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A Review of Wideband Reflectarray Antennas for 5G Communication Systems

MUHAMMAD HASHIM DAHRI[1], MOHD HAIZAL JAMALUDDIN[1], (Member, IEEE), MUHAMMAD INAM ABBASI[1], AND MUHAMMAD RAMLEE KAMARUDIN[2], (Senior Member, IEEE)

[1]Wireless Communication Centre, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia
[2]Centre for Electronic Warfare Information and Cyber, Cranfield Defence and Security, Cranfield University, Defence Academy of the United Kingdom, Shrivenham SN6 8LA, U.K.

Corresponding author: Muhammad Ramlee Kamarudin (ramlee.kamarudin@cranfield.ac.uk)

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ABSTRACT The advancement in the current communication technology makes it incumbent to analyze the conventional features of reflectarray antenna for future adaptability. This paper thoroughly reviews the design and experimental features of reflectarray antenna for its bandwidth improvement in microwave and millimeter wave frequency ranges. The paper surveys the fundamental and advanced topologies of reflectarray design implementations, which are needed particularly for its broadband features. The realization of its design approaches has been studied at unit cell and full reflectarray levels for its bandwidth enhancement. Various design configurations have also been critically analyzed for the compatibility with the high-frequency 5G systems.

INDEX TERMS Reflectarrays, bandwidth, unit cell, multi-resonance, millimeter wave, 5G.

I. INTRODUCTION

The array of elements combined together on a flat surface to reflect the incidence signals coming from a properly distant feed defines the main architecture of a reflectarray antenna [1]. The reflection of the signals can be directed like a parabolic reflector with an additional advantage of a plane and light weighted surface. Moreover, reflectarray can also perform beam scanning like a phased array antenna but without the aid of any power divider or additional phase shifters [2]. The less complex designs of reflectarray make it more cost effective especially for beam scanning applications. The bulky and curvy design of parabolic antenna is not a good candidate for high frequency applications [1]. Alternatively a reflectarray antenna can easily be designed from as low as Microwave [3], [4] to as high as Terahertz frequency range [5]–[7]. The adaptability of reflectarray to high frequencies makes it suitable for high gain and high bandwidth operation.

5th Generation (5G) communications are currently represented as a future technology which is supposed to meet the high data rate goals, roughly 1000 times faster than the current systems. The peak data rate in the order of Gbps will require fast switching mechanism which is possible at short wavelengths of mm-waves. The data rate requirements can be met by increasing the bandwidth and efficiency of the antenna systems [8]. These requirements are attainable at mm-wave frequencies. Considering the importance of mm-waves [9], recently in World Radiocommunication Conference (WRC-15) 5G frequency bands were allocated on primary basis for future developments [10]. Different frequency bands were proposed for 5G starting from 24.25 GHz up to 86 GHz. However, the mm-wave frequencies have some propagation limitations in terms of high path loss and very short communication distances. Massive improvements in architecture of current communication systems are desperately required in order to adopt 5G technology [11].

The performance of reflectarray antenna mainly depends on its design procedures [1]. Each expected output can behave differently for a same reflectarray antenna, for example a large reflecting element with small element spacing is good for low loss performance but at the cost of narrow phase range [12], [13]. Figure 1 shows the basic architecture of a reflectarray antenna with rectangular patch elements. The analysis of a reflectarray antenna can be performed by full wave technique [14] where a single element of reflectarray can be considered as an unit cell, as depicted in Figure 1.

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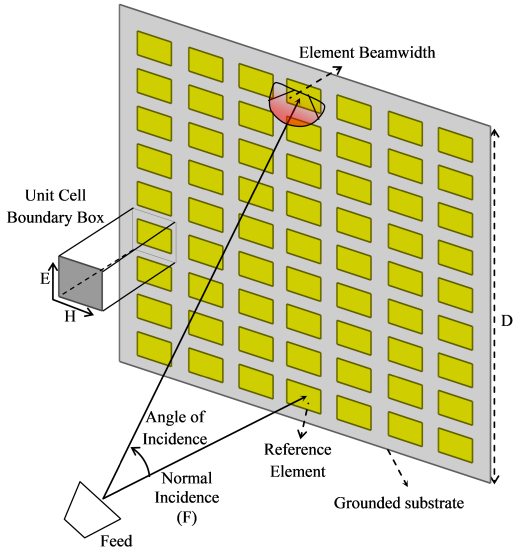


FIGURE 1. Basic architecture of a microstrip reflectarray with an offset feed.

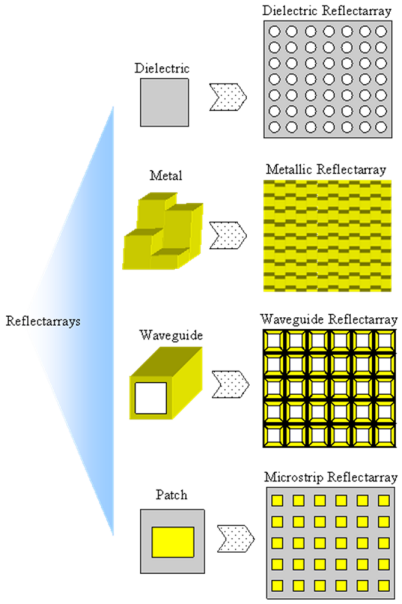


FIGURE 2. Types of reflectarrays.

The unit cell can be taken as an isolated element without mutual coupling effects or either as an array element placed in a periodic array environment with possible mutual coupling from surrounded elements [15], [16]. The first approach is easy to perform while the later one is more accurate for proper design and analysis. The performance of the unit cell reflectarray can be characterized in terms of its reflection loss, reflection phase and beamwidth [1]. Low reflection loss and wide reflection phase range are essential for a wide bandwidth reflectarray. On the other hand, unit cell beamwidth is a crucial factor to determine the size of the reflectarray which can govern its gain performance. As shown in Figure 1, a wide beamwidth is required by a corner element of reflectarray to properly accumulate the incidence signals from a distant feed. The reflection phase of a reflectarray element differs from the reference element with normal incidence, depending on the angle of incidence it holds from the feed. Therefore each element on the reflectarray should be designed with proper progressive reflection phase in order to attain high gain performance in a required direction [17]. These reflection phase variations can be achieved by elements with variable size [18], variable rotation angle [19] or by the length of the stub attached to the unit cell element [20]. The incidence angle of feed from an element depends on the distance (f) it carries from the reflectarray. A large feed distance ensures the proper accumulation of corner elements but at the cost of the large profile reflectarray antenna and high spillover losses. The feed distance is normally measured in f/D ratio where D is the longest dimension of reflectarray. A reflectarray antenna can be designed with an offset feed [21] to avoid the feed shadow created by a center feed. However, the offset feed may increase the angle of incidence for the corner elements. Conventionally reflectarray antennas are designed with a square [22] or circular aperture [23] based on the requirements.

A. TYPES OF REFLECTARRAYS

The performance of a reflectarray antenna also depends on the type and nature of the elements it holds. The characteristics of the elements and type of material used to develop them drastically affect the response of reflectarray antenna. As described in Figure 2, there are four types of reflectarrays commonly used for its performance improvement in various scenarios.

1) DIELECTRIC REFLECTARRAY

It consists of a full dielectric layer for reflectivity without the aid of any conducting resonant structure. The most common type of a dielectric reflectarray is a Dielectric Resonator Antenna (DRA) reflectarray [24]. Some other structures like air holes with variable diameter in a dielectric layer are also used [25]. Its main purpose is to remove the conductor losses from the resonant behavior of a reflectarray for bandwidth improvement. However a metallic ground plane is still needed as a supporting layer [26].

2) METALLIC REFLECTARRAY

The elimination of the dielectric substrate is utilized as a loss reducing tactic from resonating conductor structure. Variable height metallic grooves [27] or even a metallic layer separated by a ground plane without the aid of any substrate [28] can be considered as full metallic reflectarrays. Its main purpose is to improve the gain and efficiency by enhancing the reflection phase range of reflectarray antenna. This type is a good candidate for millimetre wave operation due to its flexibility for micro-level fabrications [27].

3) WAVEGUIDE REFLECTARRAY

It is also a type of metallic reflectarray where an array of waveguides is used to reflect the incident signals [29]. Variable depth of the waveguides is used to determine the

reflection phase of the reflecting signals. The first ever reflectarray was actually proposed as an array of reflecting waveguides [30].

4) MICROSTRIP REFLECTARRAY

This is the most common and widely used type of reflectarray. An array of microstrip patches used to carry by a grounded dielectric substrate as a resonant structure [31]. It holds the conducting and dielectric features which provide vast variety of design diversity. This type combines the best feature of dielectric and metallic reflectarrays. The main advantage of this type is to provide electronic beamsteering capability which is hard to find with other types of reflectarrays.

Each type of reflectarray has its pros and cons while they behave differently for different performance parameters. These different types of reflectarrays will be discussed in details in coming sections with their various bandwidth improvement approaches.

B. ANTENNAS FOR 5G

The propagation issues related with mm-waves can be avoided by selecting a suitable type of antenna for 5G systems. Array antennas are considered as a good candidate to compensate the issues regarding path loss for short range communications [32]. Two dimensional arrays with large electrical apertures can provide narrow beamwidth which is essential for 5G operations [11]. Large electrical aperture at mm-waves for 5G does not affect the physical profile of the antenna due to short wavelengths. Massive MIMO systems have also been suggested for 5G due to their possible integrity with small cells [8], [11], [33], [34]. However, compared to array antennas massive MIMO are not the potential candidate for 5G systems due to their design complexity and less adaptability with shorter wavelengths. There are many other types of antennas which can be found in the literature for proposed 5G operation [35]–[40]. Their main purpose is to achieve wide bandwidth to support high throughput of 5G systems [41]. The operation of antenna systems for 5G compatibility is largely dependent on the enhancement of its bandwidth performance. A massive bandwidth is required in mm-wave range to support high data requirements [8], [42]. Bandwidth of the order of GHz is attainable at mm-wave frequency range but some extra design efforts are still required to fully utilize it with other requirements.

However, by just enhancing the bandwidth of proposed antenna does not solve all issues regarding 5G compatibility. Significant improvements in some other parameters like gain, efficiency, polarization diversity and adaptive beamsteering are also considered as a need of time [11], [42]–[44]. It is because, the antenna performance for 5G can directly depend on the mode of antenna operation. Antenna used for transmission or reception can significantly affect its required parameters for 5G operation. It is widely believed that the requirement of improvement in antenna parameters for transmission is higher than the same parameters for reception.

Phased array antenna is the nearest possible competitor of reflectarray antenna for 5G operation but it faces efficiency lacking problems at millimeter waves due to its additional loss performance at high frequencies [45]. Moreover its design complexity and power consumption are also major issues at millimeter wave frequencies. On the other hand, the discussed antenna parameters for possible 5G application are inevitable with reflectarray antenna. Its bandwidth can be enhanced by optimizing its unit cell designs with different substrate thicknesses [46]. The high gain performance can be obtained by increasing the size of the reflectarray which can produce sharp beams [1]. Its reflection loss performance along with its feeding mechanism can be optimized for efficiency enhancement. Different design configuration of patch elements can be utilized for various polarization combinations. Furthermore, the incident signal from feed or the reflectivity of the reflectarray can be dynamically tuned to get adaptive beamsteering [47].

There are a lot of techniques mentioned in the literature for the enhancement of each discussed parameter of reflectarray. However in this work, the emphasis has been given specially on the design configuration needed for reflectarray bandwidth improvement. Some selected works have been analyzed thoroughly for different reflectarray design specifications in microwave and millimeter wave frequency ranges. A detailed analysis has been provided based on various unit cell and full reflectarray designs. The bandwidth performance of unit cells with single and multi-resonance behavior, and attached open ended stubs have been discussed thoroughly. Various dual band designs and their effect on bandwidth enhancement have also been analyzed. Finally some novel techniques to acquire broadband characteristics in reflectarrays are also provided.

II. REFLECTARRAY BANDWIDTH ENHANCEMENT

The upcoming future technologies will require a very wide frequency bandwidth to transfer high definition data for various users at a time. Reflectarray antenna is generally considered as a narrow bandwidth antenna due to its high loss performance [48], [49]. The conductor material used for the patch elements along with the dielectric material are the main contributors for high loss performance [50]. Along with the high loss performance, differential spatial phase delays and resonant behavior of reflectarray are also the main reasons behind its narrow band performance [1]. Due to the planar structure of reflectarray, the path lengths between feed and its elements varies from its center to its corner. This phenomenon produces undesired reflections of incident signals of same frequency and limits the bandwidth performance of reflectarray. A reflectarray is required to be designed with progressive phase distribution with minimum phase errors to counter this problem. Additionally, the elements on the surface of reflectarray are commonly designed by considering a single resonant frequency which also limits its bandwidth performance. The range of the operating frequencies of a reflectarray antenna mainly depends on its designing

procedures. The bandwidth of reflectarrays can be divided into two sections; unit cell bandwidth and full reflectarray bandwidth [51]. Unit cell bandwidth depends on the slope of the reflection phase curve while the full reflectarray bandwidth has usually been considered at 1-dB drop or 3-dB drop value on the gain-frequency curve. The unit cell element is the basic building block of a full reflectarray and it is also responsible for the performance improvement of full reflectarray. Various design configurations based on unit cell element and full reflectarray have been thoroughly considered by many researchers for the purpose of bandwidth enhancement.

Some conventional techniques involving the bandwidth enhancement of reflectarrays include; coupling of multiple resonances together [52]–[54], coupling of unit cells with true time delay lines or stubs [55] and multi-band designs [22], [56]. Various design configurations based on different patch elements, multi-layered cascaded substrates and aperture coupled elements were normally considered for the stated approaches. The variation in the thickness of the dielectric material has also been considered as an important parameter to improve the bandwidth performance of reflectarrays [46], [49]. Some selected works based on the mentioned conventional approaches along with some latest techniques for reflectarray bandwidth improvement have been thoroughly discussed in the following sections.

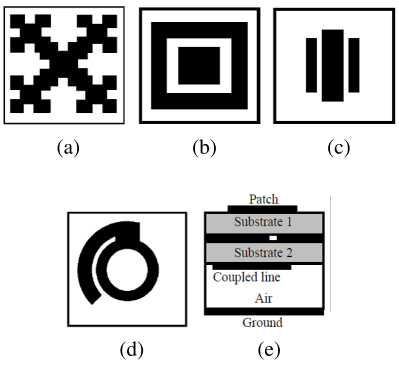


FIGURE 3. Broadband reflectarray elements (a) solo element [59] (b) combination of elements [60] (c) parasitic elements [63] (d) element with open ended stub [65] (e) element with aperture coupled delay line [67].

As aforementioned, the design parameters of the reflectarray can be divided into two sections; the resonant element design and the full reflectarray design. The analysis of the techniques involving both approaches can further be utilized for the improvement of the bandwidth performance. Various resonant element designs with some advanced techniques have been recently noted from the literature which include novel solo elements [57]–[59], combination of elements [60]–[62], parasitic elements [63], elements with open ended stubs [64]–[66] and elements with aperture coupled delay lines [67]. Figure 3 shows some of the selected resonant elements used for bandwidth enhancement strategy. The Fractal element [59] shown in Figure 3(a) was used to get multi-resonance response due to the modification of current distributions on its surface which leads to increase the reflection phase range and hence bandwidth. Square patch combined with square ring shown in [60] Figure 3(b) was set to get dual resonance response for bandwidth enhancement. Figure 3(c) depicts the dipole element surrounded by two parasitic dipoles [63]. The parasitic dipoles were not the part of resonant structure and only used to modify the surface capacitance and inductance of the dipole patch element. The modification in the reflection phase curve was then obtained by varying the lengths of the parasitic elements which leads to enhance the bandwidth performance. In Figure 3(d) an open ended phase tuning stub was attached with a circular ring [65]. The stub was used to introduce the time delay for the reflection of the signals, due to that delay the reflection phase curve smoothed and bandwidth increased. The aperture coupled cascaded element [67] shown in Figure 3(e) also depicts a very common type of design for bandwidth enhancement. The coupled line was used to modify the capacitances between patch and ground plane. This modification leads to a change in the surface currents and electric field distributions which are related to the frequency of operation and bandwidth performance.

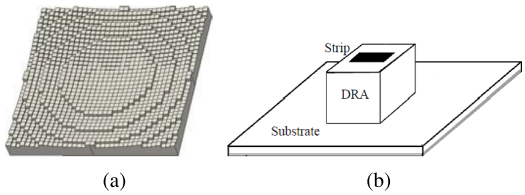


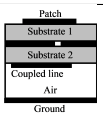
FIGURE 4. Some design configurations of reflectarrays (a) full conductor reflectarray [27] (b) reflectarray DRA element [26].

The bandwidth of a full reflectarray antenna can also be improved by considering many factors. It can be evaluated based on its inter-element spacing [60], [67], [68], feeding mechanism [69] and its design approaches [26], [27]. Two design approaches of a reflectarray antenna, other than the conventional approach, are shown in Figure 4. A full conductor reflectarray [27] is shown in Figure 4(a) where the height of the patches was varied to get the progressive phases for the maximum reflectivity in the desired direction. This non-resonant structure improves the bandwidth due to the extraction of dielectric losses. Figure 4(b) depicts a three dimensional reflectarray element based on reflectarray DRA (dielectric resonator antenna) technology [26]. The dimensions of the strip printed over the DRA were varied to form a full reflectarray antenna with progressive reflection phase. The reflectarray DRA is also a good candidate for bandwidth enhancement due to its conductor less design which reduces mutual coupling between the elements. The advanced design strategies for bandwidth enhancement of a full reflectarray will also thoroughly be discussed in the upcoming sections.

A. SINGLE AND MULTI-RESONANCE ELEMENTS

Many techniques have been found in the literature where the unit cell element of the reflectarray was taken into the

TABLE 1. Broadband elements for reflectarray antenna design (Bandwidth refers as 1-dB gain drop reflectarray bandwidth).

Element shape	Design	Frequency (GHz)	Phase swing (°)	Bandwidth (%)
Phoenix [70]		10	360	29
Fractal [71]		13.58	500	15.24
Cross Loop [72]		30	465	25.16
Meander [73]		10	500	26
Ellipse rings [74]		11	420	18.18
Parasitic dipoles [63]		2.05	360	7.8
I-Shaped Dipole [77]		12.5	800	16
Parallel dipoles [80]		15	1000	32.53
Phase delay line [81]		8.5	1000	16.47
Lattice Stubs [82]		13.5	600	20
Aperture coupled [83]		20	360	17

consideration for the enhancement of the bandwidth performance. The main goal was to achieve a full phase swing of 360° with the single resonance elements in order to eradicate the phase error limitation for bandwidth enhancement. The other technique was involving two or multi-resonance elements where the reflection phase was extended up to many full cycles to significantly improve the linear phase bandwidth. Table 1 summarizes some selected designs and their features based on the techniques discussed in previous section. Some latest and widely used elements are discussed here in details for the understanding of the concept.

A single resonance Phoenix element mentioned in Table 1, was proposed in [70] for the enhancement of bandwidth performance. It is called Phoenix element because it has rebirth capability. The element is composed of a circular patch with a concentric circular ring. A circular ring was then introduced which moves from inner radius of the outer circular ring to the outer radius of the circular patch in order to obtain a full 360° reflection phase cycle without compromising on the overall structure of the element. A 225 Phoenix element reflectarray provided a 1-dB bandwidth performance of 29% while operating at 10 GHz. The thick substrate with an air gap was also a main reason behind its wide bandwidth. A similar design was also reported in [58] operating on 5 GHz frequency where a rectangular slot within a rectangular ring was used for the rebirth capability. The main problem with the single resonance broadband elements such as Phoenix elements is their design complexity at high frequencies.

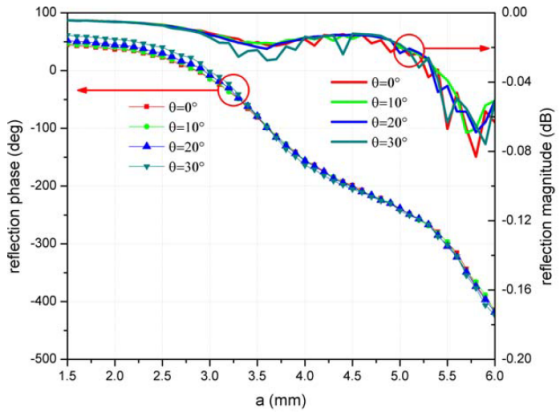


FIGURE 5. Reflection phase and reflection magnitude of fractal element at different incident angles as a function of fractal length [71].

A single layer dual resonance element with a hexagonal patch surrounded by two fractal rings was reported in [71]. Figure 5 shows its reflection response in terms of phase and magnitude. It can be seen from Figure 5 that, the reflection magnitude confirms the dual resonance response of the fractal element which is responsible for the extension of the reflection phase range beyond 360°. The fractal lengths of rings were varied to get a 500° phase variations for a 469 element center feed reflectarray at 13.58 GHz. A novel honeycomb lattice instead of a conventional square lattice was used to enhance the full reflectarray bandwidth performance up to 15.24%. A single compound cross loop element [72] shown in Table 1 was used to get a dual resonance response with 465° phase swing at 30 GHz. A 1-dB gain drop bandwidth of 25.16% was achieved with a linear array of 112 compound elements. The next elements listed in Table 1 are the combination of two different elements. The Meander shape [73] element is the combination of a Meander square patch surrounded by a Meander square ring. The other element is made of two elliptical rings [74] with different radii and resonating at two different frequencies. It can be seen from Table 1 that, the Meander shaped element has a wider reflection phase swing of 500° as compared to dual elliptical ring element which has 420° reflection phase swing.

On the other hand, the 1-dB gain drop bandwidth of Meander element reflectarray is 26% as compared to 18.18% of dual elliptical ring element. The lower bandwidth performance of dual elliptical ring elements is due to its narrower reflection phase swing as compared to Mender element. The parasitic elements were also used in [63] to increase the bandwidth performance of a single element. A dipole element surrounded by two parasitic dipoles was used for that purpose. A full cycle of 360° reflection phase swing was obtained by the help of parasitic elements. This technique is useful with thick substrate to achieve proper phase shift with wide bandwidth. Although its 1-dB gain drop bandwidth (7.8%) was quite low which is mainly because of its low operating frequency and single resonance at 2.05 GHz. The other parameters such as array structure, feed type and f/D ratio of stated designs are not discussed here in the comparison for the sake of clarity. The effects of these parameters on the bandwidth performance will be discussed later in coming sections. Some other combination of elements such as rectangular patch with rectangular ring [60], multi-cross loop element [75], circular ring surrounded by a square concentric ring [61] and three parallel dipoles [76] were also reported with multi-resonance capabilities for bandwidth enhancement.

An I-shaped dipole with two concerted rectangular rings designed at 12.5 GHz was reported in [77] with multi-resonance capabilities. The three resonances of the element were due to its three different resonant structures which can extend its reflection phase swing up to 800°. A 1-dB gain drop bandwidth of 16% was also obtained with a 10×10 reflectarray. Other similar elements related with the stated element and reported in the literature are I-shaped dipole surrounded by two concentric open rings [78] and I-shaped dipole surrounded by a circular ring [79]. It was noticed that, an I-shaped element compared to other elements provides more design flexibility while used with other resonant structures to achieve wide phase response. Another considerable multi-resonance element proposed in [80] was comprised of five parallel dipoles. This element attained a 1000° reflection phase swing with three resonances. It obtained a 1-dB gain drop bandwidth of 32.53% operating at 15 GHz.

It can be observed from reported literature that, the single elements were more vulnerable to achieve wide bandwidths compared to the combination of elements. On the other hand their design complexity is much lower than their other counter parts. The simple tactic to increase the bandwidth performance was to increase the number of resonant structures in the element. But it leads to more complex designs with difficulties in handling the dimensions while obtaining progressive phase distributions. Moreover, various resonances for the single unit cell increase the chances of mutual coupling between resonances and make it difficult to get low side lobe levels in full reflectarray operation. In order to reduce these effects, a fine phase tuning with perfect design and fabrication of full reflectarray is required. An increasing frequency could make it more difficult to operate easily for the same parameters of the lower frequencies. Most of the broadband elements reported in this section were fabricated over a thick substrate, some of them with an air gap between the substrate and the ground plane. It is an easy and common approach to enhance the bandwidth performance of the reflectarray antenna. It shows that, the elements were used only for the enhancement of reflection phase range through multi-resonance responses while the thick substrate was offering the wide bandwidth to each resonance due to its low loss performance.

B. ELEMENTS WITH OPEN ENDED STUBS AND COUPLED DELAY LINES

In previous section the unit cell element or the resonant structure itself was responsible for the controlling of its reflection phase range and bandwidth. Another useful approach to tune reflection phase behavior of the unit cell is to attach an extra phase tuning stub or delay line to the resonant structure. This method provides an independent control of reflection phase range without disturbing the dimensions of resonant structure. In this tactic the length of the tuning stub or the delay line is solely responsible for the reflection phase tuning of single or multiple resonances. The operation mechanism of phase tuning stub or delay line is almost same. These are used to introduce a time delay to the reflected signal, consequently the linearity in the reflection phase increases. Moreover the presence of the tuning stub or delay line introduces extra capacitive and inductive loading to the actual resonant structure. This capacitive and inductive loading can be modified by varying the length of the tuning stub or delay line. As a result the surface current distribution of the resonant structure also varies and a change in the reflection phase can be obtained.

A reflectarray unit cell element with three circular rings and quasi spiral phase delay lines attached with outer rings [81] can be seen in Table 1. It is a three resonance structure with a phase tuning of 1000° at 8.5 GHz by controlling the lengths of quasi spiral phase delay lines. A full reflectarray was designed and tested to get a 1-dB gain drop bandwidth of 16.47%. A quasi spiral combination of phase delay lines provide more flexibility in terms of phase tuning compared to a single phase delay line [65], [66]. A similar type of design with symmetrical open ended stubs attached in the center of a square patch was reported in [82]. The length of the lattice stubs was varied to achieve a 600° reflection phase swing at 13.5 GHz. This phase swing was used to form a full reflectarray with 20% 1-dB gain drop bandwidth. Although the unit cell bandwidth of this design was lesser than that of the previous design but its full reflectarray bandwidth was wider than previous design. This was mainly because of the higher frequency of operation of this design which was supposed to increase the bandwidth performance.

The aperture coupled delay line with cascaded structure [67] is a very common and mostly used technique for bandwidth enhancement with single resonant structure. The dimensions of the resonant structure remain same for all the

reflection phase values due to the involvement of coupled delay line for phase control. Additionally the cascaded structure increases the electrical thickness of the substrate which is also essential for the wide bandwidth performance. A similar design is shown in Table 1 with a square patch as a resonant structure [83]. A full reflection phase cycle of 360° was achieved by controlling the length of the delay line at 20 GHz. Different element spacing and reflectarray sizes were also tested in reported work for bandwidth enhancement. It was shown that the 1-dB gain drop bandwidth improved with the reduction in the size of the reflectarray. A maximum 1-dB gain drop bandwidth of 17% was noticed for a circular aperture reflectarray with a diameter of 12.6λ. The effects of reflectarray size and element spacing on bandwidth performance will further be discussed in upcoming sections.

It can be observed that the elements with phase tuning stubs attached with resonant structure hold relatively less design complexity as compared to aperture coupled elements. But the later one provides wide bandwidth performance even with the single resonant structure. Adding a variable length, non-resonant phase tuning line with resonant structure can also increase the chances of unwanted reflections from the reflectarray aperture. If not handled carefully, these unwanted reflections can degrade the performance of reflectarray antenna in terms of high cross polarization and high side lobe levels. Due to variable dimensions of phase tuning line, it is obvious that each element on reflectarray will then hold a different size of tuning stub. This introduces asymmetry in the overall design of reflectarray which could lead towards unwanted polarization reflections. This issue can be resolved if the asymmetry is eliminated from the reflectarray design.

C. DUAL BAND DESIGNS

The bandwidth of the reflectarray antenna can also be improved by extending its operation to a different band of frequency. Although the independent bandwidth of the each band can be controlled by the same techniques as discussed before, but its dual band operation can enhance its performance for a wider range of applications. The effect of mutual coupling can also be minimized due to the large separation of frequency bands. Two main approaches are widely used for the dual band operation of reflectarray. First one involves the dual layer configuration where each layer represents its own band of operation. The other represents the single layer design with two different resonant structures for each band of frequency.

An interesting design of dual layer reflectarray operating in X-band and Ka-band frequency ranges was proposed in [84]. The design layout of the dual band reflectarray has been shown in Figure 6. It can be seen from Figure 6 that, two different layers separated by an air gap were selected for two different band of operation. A frequency selective surface (FSS) backed Ka-band layer was placed in front of a solid ground backed X-band layer. Double square ring elements were used for the resonant structures for both selected bands

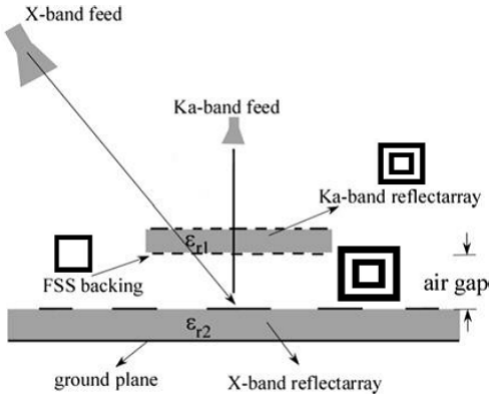


FIGURE 6. Dual layer reflectarray with Ka/X-band of operation [84].

whereas a single square ring was selected as an FSS. Dual feed mechanism was used for each band of operation. The purpose of using FSS backed Ka-band layer was to reduce the blockage of signals coming from X-band feed horn antenna. It was also shown that due to the FSS ground the X-band feed blockage was negligible. On the other hand due to an FSS ground the individual bandwidth of Ka-band operation was reduced compared to a solid ground. The reflectarray was set to reflect the signals at 32 GHz and 8.4 GHz in the same direction. Although this design offered a wide dual band operation but its design complexity and bulky structure were marked as its main disadvantages.

Another design of dual layer reflectarray for X/Ku-band operation [85] by eliminating the effects of large air gap and ground plane of first layer is shown in Figure 7(a). The ground-less upper layer was set for X-band (10 GHz) operation with a cross dipole element whereas dual circular ring element was used at the lower Ku-band (15 GHz) layer. Unlike previous designs, in this design both layers had same aperture sizes and the whole structure was illuminated by a single feed horn antenna. The wide band operation of dual band reflectarray can be seen from Figure 7(b) where the radiation patterns were plotted at various frequencies. It can be observed that the proposed dual band reflectarray can operate at 10 GHz and 11 GHz for X-band along with 14.5 GHz and 15 GHz for Ku-band frequencies. Apart from all its advantages, a drawback of high side lobe level was noticed at X-band operation. This is mainly because of the mutual coupling between two resonant structures operating at different bands of frequencies. This effect can be minimized by carefully selecting the dimensions of the resonant elements for progressive phase distribution but cannot be completely eliminated.

The single layer dual band designs provide ease of designing and fabrication unlike dual layer designs. A single layer design operating at same frequency bands like previous dual layer design was reported in [86]. The unit cell element of this design which was actually the combination of two elements can be seen in Figure 8(a). The square patch with slots was used for Ku-band operation while a surrounded square ring

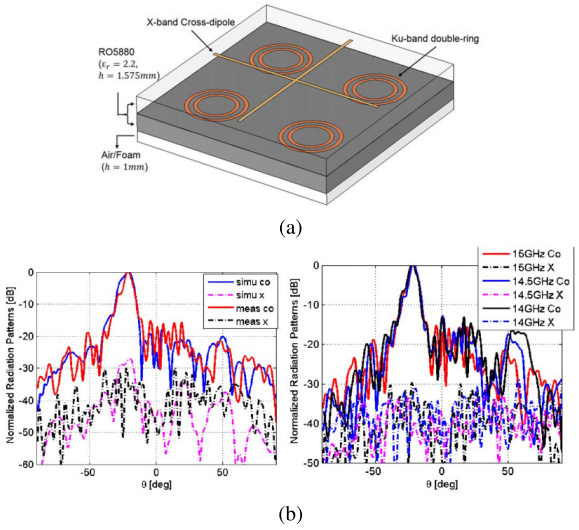


FIGURE 7. X/Ku-band reflectarray with dual layer and dual band operation [85] (a) Dual layer unit cell design (b) Measured radiation patterns with wideband operation.

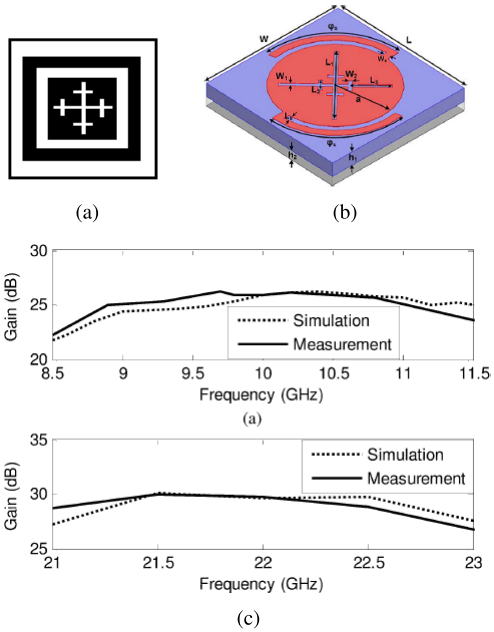


FIGURE 8. Single layer dual band reflectarray elements (a) Reflectarray element for X-band and Ku-band operation [86] (b) Reflectarray element for X-band and K-band operation [64] (c) Gain versus frequency curves of X/K-band reflectarray [64].

was operating in X-band frequency range. The slots were created inside the square patch for bandwidth enhancement. The dimensions of the unit cell were varied to get the phase distributions for full reflectarray design. A single prime feed was used to illuminate the full reflectarray with dual band reflected beams in the same direction. A 1-dB gain drop bandwidth of 16.95% and 14% was attained by operating at 8.2 GHz and 13.2 GHz frequencies respectively.

Varying the dimension of the whole resonant structure for progressive phase distribution in dual band reflectarrays is a very critical issue for optimized designing. The same can also be done with open ended phase tuning stubs as discussed in previous section. An X/K dual band reflectarray with single layer and single element attached with dual phase tuning stubs was recommended in [64]. As depicted in Figure 8(b) the unit cell was composed of a slotted circular element with two open ended stubs attached for phase tuning purpose. The lengths of the stubs were varied to get a 500° and 800° reflection phase swing in X-band and K-band respectively. A separate feed was selected for reflectarray in each band of operation. Figure 8(c) shows the gain versus frequency curves of the reflectarray for dual band operation. It can be observed from Figure 8(c) that, the proposed reflectarray was able to achieve a 1-dB gain drop bandwidth of 15.98% and 9.09% at 10.2 GHz and 22 GHz respectively. It can be analyzed from the proposed design that, the involvement of single element for dual band operation drastically reduces the efficiency at higher band of operation. 25% of efficiency was noticed at K-band as compared to 47% of X-band. Some other types of elements like an I-shaped element for X/Ku-band operation [87] and a slotted DRA reflectarray element in C/X-band operation [88] were also reported in the literature for bandwidth enhancement strategy.

It can be analyzed from the reported results that, some of the designs were keen to operate with single feed while others with dual feed mechanism. The single feed was used when two frequency bands of operation were narrowly joined with each other like X-band and Ku-band. On the other hand the dual feeds were used with X-band and K-band operated designs where the separation between the frequency bands was large enough to support a single feed. The single layer dual band designs were easily fabrication oriented but at the cost of higher designing risks to support dual frequency bands on a single unit cell. Alternatively two different elements for dual layer dual band operation were easy to separately design but with some fabrication related issues due to the attachment of two substrates together.

D. OTHER NOVEL APPROACHES

Controlling the bandwidth performance of a reflectarray antenna by its unit cell element design is the most commonly used tactic. Alternatively the full reflectarray bandwidth also depends on some factors which can be considered for its performance improvement. These factors involve the parameters related to the collective designing and positioning of the unit cell elements on reflectarray surface along with its feeding mechanism.

A method was reported in [89] for a broadband reflectarray antenna with true time delay strategy. The unit cell elements were designed to momentarily hold the incident signals and introduce a time delay to the reflected beam of the reflectarray antenna. The introduction of this time delay between incident and reflected singles was used to increase the reflection phase range and significantly enhance the bandwidth performance of the full reflectarray antenna. The miniaturized unit cell was composed of various stacked layers consisting non-resonant

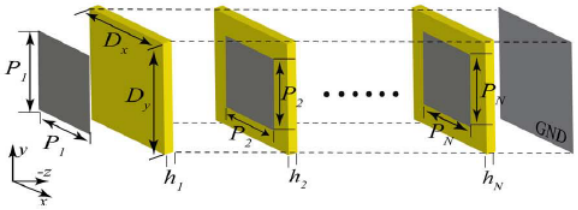


FIGURE 9. True time delay unit cell for broadband reflectarray antenna [89].

frequency selective surface elements backed by a ground plane. The stacked non-resonant patches separated by thin dielectric substrates have been shown in Figure 9. The purpose of each stacked layer was to introduce the time delay response in the incident field. A maximum time delay of 160 picoseconds was obtained to extend the bandwidth performance up to a full X-band (8-12 GHz) frequency range. The stated strategy is very useful for bandwidth enhancement in fixed beam reflectarrays but it can also affect its performance in terms of its efficiency and gain.

It was observed that the design of the reflectarray antenna usually consist of all identical patches on its surface. However the combination of different patch elements on same reflectarray surface can also be used for its performance enhancement as proposed in [90]. The combination of square patch (SP), square ring (SR) and ring loaded patch (RLP) were utilized together to form a single layer reflectarray antenna at 15 GHz as shown in Figure 10(a). This approach was used to combine the benefits of all patches and compensate their drawbacks on one another. It can be seen from Figure 10(b) that the 1-dB gain drop bandwidth of the reflectarray was improved from 9.7% to 11.7% when it was used without and with the combination of proposed patch elements respectively. It can also be observed that the gain performance of the reflectarray antenna was also significantly improved with proposed configuration.

In another notable work [91], the spacing between the elements of the reflectarray was taken into account for the investigation of its gain and bandwidth performances. Double concentric ring element was used as the unit cell with various sub-wavelength element spacing of λ/2, λ/3, λ/4 and λ/5 operating at 10 GHz frequency. The double concentric ring element also had a wide bandwidth performance with a maximum 600° reflection phase range at λ/2 element spacing. The performance analysis of four equal aperture reflectarrays was tested with different element spacing. Figure 11 shows the gain-frequency relation of proposed sub-wavelength spacing reflectarrays. It can be clearly analyzed that, the gain drop bandwidth was significantly improved with the reduction in the element spacing of the reflectarray. A maximum 2-dB gain drop bandwidth of 33% was obtained with an element spacing of λ/4. On the other hand the maximum gain was obtained with λ/2 element spacing. A significant reduction in the gain performance of reflectarray was noticed when the element spacing was decreased from λ/2 to λ/5.

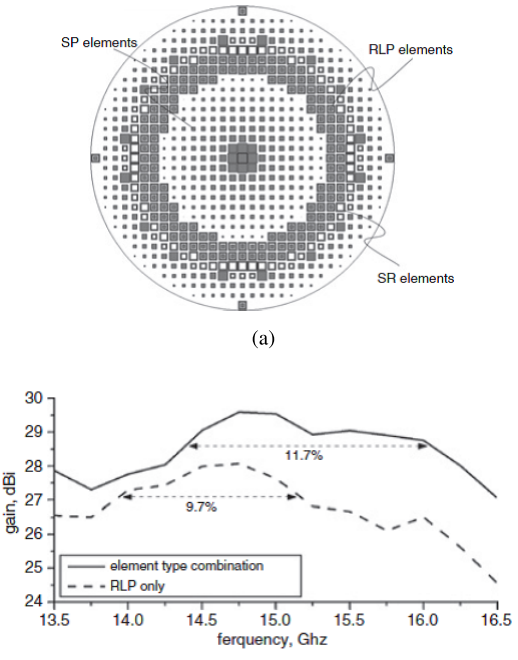


FIGURE 10. Reflectarray with combination of three types of elements [90] (a) reflectarray design (b) comparison of the performance of reflectarray with and without the combination of element types.

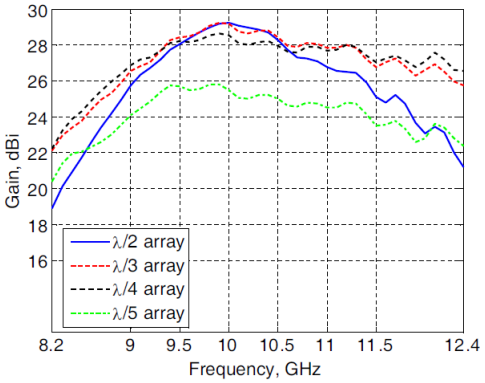


FIGURE 11. Gain-frequency plot of reflectarrays with different element spacing [91].

The aperture efficiency of reflectarray was also reduced from 40.1% to 18.1% with the reduction in element spacing. In order to keep the same aperture size for different element spacing the number of elements on reflectarray was significantly increased which triggered a higher design complexity.

Most of the bandwidth improvement strategies of reflectarray were linked with design parameters of single and full reflectarray. On the other hand some other parameters like the position of feed can also affect the performance of reflectarrays. Bandwidth, gain and efficiency of a reflectarrays are directly related with its feeding mechanism. In a similar work reported in the literature [69], the impact of the feed position on the performance of reflectarray was examined. It was shown that the feed position can considerably affect the

operating frequency and gain of the reflectarray. The selected unit cell of the reflectarray comprised of three rectangular loops followed by a thick grounded substrate. Three different positions of 16° offset feed comprising 33cm, 40cm and 47cm away from reflectarray were analyzed for same reflectarray. It was shown that as the feed position moved from 33cm to 47cm the operating frequency of reflectarray was also changed from 10 GHz to 15 GHz. The 1-dB gain drop bandwidth performance of reflectarray was also improved from 13% to 15.33% for the selected movement of feed. The maximum bandwidth of 26.4% was achieved for 40cm feed position. The increment in the gain performance of reflectarray was also observed but with degradation in the aperture efficiency as the feed moved away from the reflectarray.

TABLE 2. Summary of the main bandwidth enhancement techniques (Symbols refer as H=High, N=Neutral and L=Low).

Parameters	Multi-resonance elements		Elements with coupled delay Lines		Dual-band designs	
	Single element	Combination of elements	Open ended stubs	Aperture coupled	Single layer	Multi Layer
Bandwidth	N	H	N	H	N	H
Loss	N	H	N	L	H	L
Complexity	H	H	L	H	N	H
High frequency compatibility	N	L	N	N	L	N

E. CRITICAL ANALYSIS

The bandwidth enhancement of full reflectarray always requires some extraordinary efforts for the designing which increases the possibility of higher design complexity. The design complexity could be the main limitation faced by these bandwidth enhancement techniques in complying with the future 5G systems. The increment of the operating frequencies from microwave to millimeter waves can drastically affect the design sensitivity of the discussed techniques. The shorter wavelengths can be more prone to the performance degradation of reflectarrays with small fabrication errors. Table 2 summarizes the performance analyses of the discussed broadband approaches for reflectarrays. Although the performance of each tactic also depends on the selection of its patch element but a common hypothesis can be made based on the reported literature. As it is mentioned in Table 2 that, the multi-layer and aperture coupled cascaded designs offer wider bandwidth performance compared to single layer due to their thick substrate. A thicker substrate as compared to single layer also allows them to draw less reflection losses for the reflectarray operation. Alternatively single layer designs are more prone to get high reflection losses due to thin substrates. The loss performance of single layer dual-band designs and combination of elements for multi-resonances is higher as compared to other single layer techniques. It is mainly because of the less electrically conducting areas of their patch elements which are commonly used to achieve wide reflection phase swing for bandwidth enhancement. The patch elements with less electrical areas such as rings and loops are more flexible in dimension to get wide progressive phase distributions. The multi-layer designs also face more design complexity due to the attachments of multiple layers together. The designs with combination of elements for multiple resonances and dual-bands are also complex due to the handling of two or more resonant structure for bandwidth enhancement. The elements with open ended phase tuning stubs are less complex than other approaches because of the non-resonant behavior of the tuning stubs. The compatibility of these design approaches with high frequency 5G reflectarrays depends on the consistency of their performance. The single layer designs with combination of elements are less likely compatible with higher frequencies where two or more resonant structure could make it more difficult to perform progressive phase analysis with short dimensions. The other single layer structure with multi-resonances and connected with open ended stubs are possibly compatible with higher frequencies because of their simple designs. The multi-layer designs could make it difficult to reach out the requirements for higher frequencies due to their fabrication sensitivity. On the other hand, the use of conventional patch elements with multi-layer designs could possibly increase their chances of compatibility.

III. CONCLUSIONS

It can be concluded through the discussion on various design and architectural features that the bandwidth improvement in reflectarrays is possible for advance future systems. The required bandwidth enhancement can either be achieved by selecting a proper unit cell design or by suitably modifying the whole reflectarray structure. Additionally, the cost effective and less complex design requires some extra-ordinary experimental efforts to be made. The increasing design sensitivity with high frequency is the main issue highlighted for 5G communication systems which can be extended as a potential future research possibility. This issue can be tackled with the involvement of the computer numerical control technology in reflectarray design and fabrication. The information provided in this paper on broadband features of reflectarray antenna can be taken as an initial platform for further studies on its improvement. The involvement of some other features like cost, material properties and power consumption related to high frequencies can make it more challenging for future research.

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MUHAMMAD HASHIM DAHRI received the B.Eng. degree in telecommunications from the Mehran University of Engineering and Technology, Pakistan, in 2010, and the master's degree in electrical engineering from Universiti Tun Hussein Onn Malaysia in 2014. He is currently pursuing the Ph.D. degree with the Wireless Communication Center, Univerisiti Teknologi Malaysia. He has authored over 20 research papers in various indexed journals and conference proceedings. His research interests include reflectarray antennas, planar printed antennas, and tunable materials for antenna design.

MOHD HAIZAL JAMALUDDIN received the bachelor's and master's degrees in electrical engineering from Universiti Teknologi Malaysia, Malaysia, in 2003 and 2006, respectively, and the Ph.D. degree in signal processing and telecommunications, with a focus on microwave communication systems and specially antennas, such as dielectric resonator and reflectarray and dielectric dome antennas, from the Université de Rennes 1, France, in 2009. He is currently a Senior Lecturer with the Wireless Communication Center, Faculty of Electrical Engineering, Universiti Teknologi Malaysia. He has authored over 25 papers in reputed indexed journals and conference proceedings. His research interests include dielectric resonator antennas, printed microstrip antennas, MIMO antennas, and DRA reflectarray antennas.

MUHAMMAD INAM ABBASI received the B.Sc. degree in electrical engineering, with major in telecommunication, from the Center for Advanced Studies in Engineering, University of Engineering and Technology at Taxilla, Taxilla, Pakistan, and the master's degree by research and the Ph.D. degree in electrical engineering from Universiti Tun Hussein Onn Malaysia (UTHM) in 2011 and 2016, respectively. He joined the Wireless and Radio Science Center, UTHM, as a Graduate Research Assistant, in 2009. He is currently a Post-Doctoral Research Fellow with the Wireless Communication Center (WCC), Universiti Technologi Malaysia. He has authored one book and over 40 research papers in internationally indexed journals and conferences. His current research interests include high performance planar and printed antenna design, passive and reconfigurable reflectarray and planar reflector antennas, and novel materials for the design of enhanced performance antennas.

MUHAMMAD RAMLEE KAMARUDIN (M'08–SM'13) received the degree (Hons.) with major in electrical and telecommunication engineering, from Universiti Teknologi Malaysia (UTM), Johor Bahru, Malaysia, in 2003, the M.S. degree in communication engineering from the University of Birmingham, Birmingham, U.K., in 2004, and the Ph.D. degree, under the supervision of Professor P. Hall, from the University of Birmingham in 2007. He was an Associate Professor with the Wireless Communication Center, Universiti Teknologi Malaysia, Malaysia, until 2017. He is currently a Senior Lecturer with the Center for Electronic Warfare, Information and Cyber, Cranfield Defense and Security, Cranfield University, U.K. He has authored a book chapter of a book entitled *Antennas and Propagation for Body-Centric Wireless Communications*. He has authored over 200 technical papers in journals and proceedings, including the IEEE TRANSACTION ON ANTENNA AND PROPAGATION, the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTER, the *IEEE Antenna Magazine*, the IEEE ACCESS, the *International Journal of Antennas and Propagation*, the *Progress in Electromagnetics Research*, the *Microwave and Optical Technology Letters*, and the *Electronics Letters*. His research interests include antenna design for 5G, wireless on-body communications, in-body communications (implantable antenna), RF and microwave communication systems, and antenna diversity. He is a member of the IEEE Antennas and Propagation Society, the IEEE Communication Society, the IEEE Microwave Theory and Techniques Society, the IEEE Electromagnetic Compatibility Society, and the IET, and an Executive Member of Antenna and Propagation, Malaysia Chapter.

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Dahri, Muhammad Hashim; Jamaluddin, Mohd Haizal; Abbasi, Muhammad Inam; Kamarudin, Muhammad Ramlee

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