed in [95]. The structure resulted in a very narrow AR B.W. of only 1.4 % when compared to other works with similar layout and frequency of operation, in addition to the limited spectrum utilization, where AR/S11 is 29.6%.

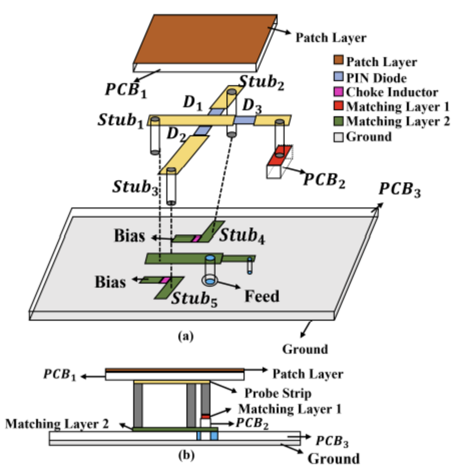

Fig 6. Polarization reconfigurability in the 4G spectrum using multiple PIN diods. Adapted from [80].

A key observation on polarization reconfigurability in the 4G spectrum:

• The utilization of multiple PINs improves the axial ratio (AR B.W.) bandwdith and the spectrum utilization (AR/S11B.W.). This can be observed when comparing [19], [20], [22], [27] (100%, 66.67%, 100%, 34.48%, respectively) to [21], [27], [36], and [41] (28.57%, 19%, 22% and 14.81%, respectively) in terms of AR/S11 B.W. as well as when comparing [29], [30], [44] (19.2%, 20.8%, 23.5%, respectively) to [21], [36], [41] and [43] (1.6%, 2.3%, 4.5% and 0.83%, respectively) in terms of the achieved AR B.W.

B. Polarization Reconfigurability in the 5G Spectrum

PIN and Varactor diodes were also used to employ polarization diversity in the 5G spectrum [28], [31], [34], [35], [47], [59], [60], [61]. Researchers have developed both simple designs with two diodes [57] and complex ones with multiple diodes [38], [44], [45], [58] as classified. An advanced structure was demonstrated by Wu et al. in [98] as shown in Fig.10. The design consists of multiple layers. A 3 × 4 patch array is printed on the upper substrate, shown in Fig. 6(a), nine PIN diodes were used to electrically connect the patches, enabling polarization reconfgiruability based on the diodes states, while eight inductors are implemented to electrically connect the elements along the direction of polarization. The bottom substrate, shown in Fig.6(b), was utilized for the DC biasing lines, as well as a co-planar waveguide (CPW). In between both substrates, a ground plane was implemented with a slant slot at θ = 40◦ . The structure offers LP as well as LHCP senses depending on the PINs states. The antenna covers the 5G WiFi communications band with a high AR/S11 B.W. of 75 %. This is a very reasonable spectrum utilization as the AR B.W. and the S11 B.W. are reasonably wide; 16.36% and 21.8%, respectively.

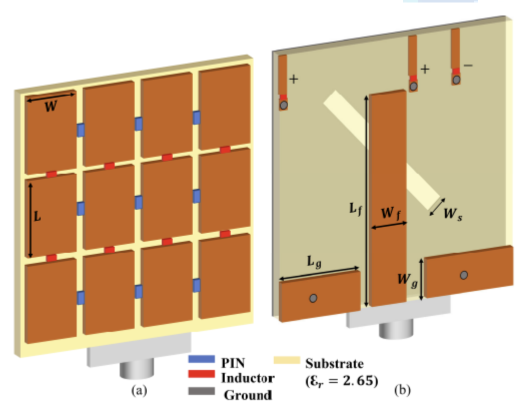

Fig 7. Polarization reconfigurability in the 5G spectrum using multiple PIN diodes. (a) front view and (b) back view. Adapted after [98].

The work done in [24] and [25] offer both LP and CP diversity reconfigured using four PIN diodes. The design in [55] was superior in terms of AR B.W. (16 %) as well as the spectrum utilization AR/S11 B.W. (100%), compared to the one in [54] which offers only 7.1% AR B.W. and 94.44 % AR/S11 B.W.. Despite the work done in [58] utilized nine PIN diodes, it achieved less polarization states (only LP and LHCP) with narrower AR/S11 B.W. (75%) compared to the design in [85] which supports the same frequency band and utilizes only 4 PIN diodes. On a similar observation, the work done in [58] used 64 diodes to achieve polarization diversity within the frequency

International Journal of Research and Development in Applied Science and Engineering (IJRDASE)
ISSN: 2454-6844

range in [57], yet, the spectrum utilization in [58] (AR/S11 B.W. = 52.2 %) is almost half of it is in [57] (AR/S11 B.W. = 100%). It is observed that utilizing multiple PIN didoes does not ensure better performance for polarization diversity, as seen from comparing [65] and [68], as well as [28] and [67] in terms of AR/S11 B.W. Despite Varactor diodes are not commonly used to reconfigure polarization in the 5G spectrum, the design in [19] utilized two Varactor diodes to offer four polarization states, with CP and LP diversity. The reported spectrum utilization AR/S11 B.W. in [19] is only 19%, which is humble as compared to the full spectrum utilization achieved in [17] of 100%. Reconfigurable polarization works were also reported for 5G mm - wave applications as proposed in [21], [100], and [1]. All proposed structures in are designed in the Ka band at a center frequency of 28 GHz for satellite communication purposes and all utilized four PINs to implement polarization diversity. The work done in [10] presented the widest S11 B.W. (26.13 - 29.49 GHz) while offering only LP diversity (VP and HP). On the other hand, the work done in [21] offered a much better spectrum utilization with AR/S11 B.W. of 46% compared to AR/S11 B.W. of 20.27% for the work in [1], however, the latter work has the advantage of offering LP state in addition to the two CP polarization states as shown.

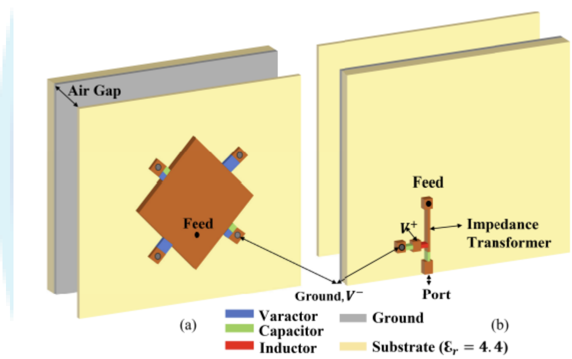

Fig 8. Frequency reconfigurable antenna design using multiple varactors. Adapted from.

A. Frequency Reconfigurability in the 4G Spectrum

Many recent works in the open literature have presented frequency reconfigurable 4G antennas using PINs and Varactors [7], [24], [14], [15], [16], [17], [18]. Row and Tsai proposed a right hand circularly polarized square patch with 4 varactor diodes connected to the center of the four edges of the patch, as illustrated in Fig.12, to tune the frequency between (1.97 - 2.53 GHz) for WLAN applications. The design consists of multiple substrate layers separated by an air gap, where the top layer is used for the patch antenna and the bottom layer is used for the feedline and biasing circuits. The employed varactors are identical and are used to tune the resonant frequencies of the dual orthogonal modes (TM10, TM01) responsible for the RHCP, while the capacitors are utilized to produce the required phase difference of the two modes. The design accomplished a TR of 44.8 %, with a FBW ranging from 4% to 9.09%, leading to a significant improvement in the FBW, with a FBWC of 127.25%. Varactors were used to implement frequency reconfigurability in the 4G spectrum with relatively more designs than the ones in which PINs are employed [7], [14], [16], [17], [18]. The proposed designs in [16], [17], and [18] have opted for similar frequency ranges around 2.4 GHz, using two, four and eight varactors, respectively. The designs support multiple services such as WLAN, Bluetooth and LTE. The designs in [16], [17], and [18] offered a FBW of 1.63%, 9.09% and 17.42%, respectively. A clear improvement can be noted between the number of Varactors employed and the resulting FBW, where the available FBW for WLAN and Bluetooth applications increases with number of Varactors used. This indicates better coverage for the applications at hand. The same trend can be noted in terms of the FBWC, where the works in [16], [17], and [18] achieved a FBWC of -58.25%, 127.25% and 190.33%, respectively. In terms of the TR, the antennas in [17] and [18] achieved a TR of 24.88% and 32.91%, respectively, which confirms the performance improvement as the number of varactors increases. Furthermore, the works done in [7] and [14] are designed for GPS services using eight and twenty five varactors, respectively. The work in [7] have offered a significant advantage of providing independently reconfigurable dual bands centered around 0.9 GHz and 1.7 GHz, while [14] offer a single reconfigurable band centered around 1.8 GHz. The second band offered by [7] (1.5 - 1.87 GHz) greatly overlaps with that offered by [14] (1.72 - 1.95 GHz), however, the achieved FBW, TR as well as FBWC by utilizing 8 varactors in [7] (6%, 22% and 500%) are larger than the ones achieved using 25 varactors in [14] (4.59%, 13% and 99.56%). On the other hand, PIN diodes are also used to tune bands in the 4G spectrum used for WLAN, GPS and GSM [14], [15]. As summarized, the design proposed in [34] utilize a single PIN diode to tune dual bands centered around (1.55, 2.55 GHz) to (1.65, 2.49 GHz). While the dual band approach is advantageous, the FBW obtained in the first band is low (0.64%), and it is improved to 1.81% upon tuning. On the other hand, the FBW achieved in the second band has noticeably deteriorated upon tuning with FBWC of -41.6% (FBW = 2.55% to 1.6%). This indicates that the available FBW may not fully cover the 2.4 spectrum for WLAN services. When comparing [14] to [15], in which a single band is tuned into four bands across 1.6 - 2.71 GHz by employing three PINs, a larger FBW is obtained in each designated band in [105], ranging from 6% to 17%. This shows that the use of large number of PINs, increases the FBW and hence the FBWC for WLAN and WiFi services as confirmed from the figures reported in [14] and [15]. Finally, in terms of the services provided in the 4G spectrum, designs in [17] and [18] support most of the applications successfully, while [7], [14] can only support GPS. Furthermore, the design in [16] offers great solution for cognitive radio applications. However, the narrow FBW offered can partially satisfy WLAN and LTE applications whereas the design in [15] can satisfy services like LTE, Bluetooth and WLAN.

B. Integrated 4G/5G Frequency Reconfigurable Antennas

The idea behind frequency tuning have emerged from the need to support multiple standards in the 4G and 5G spectrum using the same hardware. Under this context, in several modern works multiple 4G and 5G (Sub-6 GHz) services were supported by one integrated 4G/5G antennas [4], [15], [19], [61], [13], [19], [10], [11], [12] as illustrated. Han et al. proposed a patch antenna designed with two L -shaped and one U - shaped slots engraved in the ground as illustrated in Fig. Three PIN diodes are utilized for frequency reconfigurability in the 4G and the Sub-6 GHz 5G spectrum, to cover LTE 2300, AMT and WLAN services. Diode D1, shown in Fig.7, controls the band response, switching between dual bands when D1 is OFF and a single band when D1 is ON, while D2 and D3 are utilized to tune the operating frequency in each of the bands namely, (2.39, 4.59 GHz) when both D2 and D3 are OFF, and (4.32, 5.64 GHz) when both are ON. One highlight for this design is the excellent TR in the designated bands with a TR of 86.42 % and (57.5%, 20.5%) for the single and dual bands, respectively. In addition, the obtained FBW improves upon tuning to higher frequencies, as can be observed for both the single band (FBW = 2.6% to 6.5%) with an excellent FBWC of 150%, as well as the dual bands (FBW = 6.7% to 7.4%, 2.7% to 4.6%) with FBWC of 10.44% and 70.37%, respectively. The employment of multiple diodes makes the design relatively complex. Other structures, which utilizes PIN diodes to tune frequency in the 4G/5G spectrum, are reported in [4], [15], and [19]. In these modern designs, the FBW provided was reconfigured between a single band and dual bands [4], [15], [19], as well as triple bands [4]. The works done in [15], [19], and [4] support multiple applications including 5G WiFi, 4G WLAN and Bluetooth. The design in [15] provides the largest FBW of 28% for 5G WiFi applications, compared to the FBW reported in [109] (6.5%) and in [15] (10.16%). In terms of the 4G WLAN and Bluetooth applications, the largest FBW of 19.23% was achieved in [4] with a dual band reconfiguration. The FBW obtained in the same 4G WLAN spectrum in [15] is 16.66%. The reported work in [109] provided the largest TR for both single (86.42%) and dual bands tuning (57.5%, 20.5%), relative to [4] (35.29%) for single band and [4], [15] for dual band tuning of (21.27%, 14.88%) and (31.57%, 10.71%), respectively, as illustrated. One highlight for utilizing PIN diodes for reconfiguring the 4G/5G spectrum into single, dual and triple bands would be the enhanced range of covered frequencies resulted from multi - band reconfiguration, which is observed in [4], [15], and [19].

Regarding the FBWC in the 4G/5G designs, the review of the reported works in [4], [15], and [109], which employed one, three and four PIN diodes respectively, reveals that employing a larger number of PIN diodes helps in increasing the FBW upon tuning. This is observed from the comparison of the FBWC values of reconfigured dual bands in [15] (45.5%, -10.08%) to the ones in [4] and [109] (21.27%, 14.88%) and (10.44%, 70.37%).

It is also observed that employing more PINs results in more band reconfigurations. However, this comes at a cost of increasing the footprint. This is highlighted when comparing the work in [109] of footprint (27 × 25 mm2) which utilizedthree PINs to the work in [4] of footprint (40 × 32 mm2), which emplyed four PINs.

The antennas presented in [19], [13], and [11] support similar applications using four, three and five PINs, respectively, including 2.4 GHz WLAN, Bluetooth and 3.5 GHz WiMAX. The structure in [13] offered an excellent Tuning Range (TR) of 76.13% compared to the TR values calculated from the data in [19] and [11] (27.28% and 57.81%, respectively.) For the 2.4 GHz WLAN band, the work presented in [19] offered a higher FBW of 12.24%, compared to the FBW in [13] and [11] which are 8.7% and 7.7%, respectively. However, for the 3.5 GHz WiMAX band, the work in [103] offered the largest FBW of 11.2%, compared to the FBW reported in [110] (5.5%) and in [19] (6.57%). Besides, the FBW demonstrated in [13] have generally improved upon tuning, with FBWC of 26.43% and 28.73%, for center frequencies 3.5 GHz and 5.35 GHz, respectively. However, a general FBW decrease was seen in [19] and [11] where the FBW deteriorated upon tuning to record an FBWC of46.32% and -30.3%, respectively.

Varactors were also implemented for tuning purposes between 4G and 5G under similar bands [61], [11], [12]. The reported work in [11] have achieved the largest FBW for 2.4 GHz WLAN applications of 47.6%, with an incredible TR of 143.75%, which makes the design appropriate candidate for WLAN and Bluetooth, as well as for 5G WiFi and WiMAX applications. However, the FBW decreased upon tuning over the vast tuning range, with an FBWC of - 64.87%. On the other hand, the antennas presented in [61] and [12] have offered relatively narrow FBW, which is suitable for IoT applications. The design in [7] implemented three Varactors to achieve a FBW and TR values of of 2.41% and 41.5%, respectively, while the design in [12] used nine Varactors to offer a maximum TR of only 22.8 % and a maximum FBW of 5.18%. However, one merit for the design in [12] is the independently tunable triple band response, which irrespective of the narrow FBW in the first and second band (FBW = 1%) offers more coverage among the Sub-6 GHz spectrum. In terms of the applications designated in the 4G and 5G bands (Sub-6 GHz), 4G application are included, where LTE 2300 was fully supported in [15], [13], [11], and [21]. The work in [4] has fully enabled LTE 2500, in addition to Bluetooth and WLAN that were covered in [4], [15], [19], [13], and [11]. Additional 5G services such as AMT (4.4 - 4.5) were supported in [19], 5G WLAN (5.725 - 5.825) in [4], [15], [19], and [11] and 3.5 GHz WiMAX (3.4 - 3.5) in [4], [15], [13], and [11]. The proposed antennas offer a great solution for the infrastructure required while taking a step into 5G but still need to support the established applications and standards.

C. FREQUENCY RECONFIGURABILITY IN THE 5G SPECTRUM

Frequency tuning was also investigated in the 5G spectrum. The contemporary reported works found under in this spectrum were reviewed and compared [20], [13], [14], [15], [16] as demonstrated. The design presented in [13] utilized four PINs to target 5G WLAN and 3.5 GHz WiMAX applications. The design achieved a TR of 44.44% but a decreasing FBW (FBWC

= −40%), where the FBW offered for 5G WLAN band is 19.8%. The structures presented in [20] and [14] proposed tunable bands residing in the Sub-6GHz and utilized a combination of PINs and Varactors to support 5G WLAN applications. The design in [14] proposed an Ultra Wide Band (UWB) spanning from 3.19 to 5.47 GHz in addition to a tunable narrow band, while the work in [20] offered two bands, each can be tuned to three center frequencies, namely (3.21, 3.5, 3.63 GHz) and (4.76, 5.04, 5.42 GHz), respectively. The two bands together form an overlapping spectrum from 3.04 GHz to 5.89 GHz. When considering the works done in [20] and [14], the work in [20] achieved a higher TR of 51% compared to the TR of 44% achieved in [114]. On the other hand, a superior FBW improvement in [20] was calculated upon tuning from 15.3% to 39.7% (FBWC = 159.47%). Similarly, the FBW achieved in [14] improved upon tuning from 5% - 7.84%, where the FBWC calculated was 56.8%.

The significant FBW improvement calculated from [20] and [14] indicates the advantages of employing PINs and Varactors in the same structure. Varactors are able to tune the band locally, while the discrete nature of PIN diodes enables significant shift in the operating frequency or change its reconfiguration by manipulating the electrical length of the antenna. Therefore, using PINs and Varactors for frequency tuning in the same antenna structure reaps the benefits of both diodes; employing multiple PINs enables multiple band reconfiguration, hence, a wider TR, while Varactors improve the FBW upon tuning, resulting in a significant FBWC. This is highlighted when comparing the designs in [20] and [14] to the work done in [13], which used four PIN diodes and obtained results inferior to [20] and [14].

4. Conclusion:

A critical review of many modern 4G, 4G/5G and 5G implementations employing PIN diodes and Varactors for frequency or polarization reconfiguration was presented. The review of the reported works was done based on existing and newly defined figures of merits. For polarization diversity, the defined spectrum utilization, which is calculated based on the available axial ratio bandwidth and the impedance bandwidth was shown very useful in revealing the actual bandwidth available for the supported applications upon reconfiguration. Many modern designs failed to achieve full spectrum utilization, however it was observed that employing multiple PIN diodes for polarization diversity can improve the spectrum utilization and the axial ratio bandwdith in the 4G spectrum. For frequency reconfigurability, the comparison of the change in fractional bandwidth upon frequency tuning was shown essential in judging upon the performance of the reviewed reconfigured antennas in terms of the available fractional bandwdith for the supported applications upon tuning. It was observed that the employment of both PIN and Varactor diodes in one structure is very useful in improving the fractional bandwdith and tuning range in the 5G spectrum.

References

[1] C. Zhang, S. L. Ariyavisitakul, and M. Tao, "LTE-advanced and 4G wireless communications [guest editorial]," IEEE Commun. Mag., vol. 50, no. 2, pp. 102–103, Feb. 2012.

[2] J.-H. Lu and J.-L. Guo, "Small-size octaband monopole antenna in an LTE/WWAN mobile phone," IEEE Antennas Wireless Propag. Lett., vol. 13, pp. 548–551, 2014.

[3] N. O. Parchin, H. J. Basherlou, Y. I. A. Al-Yasir, A. M. Abdulkhaleq, and R. A. Abd-Alhameed, "Reconfigurable antennas: Switching techniques—A survey," Electronics, vol. 9, no. 2, p. 336, Feb. 2020.

[4] H. Dildar, F. Althobiani, I. Ahmad, W. U. R. Khan, S. Ullah, N. Mufti, S. Ullah, F. Muhammad, M. Irfan, and A. Glowacz, "Design and experimental analysis of multiband frequency reconfigurable antenna for 5G and Sub-6 GHz wireless communication," Micromachines, vol. 12, no. 1, p. 32, Dec. 2020.

[5] W. Pan, C. Huang, P. Chen, M. Pu, X. Ma, and X. Luo, "A beam steering horn antenna using active frequency selective surface," IEEE Trans. Antennas Propag., vol. 61, no. 12, pp. 6218–6223, Dec. 2013.

[6] M. W. Young, S. Yong, and J. T. Bernhard, "A miniaturized frequency
reconfigurable antenna with single bias, dual varactor tuning," IEEE Trans. Antennas Propag., vol. 63, no. 3, pp. 946–951, Mar. 2015.

[7] N. Nguyen-Trong, A. Piotrowski, and C. Fumeaux, "A frequencyreconfigurable dual-band low-profile monopolar antenna," IEEE Trans. Antennas Propag., vol. 65, no. 7, pp. 3336–3343, Jul. 2017.

[8] S. Gao, A. Sambell, and S. S. Zhong, "Polarization-agile antennas," IEEE Antennas Propag. Mag., vol. 48, no. 3, pp. 28–37, Jun. 2006.

[9] L. Kang, H. Li, J. Zhou, and S. Zheng, "An OAM-mode reconfigurable array antenna with polarization agility," IEEE Access, vol. 8, pp. 40445–40452, 2020.

[10] M. N. Osman, M. K. A. Rahim, M. R. Hamid, M. F. M. Yusoff, and H. A. Majid, "Compact dual-port polarization-reconfigurable antenna with high isolations for MIMO application," IEEE Antennas Wireless Propag. Lett., vol. 15, pp. 456–459, 2016.

[11] C. G. Christodoulou, Y. Tawk, S. A. Lane, and S. R. Erwin, "Reconfigurable antennas for wireless and space applications," Proc. IEEE, vol. 100, no. 7, pp. 2250–2261, Jul. 2012.

[12] I. Ahmad, H. Dildar, W. U. R. Khan, S. A. A. Shah, S. Ullah, S. Ullah, S. M. Umar, M. A. Albreem, M. H. Alsharif, and K. Vasudevan, "Design and experimental analysis of multiband compound reconfigurable 5G antenna for sub-6 GHz wireless applications," Wireless Commun. Mobile Comput., vol. 2021, pp. 1–14, Apr. 2021.

[13] R. L. Haupt and M. Lanagan, "Reconfigurable antennas," IEEE Antennas Propag. Mag., vol. 55, no. 1, pp. 49–61, Feb. 2013.

[14] N. O. Parchin, H. J. Basherlou, Y. I. Al-Yasir, R. A. Abd-Alhameed, A. M. Abdulkhaleq, and J. M. Noras, "Recent developments of reconfigurable antennas for current and future

wireless communication systems," Electronics, vol. 8, no. 2, p. 128, 2019.
[15] R. Shanmugam, "Design and analysis of a frequency reconfigurable pentaband antenna for WLAN and 5G applications," J. Electromagn. Eng. Sci., vol. 21, no. 3, pp. 228–235, Jul. 2021.
[16] F. Zadehparizi and S. Jam, "Increasing reliability of frequencyreconfigurable antennas," IEEE Antennas Wireless Propag. Lett., vol. 17, no. 5, pp. 920–923, May 2018.
[17] M. M. Fakharian, P. Pezaei, A. A. Orouji, and M. Soltanpur, "A wideband and reconfigurable filtering slot antenna," IEEE Antennas Wireless Propag. Lett., vol. 15, pp. 1610–1613, 2016.
[18] L. Pazin and Y. Leviatan, "Reconfigurable slot antenna for switchable multiband operation in a wide frequency range," IEEE Antennas Wireless Propag. Lett., vol. 12, pp. 329–332, 2013.
[19] G. Jin, C. Deng, J. Yang, Y. Xu, and S. Liao, "A new differentially-fed frequency reconfigurable antenna for WLAN and sub-6GHz 5G applications," IEEE Access, vol. 7, pp. 56539–56546, 2019.
[20] T. Li, H. Zhai, L. Li, and C. Liang, "Frequency-reconfigurable bow-tie antenna with a wide tuning range," IEEE Antennas Wireless Propag. Lett., vol. 13, pp. 1549–1552, 2014.
[21] Z. Zhang and Z. Pan, "Design of reconfigurable bandwidth filtering antenna and its applications in IR/UWB system," Electronics, vol. 9, no. 1, p. 163, Jan. 2020.
[22] P. F. Hu, Y. M. Pan, X. Y. Zhang, and B.-J. Hu, "A filtering patch antenna with reconfigurable frequency and bandwidth using F-shaped probe," IEEE Trans. Antennas Propag., vol. 67, no. 1, pp. 121–130, Jan. 2019.
[23] N. Ojaroudi, S. Amiri, and F. Geran, "A novel design of reconfigurable monopole antenna for UWB applications," Appl. Comput. Electromagn. Soc. J., vol. 28, no. 7, pp. 633–639, 2013.
[24] J. Deng, S. Hou, L. Zhao, and L. Guo, "Wideband-to-narrowband tunable monopole antenna with integrated bandpass filters for UWB/WLAN applications," IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 2734–2737, 2017.
[25] P. Y. Qin, F. Wei, and Y. J. Guo, "A wideband-to-narrowband tunable antenna using a reconfigurable filter," IEEE Trans. Antennas Propag., vol. 63, no. 5, pp. 2282–2285, May 2014.
[26] M.-C. Tang, Z. Wen, H. Wang, M. Li, and R. W. Ziolkowski, "Compact, frequency-reconfigurable filtenna with sharply defined wideband and continuously tunable narrowband states," IEEE Trans. Antennas Propag., vol. 65, no. 10, pp. 5026–5034, Oct. 2017.
[27] I. F. Da Costa, S. A. Cerqueira, D. H. Spadoti, L. G. Da Silva, J. A. J. Ribeiro, and S. E. Barbin, "Optically controlled reconfigurable antenna array for mm-Wave applications," IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 2142–2145, 2017.
[28] P. Alizadeh, A. S. Andy, C. Parini, and K. Z. Rajab, "A reconfigurable reflectarray antenna in Ka-band using optically excited silicon," in Proc. 10th Eur. Conf. Antennas Propag. (EuCAP), Apr. 2016, pp. 1–5.
[29] P.-J. Liu, D.-S. Zhao, and B.-Z. Wang, "Design of optically controlled microwave switch for reconfigurable antenna systems," in Proc. Int. Conf. Microw. Millim. Wave Technol., vol. 1, Apr. 2007, Art. no. 90505001.
[30] Y. Tawk, J. Costantine, F. Ayoub, C. Christodoulou, D. Doyle, and
S. A. Lane, "Physically reconfigurable antennas: Concepts and automation," in Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting, Jul. 2017, pp. 419–420.
[31] I. T. McMichael, "A mechanically reconfigurable patch antenna with polarization diversity," IEEE Antennas Wireless Propag. Lett., vol. 17, no. 7, pp. 1186–1189, Jul. 2018.
[32] J. Costantine, Y. Tawk, S. E. Barbin, and C. G. Christodoulou, "Reconfigurable antennas: Design and applications," Proc. IEEE, vol. 103, no. 3, pp. 424–437, Mar. 2015.
[33] P. Liu, S. Yang, X. Wang, M. Yang, J. Song, and L. Dong, "Directivityreconfigurable wideband two-arm spiral antenna," IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 66–69, 2016.
[34] Z. Hu, S. Wang, Z. Shen, and W. Wu, "Broadband polarizationreconfigurable water spiral antenna of low profile," IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 1377–1380, 2017.
[35] S. Wang, L. Zhu, and W. Wu, "A novel frequency-reconfigurable patch antenna using low-loss transformer oil," IEEE Trans. Antennas Propag., vol. 65, no. 12, pp. 7316–7321, Dec. 2017.
[36] S. J. Mazlouman, A. Mahanfar, C. Menon, and R. G. Vaughan, "A review of mechanically reconfigurable antennas using smart material actuators," in Proc. 5th Eur. Conf. Antennas Propag. (EUCAP), Apr. 2011, pp. 1076–1079.
[37] T. N. Ibrahim, T. Harvey, B. Dane, P. L. Craig, and M. W. Thomas, "Mechanically reconfigurable, dual-band slot dipole antennas," IEEE Trans. Antennas. Propag., vol. 63, no. 7, pp. 3267–3271, Jul. 2015.
[38] P. Sanchez-Olivares and J. L. Masa-Campos, "Mechanically reconfigurable conformal array antenna fed by radial waveguide divider with tuning screws," IEEE Trans. Antennas Propag., vol. 65, no. 9, pp. 4886–4890, Sep. 2017.
[39] T. S. Teeslink, D. Torres, J. L. Ebel, N. Sepulveda, and D. E. Anagnostou, "Reconfigurable bowtie antenna using metal-insulator transition in vanadium dioxide," IEEE Antennas Wireless Propag. Lett., vol. 14, pp. 1381–1384, 2015.
[40] M. Wang, I. M. Kilgore, M. B. Steer, and J. J. Adams, "Characterization of intermodulation distortion in reconfigurable liquid metal antennas," IEEE Antennas Wireless Propag. Lett. , vol. 17, no. 2, pp. 279–282, Feb. 2018.
[41] G. B. Zhang, R. C. Gough, M. R. Moorefield, K. J. Cho, A. T. Ohta, and W. A. Shiroma, "A liquid-metal polarization-pattern-reconfigurable dipole antenna," IEEE Antennas Wireless Propag. Lett., vol. 17, pp. 50–53, 2018.
[42] I. F. Akyildiz, D. M. Gutierrez-Estevez, and E. C. Reyes, "The evolution to 4G cellular systems: LTE-advanced,"

Phys.Commun., vol. 3, no. 4, pp. 217–244, 2010. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1874490710000303

[43] F. Firmin. (2015). 3GPP Portal. [Online]. Available: https://portal. 3gpp.org/desktopmodules/Specifications/SpecificationDetails. aspx? specificationId=1072

[44] S. Frattasi, H. Fathi, F. H. P. Fitzek, R. Prasad, and M. D. Katz, "Defining 4G technology from the users perspective," IEEE Netw., vol. 20, no. 1, pp. 35–41, Jan. 2006.

[45] R. S. H. Istepanaian and Y.-T. Zhang, "Guest editorial introduction to the special section: 4G health—The long-term evolution of m-health," IEEE Trans. Inf. Technol. Biomed., vol. 16, no. 1, pp. 1–5, Jan. 2012.

[46] P. P. Parikh, M. G. Kanabar, and T. S. Sidhu, "Opportunities and challenges of wireless communication technologies for smart grid applications," in Proc. IEEE PES Gen. Meeting, Jul. 2010, pp. 1–7.

[47] M. Y. Rhee, "4G wireless internet communication technology," in Wireless Mobile Internet Security. Wiley, 2013, pp. 439–465, doi: 10.1002/9781118512920.ch13.

[48] H. T. Chattha, "4-port 2-element MIMO antenna for 5G portable applications," IEEE Access, vol. 7, pp. 96516–96520, 2019.

[49] Q. Wu, P. Liang, and X. Chen, "A broadband ±45◦ dual-polarized multiple-input multiple-output antenna for 5G base stations with extra decoupling elements," J. Commun. Inf. Netw., vol. 3, no. 1, pp. 31–37, Mar. 2018.

[50] (Jun. 2022). 5G Spectrum—GSMA. [Online]. Available: https://www.gsma.com/spectrum/wp-content/uploads/2022/06/5GSpectrum-Positions.pdf

[51] M. Khalily, R. Tafazolli, P. Xiao, and A. A. Kishk, "Broadband mmWave Microstrip array antenna with improved radiation characteristics for different 5G applications," IEEE Trans. Antennas Propag., vol. 66, no. 9, pp. 4641–4647, Sep. 2018.

[52] S. Kumar, A. S. Dixit, R. R. Malekar, H. D. Raut, and L. K. Shevada, "Fifth generation antennas: A comprehensive review of design and performance enhancement techniques," IEEE Access, vol. 8, pp. 163568–163593, 2020.

[53] Requirements, Evaluation Criteria and Submission Templates for the Development of IMT-2020, document M.2411, Nov. 2017.

[54] X. Lu, E. Sopin, V. Petrov, O. Galinina, D. Moltchanov, K. Ageev, S. Andreev, Y. Koucheryavy, K. Samouylov, and M. Dohler, "Integrated use of licensed- and unlicensed-band mmWave radio technology in 5G and beyond," IEEE Access, vol. 7, pp. 24376–24391, 2019.

[55] H. Hui, Y. Ding, Q. Shi, F. Li, Y. Song, and J. Yan, "5G networkbased Internet of Things for demand response in smart grid: A survey on application potential," Appl. Energy, vol. 257, Jan. 2020, Art. no. 113972. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261919316599

[56] IMT Vision–Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond, document TU-R M.2083-0, 2015.

[57] M. Ikram, E. A. Abbas, N. Nguyen-Trong, K. H. Sayidmarie, and A. Abbosh, "Integrated frequency-reconfigurable slot antenna and connected slot antenna array for 4G and 5G mobile handsets," IEEE Trans. Antennas Propag., vol. 67, no. 12, pp. 7225–7233, Dec. 2019.

[57] A. Khidre, F. Yang, and A. Z. Elsherbeni, "A patch antenna with a varactorloaded slot for reconfigurable dual-band operation," IEEE Trans. Antennas Propag., vol. 63, no. 2, pp. 755–760, Feb. 2015.

[59] C. Huang, W. Pan, X. Ma, and X. Luo, "A frequency reconfigurable directive antenna with wideband low-RCS property," IEEE Trans. Antennas Propag., vol. 64, no. 3, pp. 1173–1178, Mar. 2016.

[60] L. Ge, M. Li, J. Wang, and H. Gu, "Unidirectional dual-band stacked patch antenna with independent frequency reconfiguration," IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 113–116, 2016.

[61] N. Nguyen-Trong and C. Fumeaux, "Tuning range and efficiency optimization of a frequency-reconfigurable patch antenna," IEEE Antennas Wireless Propag. Lett., vol. 17, no. 1, pp. 150–154, Jan. 2018.

[62] Skyworks. (Oct. 23, 2022). Application Note Varactor Diode. [Online]. Available: https://www.skyworksinc.com/-/media/900F2141E45048DAA0A60CD40E8F567B.pdf

[63] (Apr. 2020). Data Sheet SMV2019 to SMV2023 Series: Hyperabrupt Junction. . . Skyworks. [Online]. Available: https://www.skyworksinc.com/-/media/SkyWorks/Documents/Products/201-300/SMV2019_to_SMV2023_Series_200074S.pdf

[64] A. Singh, K. Shet, D. Prasat, A. K. Pandey, and M. Aneesh, "A review: Circuit theory of microstrip antennas for dual-, multi-, and ultra-widebands," in Modulation in Electronics and Telecommunications, G. Dekoulis, Ed. London, U.K.: IntechOpen, 2020, pp. 105–123.

[65] S. Verma and J. A. Ansari, "Analysis of U-slot loaded truncated corner rectangular microstrip patch antenna for broadband operation," AEU Int. J. Electron. Commun., vol. 69, no. 10, pp. 1483–1488, Oct. 2015.

[66] Y. Zhang, Q. Yin, M. Luo, and Y. Jiang, "The pin diode circuit designers, handbook the pin diode circuit designers, handbook, 1998," IEICE Trans. Commun., vol. 90, no. 6, pp. 1467–1473, 2007.

[67] R. Cory and D. Fryklund, "Solid state RF/microwave switch technology: Part 2," in Microw. Product Dig., 2009, p. 34.

[68] S. Dubal and A. Chaudhari, "Mechanisms of reconfigurable antenna: A review," in Proc. 10th Int. Conf. Cloud Comput., Data Sci. Eng. (Confluence), Jan. 2020, pp. 576–580.

[69] X. Li, F. Xiao, Y. Luo, R. Wang, and Y. Duan, "Modeling of high-voltage nonpunch-through PIN diode snappy reverse recovery and its optimal suppression method based on RC

snubber circuit," IEEE Trans. Ind. Electron., vol. 69, no. 6, pp. 5700–5712, Jun. 2022.