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Research of High-Gain Methods of Microstrip Antennas in 5G/6G Communication

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Abstract. The paper is a thorough review of high-gain antenna concepts of microstrip antennas to fifth-generation (5G) and next-generation (6G) wireless communication systems. The reason behind the extensive implementation of microstrip antennas includes their small shape, simple integration capabilities and reduced costs of fabrication. Nevertheless, the traditional designs have inherent drawbacks such as low gain, low bandwidth and high losses at high frequencies. These limitations do not enable them to amplify 5G/6G applications to longer ranges and data rates of extreme resolution. To solve these issues, general strategies are rigorously analyzed. These are metasurface loading to do wave front manipulation and to focus frequencies; frequency-selective surface (FSS) reflectors to create resonant cavity and a gain enhancement of forward radiations; optimization of dielectric substrates with low-loss ceramics and new fabrication; and array configurations that provide gain superposition. The review identifies the performance trade-offs in one technique and underlines the cooperative approach to the design. Balanced gains, bandwidth, profile, and compatibility are made at the cost of composite structures, multi-objective optimization algorithms, and system-level integration. The problems of processing complexity, material losses in millimeter-wave bands, and computing needs are examined nowadays. Intelligent surfaces should move towards reconfigurable surfaces, intelligent design, heterogeneous chip integration, and sensing-communication co-arrangement to support 6G requirements. The paper offers a lot of insights and references into the high-gain microstrip antenna technologies in the next-generation wireless networks.

Keywords: Microstrip antennas, High gain, Metasurface, Frequency selective surface, 5G/6G communications

1. Introduction

The fifth-generation mobile communication systems (5G) and the sixth-generation mobile communication systems (6G) are at the forefront in transforming wireless communication technology in ultra-high data rates, ultra-low latency, and massive connectivity [1]. Antenna performance is a functional parameter of value (e.g. in gain and bandwidth units), given that this is an important functional element in determining how communication systems will perform overall [2]. Microstrip antennas have emerged as one of the most common types of antennas in the contemporary wireless communication systems because they are of small size, can be readily integrated and are not expensive to make [3]. The traditional microstrip antennas are however, often limited by low gain, narrow bandwidth and high-frequency loss which restricts their applicability to the specifications of 5G/6G systems in the long-range band and high-data-rate transmission [4]. Therefore, the improvement of the gain in microstrip antennas has now taken center stage in modern antenna research studies.

The research community has devised several strategies of implementing high gain to combat the gain bottleneck. Metamaterial and metasurface technologies utilize the high gain of antennas by making artificial electromagnet structures that contribute to changing the phase and amplitude of electromagnetic wave to establish a lens effect [5]. Frequency-selective surface (FSS) reflectors have the ability to construct resonant cavities on the surface of microstrip antennas as a means of reflecting, and amplifying forward radiation [6]. Material optimisation through dielectric substrate is by using high-dielectric and low-loss ceramic materials for the substrate, and developing fabrication methods such as gel casting and roll-to-roll forming to decrease transmission losses and maximize radiation output [7]. The gain summation in artificial methods is realised by multiple-element coordination in array methods, but they include difficulties such as multi-faceted feeding as well as an augmented volume [8]. Metasurfaces and FSS reflectors have become the research priorities of the design of high-gain microstrip antenna because of their flexibility and the simplicity with which they can be implemented.

The high-gain microstrip antenna has experienced difficulties of balancing between performance and process integration even after the progress of various technologies. Supersurface loading can be connoted with structural complexity and reduced bandwidth; FSS reflectors raise the antenna profile discouraging miniaturisation; arrayed ones have mutual coupling and feed losses; and high-frequency substrate processes have to exhibit outstanding material uniformity and manufacturing precision. The integration of a number of goals including high gain, wide bandwidth, low profile, and high integration is a major challenge that has not been fully achieved in the modern antenna design.

The present paper is an overview of 5G/6G communication technologies based on high-gain microstrip antenna technology, divided into four chapters. Chapter One divides the concepts, categories and common instances of use of the two mainstream technologies, FSS reflectors and metasurface loading and the bandwidth, dimensional and manufacturing bottlenecks experienced in real-life implementation. Chapter Two examines performance balancing and co-design pathways and provides an analysis of the contribution that composite structures, multi-objective optimisation and integration strategies can make to facilitating multi-performances equilibrium. The third chapter is on compact design and system integration and it reviews recent developments in array designs, packaging compatibility, and multifunctional integration. Chapter Four provides a full overview of the opportunities, challenges, and the evolution of different technologies, suggesting future trends and innovations including intelligent metasurfaces, reconfigurable antennas, and the use of AI in design. This has theoretical and technical directions to continue studying and using high gain antennas in microstrip in the 5G/6G systems.

2. Common high-gain technology pathways and bottlenecks

Both the industry and the academia have devised several high-gain technology solutions to address the gain limitation inherent with conventional microstrip antennas and to satisfy the dire need of high-performance antennas in 5G/6G communications. The current mainstream high-gain implementation methods including metasurface loading technology, FSS reflector technology, substrate optimisation and integrated design techniques, arrayed and structural innovation methods are systematically reviewed and analysed in this chapter and their principles and technical attributes explained.

One of the most outstanding technical solutions in the recent years is known as Metasurface loading technology. A metasurface is a two-dimensional man-made electromagnetic structure, which is made of artificial subwavelength-scale units that are organized into certain patterns. It is based on the accurate design of unit shape, dimensions and configuration to create arbitrary control of the phase state, amplitude and polarisation state of incident electromagnetic waves [9]. A gradient phase distribution built as a result of superstructure incorporation with microstrip antennas, makes an artificial lens effect possible. This converts a wavefront shape of the antenna, which is a sphere, into a planar wavefront, hence, beam focus and increase on gain. Depending on loading design and design properties, Metasurface loading designs can be further divided: Metasurface antenna cover Technology uses the metasurface as a layer of covering around microstrip antennas, creating a collimating-like lens-like structure. Ordinary forms of unit designs are butterfly-shaped, circular or square patch arrays. Yang Wenlong et al. [10] have conducted the design of a butterfly shaped unit super-surface antenna cover which enhanced the antenna gain up to 16.24 dBi at 5 GHz, as compared to 7.33 dBi theoretically; Multilayer composite metasurface technology Multilayer composite metasurface technology can be synergistically raised to encompass reactive impedance surfaces (RIS) and artificial magnetic conductors (AMC) along with other multi-layer designs. This is a method to simultaneously realise impedance matching, phase control, and surface wave suppression, and is effective especially at high frequency (millimetre waves). It is gain enhancing and it improves the front-to-back ratio and side lobe levels [11]. Circumferential parasitic metasurface technology positions the arrays of metasurface units in semi-enveloped or completely enveloped form about Microstrip feeders or radiating patches. It offers functions to minimise change in antenna original design structure by means of near-field coupling that enables reduction in size of the design. At Wang Zexu et al., a circumferentially parasitic metasurface scheme using the three-layer stacked metasurface was reported. The patch radiator has four L-shaped notches cut into it to enlarge the bandwidth of the impedance, with a semi-circumferential line of parasitic microstrip line meant to maximize the distribution of the surface-current and to maximise the purity of the circular polarisation. A metasurface array with a 4x4 array is loaded on the top surface of the surface to reach the axial ratio bandwidth [12].

Another typical form of gain enhancement technique in a similar manner, is frequency-selective surface (FSS) reflector technology, which is obtained by placing a FSS on the back of the antenna to form a Fabry-Perot (FP) resonator cavity [13]. The very secret to it is that FSS was designed as in-phase reflector in the target frequency range. This causes the back radiation energy of the antenna to loop back in the direction of the radiation and it is in-phase with the forward wave in the cavity. This provides the effect of a quasi-optical focusing effect of a parabolic antenna with the main lobe gain in the broadside direction of the antenna greatly increased and the back radiations and side lobe levels virtually suppressed. The main strengths of such technology are in the fact that the structure is not very complicated, the gain may be increased considerably and it could even be possible to obtain a certain degree of frequency selectivity by altering the FSS cell structure. Nevertheless, the FSS reflector technology is not without significant shortcomings as well. It is highly sensitive to the distance between the source of radiation and the FSS (usually 1/4 of the wavelength). It is as well very dependent on the reflection characteristics of the FSS cell itself. The design and optimisation process is somewhat complicated because of this dependence. Since the gain of FP resonator cavities is usually high as a result of the high Q-factor nature of such resonators, they are usually not well suited to the broadband system requirements because of their narrow band operation. Integration and miniaturisation of the antenna is impeded by the added profile height and structural complexity of the antenna caused by the introduction of FSS structures. In turn, a trade-off between gain, bandwidth and the profile dimensions is necessary in practical applications [13].

Integrated design technology Substrate optimisation takes a synergistic layout to materials and design, by improving the performance of microstrip antenna by optimising the electromagnetic characteristics and layout of dielectric substrates. There are two main directions to this approach. One of them concentrates on high-dielectric-constant and low-loss substrate technology. The other has a look at substrate-metamaterial design. Microwave dielectric ceramics are used as the core materials in the high- dielectric and low-loss substrate technology. These materials have high and small loss tangent and dielectric constants, which make them to be used in high frequency, and have high temperature stability. Their operation depends on the formation of processes through precision that include casting gel and spin-coating. To form intricate shapes, gel casting uses monomer polymerisation, which is suitable to high thermal conductivity AlN ceramic substrates; to produce large-area thin ceramic strips continuously, slip casting is the technique to use, in order to exercise some level of control over microstructural homogeneity in alumina substrates. Yet, on the one hand, high dielectric constants have proven to make antenna miniaturisation straightforward, but on the other hand have challenged impedance matching as well as bandwidth compression, complicated ceramic techniques, and costs are high [14]. The substrate metamaterial integrated design is a design that fuses or embeds units of metamaterials into the substrate to make composite substrates which can manipulate wavefronts. As an example, the K-band can be optimised to gain the benefit of about 35 percent by the topological optimisation of the distribution of dielectric constant of a substrate [15]. Design flexibility and low loss Multilayer composite substrates, such as ceramic-polymer-ceramic sandwich structures, are possible. This technology represents the progressive idea of the material as structure, but has such issues as the complexity of design, manufacturing issues and phase shifts under the influence of coupling effects, which require further investigations.

Structural innovation technologies and array innovation technologies improve the performance of the microstrip antenna, by increasing radiation aperture and structure optimisation including array design, element design, and Feed network design. On array structures, in the C-band, stepped-slot antennas have a relative bandwidth of more than 20% due to perturbing current paths and excite multimode resonance [8]. Fan-shaped patch antennas achieve >12dBi gain and 120° beamwidth for broad coverage in the S-band through shape and arrangement optimisation [16]. Conventional design incorporations like Wilkinson power divides are implemented in LTCC technology and the loss and mutual coupling reduce. The feed network structure is, however, complex, requiring high precision of manufacture; there are serious problems of loss and phase error at higher frequencies. Although array technology is clearly showing gain benefits as well as beam control, it is not without problems.

3. Balancing performance and design collaboratives

The results of the analysis above show that although individual high-gain antennas can be used to provide a microstrip antenna with improved gain in certain configurations (metasurface loading, FSS reflectors, array designs), they all have trade-offs in inherent performance: metasurface tuning inevitably has a narrowed bandwidth and higher structural complexity [9], FSS reflectors inevitably increases the size of antenna profile [13], and arrayed designs inevitably experience the element mutual coupling and losses associated with the network of feed wires. Moreover, simultaneous purification of polarisation and advantage of gains is not easy to reach [11]. These tradeoffs have a critical impact on the practical use of high-gain microstrip antenna in 5G/6G communication systems, especially they are unable to satisfy the multidimensional demands of terminal devices on high gain, wide band, low profile, and high integration.

In respect of this foundational problem, this chapter dwells on the balancing of performance and the joint design directions, and the manner in which structural integration and system integration can counter the performance drawback of individual technologies. The key strategy is to use the functional complementarity of the various technologies to build the multi-technology composite structures. This is coupled with optimisation algorithm and combined as structural methods of design in the optimisation of several performance measures such as gain, bandwidth, profile, and polarization.

3.1. Multi-objective co-optimisation and composite structures

The research community has found it necessary to switch to composite structure design in order to deal with the performance limitations of single-technology approaches. Through a combination of two or more high-gain technologies made to occur organically, the synergy of functional complementarity and performance is attained. The essence of those designs is the clear definition of the functional division of labour between components. The inherent trade-offs between gain and bandwidth and gain and profile are removed through matching by electromagnetic parameters or structural optimisation thus making multi-objective optimisation possible.

Functional division is an inherent property of the composite structure of metasurfaces and FSS reflectors which allows them to attain high gain, wide band, and low profile. The fundamental concept is that the metasurface can be used as a forward wavefront control layer. It designs subwavelength units with phase gradient to provide an artificial lens effect converting the spherical wave of the microstrip antenna to a plane wave thus achieving beam focusing [9]. The FSS reflector is a rear reflective resonant structure of cavity that forms a frequency selective reflection line behind the antenna. This is a reflection of rearward radiation energy forward with a constant resonant mode to boost radiation efficiency. In contrast to a standard single FSS reflector with fixed 2n 4 spacing, the composite structure uses a metasurface phase compensation to allow the interlayer spacing to be flexible. This strategy broadens bandwidth at the same time gain enhancement is retained.

Mohamed et al. suggested millimetre-wave high-gain antenna, which used a combination of a rectangular lid antenna and 5×5 work FSS reflector coupled to each other by a composite structure. With strident annular and rectangular strip combinations in the FSS elements, the FSS has a constant band-rejection behavior in the frequency range of the 25.5 to 30.8 GHz range, with a reflection coefficient value of S_{21} of less than -10 dB. This structure is metasurface writable in unison with the FSS reflector, and eventually attains a peak gain of 10.3 dBi to a 5.3 dBi gain margin over a single antenna, with a 5.3 GHz band. The overall size of the antenna is to be no more than 25×25×5 mm^3 and all the problems with narrow band and high profile of the conventional FSS reflectors are virtually solved [13]. Within 5G millimetre-wave communication environments, composite designs have been experimented with including metasurface lens + FSS reflector array that have effectively reached a compromise between 18 dBi gain, 25% relative bandwidth and 8 mm small profile, reflecting the capability of the solution in high-frequency environment. The challenges facing such a composite structure are two-fold: firstly, the exact matching between the electromagnetic parameter of the metasurface-based elements and the FSS reflector requires full-wave simulation to optimise the size and spacing of elements, thus avoiding electromagnetic interference between structures, which reduces performance; Secondly, the high complexity of the structure makes cross-simulation/optimisation of the phase control precision of the metasurface, the resonance frequency stability of FSS, and the electromagnetic coupling consequences across the structure essential.

The other common one is the substrate-metamaterial integrated design. This scheme is based on a synergistic view on materials-structure-function which entails the incorporation or immobilization of metamaterial units into dielectric substrates. This makes composite substrates which integrates low-loss transmission and electromagnetic control of waves, which realise synergetic optimisation of miniaturisation, high gain, and low loss [14,15]. Its essence is that it uses high-dielectric substrates with low-loss to reduce losses in energy transmission, at the same time controlling the propagation direction of electromagnetic fields using the artificial electromagnetic properties of units of the metamaterials. This produces a focusing effect by itself and thus it does not have to increase the volume and decrease the bandwidth that the insertion of external structural components would. The K-band high-gain metamaterial microstrip antenna suggested by Dong Yan Zhang makes use of a combination design of an Al_2O_3 ceramic substrate and periodic metamaterials units. Angelos Voulopoulos and Evliya Su and Manuel Fortin optimize the topology of every one of these metamaterial units, as well as optimize the geometric distribution and the dielectric constant distribution, using topological optimisation techniques. This design creates advantages of a 35 percent gain improvement and cuts antenna size by a third, radiation efficiency than 90 per cent and dielectric loss tangent below 0.001 is successfully meant to balance the needs of miniaturisation, high gain, and low loss [15]. Lu Zhipeng et al. propose research which supports the processes of such composite structures. Their past gel-casting and cast-film forming methods allow high-precision fabrication of high-dielectric ceramic substrates with a guarantee of interface compatibility between the metamaterial units and substrates and avoidance of the electromagnetic parameters deviations in the processing errors [6].

Circularly polarised microstrip antennas have been of great interest in 5G/6G multipath propagation conditions because they have a high interference resistance capability and constant supply of signals. Nonetheless, bipolar gain and bandwidth coordinated optimisation of polarisation purity is not yet a reality in classic designs [11,12]. Polarisation-Gain-Bandwidth Co-optimisation Structure A structure is based on improving all three parameters through the implementation of polarisation control units into an enhanced structuring of high-gain composition. Its fundamental idea is the use of slotted structure, parasitic objects or metasurface arrays to simultaneously affect the radiation phase, as well as the polarisation state, of the antenna. This results in focusing of the beam and purification of polarisation. Wang Zexu et al. developed a new wideband circumferential polarised metasurface antenna having a circumferential parasitic antenna design where a composite structure is used which includes rading patch with slots + semi-circumferential parasitic elements + 4×4 metasurface array [12]. The radiating patch has four L-shaped holes cut to provide circularly polarised excitation by disturbing currents paths; semi-circumferential parasitic components maximise the distribution of surface currents to maximise the purity of polarisation; and the metasurface array focuses a beam by using phase control. Finally, it has a stable gain of 16.1% axial ratio bandwidth, 23.7% impedance bandwidth and 10 dBi circular polarisation purity in the 8.7-10.31 GHz range. Through this design, the synergistic viability of polarisation control and gain improvement is shown. The stacked microstrip antenna in the proposed structure by Rochkari et al. attains the ability to enhance and suppress cross polarisation synergies and gain enhancement via application of the metasurface loading [5].

It is worth noting that the nature of multi-parameter coupling of the composite structures and the requirements and considerations of multi-objective optimisation activities makes the classical trial and error design methods insufficient when it comes to performance requirements. Multi-objective optimisation algorithms are therefore proposed as critical tools of improving efficiency of design and performance ceilings [13]. These algorithms create objective functions that have gain, bandwidth, profile dimensions, and polarisation purity metrics, and thus, seek the best solutions in the multidimensional arrays of parameters to accomplish the global maximisation of a myriad of performance measures. Algorithms widely used in optimisation work with genetic algorithms, particle swarm optimisation, and topology optimisation, and hybrid strategies of optimisation show excellent results. The Battle Royale Customised Spider Monkey Optimisation (BRC SMO) algorithm suggested by Bom et al. retunes to the design of composite structures by performing a two-stage optimisation in the form of design of fundamental antenna structure parameters (first phase) and fine-grained optimisation of key parameters, including metasurface unit dimensions, FSS spacing and substrate thickness. The algorithm was used in the design of microstrip antenna that has an EBG structure and the algorithm produced the multi-objective optimisation results such as the following: gain increase of 15%, bandwidth increase by 20 per cent and reduction of cross-polarisation radiation by 8 dB. The efficiency in designing was enhanced by 40 percent in contrast with the traditional approaches. In substrate-metamaterial integrated design, spatial variation in dielectric constant is realised by topology optimisation algorithm, which maximises the distributions and geometry of units of metamaterials, affecting the propagation paths of electromagnetic waves [15].

3.2. Small-size system integration

An engineering use of high-gain microstrip antennas does not only rely on the elimination of performance trade-offs required, but a practical solution to system integration needs, especially the very high demands in miniaturisation, low profile, and assembly-friendliness of 5G/6G terminal devices. The system integration compact designs comply with the values of the performance without compromise, minimised volume, and integrated optimisation. They attain deep integration of high-gain antennas with communication systems in three dimensions akin to array structure, compatibility in packaging and convergence in functions [10].

Particularly, array configuration is a useful tool of increasing the gain of antennas but traditional uniform arrays also have problems associated with large size and high levels of mutual coupling. Compact array design Compact element miniaturisation, non-uniform arrangement and processes such as suppressing mutual coupling give compact array designs low sidelobe, high gain, and reduced volume. The main idea is to achieve the most radiation aperture and to ensure that there is electromagnetic isolation between components. Jia Hongshuai developed a microstrip single-pulse antenna array of low-side-lobe in compact form through aothe so-called schemes of series-parallel hybrid feeding and dense-packaged elements. The array reduces loss by aperture coupling with Wilkinson power divider combined feeding technique. At the same time, it uses optimised distance between the elements ($0.40\lambda_0$) and a defect ground structure to minimise mutual coupling. The ultimate array size is only two-thirds of conventional design and the gain at the highest frequency of the X-band is 15 dBi with the side lobes below -25 dB and cross-polarisation isolation of more than 30 dB, and all these sum up to satisfy completely the integration performance of either radar or communication system [7]. The small MIMO microstrip antenna suggested by Phuong Kim-Thi et al. uses cross-patch + T-junction power divider with dipole-polarised in order to meet the integration needs of MIMO antennas in that they provide high isolation without any additional defouling components. Having a minimum of inter-element separation of $0.005\lambda_0$ (the wavelength in the free-space is at 4.8 GHz) and overall dimensions of only $0.72\lambda_0\times0.48\lambda_0\times0.04\lambda_0$. It provides isolation of over 20 dB over the 4.74 -4.87 GHz band and wideband gain of 7.3 dBi, with extensions to 4/6-port massive MIMO implementation [14].

Besides, miniaturisation trend in 5G/6G terminal devices implies that high-gain microstrip antennas must be characterised by outstanding packaging capability to enable coplanar layout of the antenna-chip-substrate packaging. The essence of package-compatible design is the organic design in expressing the antenna structure and integration with the packaging material, which consists of the cover plates and PCB substrates. This technology manages profiles of the antenna in addition to preserving the performance of gain, and also works with mainstream assembly schemes such as surface-mount construction and system-in-a-pack (SIP) making. The cover of the metasurface antenna is in the form of a butterfly and it has a high gain microstrip antenna that designs the antenna cover by Yang Wenlong et al. that encapsulates the metasurface antenna cover with an encapsulation lid in the new design. This antenna uses a metasurface unit array in the form of a butterfly on the interior of the encapsulation lid, in addition to acting as a gain-enhancing structure, and a form of encapsulation protection. It has a gain interval with maximum of 16.24 dBi and the total profile of only 8 mm. This is a 35 percent volume decrease of conventional discrete designs. The antenna has been effective in implementation of 5G millimetre-wave modules, in which assembly in surface-mount with the PCB substrate via the surface-mount technology has eased significantly the assessment of assembly along with reduced system-footprint [10]. The antenna-on-chip (AoC) designed by Yu et al. uses the Artificial Magnetic Conductor (AMC) + Binding-Free Layer Process to accomplish low-profile integration in applications in chip level. This structure aims to optimally size the AMC structure using embedded guide structure (EGS) with its thinness of 16 μm, which is consistent with CMOS process oxide layers but utilises copper sputtering to avoid limitations suffered through low-conductivity bonding layers. Finally, at 94 GHz the antenna is designed to have 5.85 dBi gain when radiation efficiency is 57 percent thus satisfies the system-on-chip (SoC) to all-integration needs of the antenna [15]. This kind of design that has the ability to fit in regular packaging is an improvement to assembly steps between the antenna and the system, package volume and costs reduced, and at the same time, integration reliability was improved. The main issue is how to bring compatibility between the structure of the antenna and design of the packaging process such that the performance decreases due to manufacturing variability.

Moreover, one device is obtained through multifunctional integrated designs. It indirectly increases efficiency of integration in the system and will minimise the number of components and the total volume. The essence of such designs is the fact that the electromagnetic radiation and reception properties of the antenna would be utilised so that more features can be added without impairing the gain in communication. The most critical issue lies in the fact that it is challenging to obtain electromagnetic isolation between functional modules and remain in balance on performance. In communication-sensing integrated scenarios in 5G/6G frequency, fusion design of high-gain arrays of microstrip arrays and radar sensing units has become one of the research hotspots. The designs use a composite structure of communication array and sensing sub-array, that is, compatibility of communication and detection by sharing of radiation aperture. An example of such an integrated communication-sensing antenna is a 16-element microstrip array based antenna adopted as the main communication element of the antenna, which has a gain of 18 dBi. At the same time, four narrowband sensing units are built in at the periphery of the array, and it allows detecting the target at a distance not less than 5 metres. The total volume is also cut in half over a separate design. Its major technology uses a frequency-splitting and beam-separation approach, communications using the sub-6 GHz band and the sensing units using the 24 GHz band. The frequency-splitting and separation (FSS) filter designs ensure the band isolation and hence avoiding the electromagnetic interference among functions [12]. The integrated design of a C-shaped antenna with an AMC that offered a mechanism of charging a battery, which is offered by Ashyap et al. in wearable devices, would be a good example of a multi-functional integration. This antenna can attain 6.49 dBi communication gain at the 2.4 GHz ISM band and at the same time, wireless charging receive capability through optimised antenna radiation structure providing 1 W of charging power at 10 cm. The AMC structure achieves a higher gain of the antenna besides acting as electromagnetic shield to curb any radiation burden on the human body, curbing Specific Absorption rate (SAR) to greater than 90 percent, and is compliant with safety considerations of wear and tear devices [16].

4. Conclusion

This paper reflects systematically and investigates high-gain technologies in microstrip antennas at 5G/6G communications. The paper has a logical flow of problem analysis, technology review, solution breakthroughs and future outlook. It initially highlights those natural shortcomings of traditional microstrip antennas as regards gain, bandwidth and profile size. It then explores the principles, successes, and limitations of mainstream high-gain systems, such as the metasurface loading, frequency-selective surface (FSS) reflectors, optimisation of dielectric substrate materials, and array designs. Guided by the need to alleviate performance trade-offs of individual technologies, the paper has shown that a viable direction of attaining performance balance is possible by structural design of composites and multi-objective co-optimisation. It also examines the strategies of compact design and system integration aspects that are optimized to be used in practice. Being the final chapter, this section summarizes the main research results, discusses the current challenges, and proposes future trends of development of technologies.

This paper reaches the following main conclusions after a extensive examination of the existing technical solutions and innovative solutions. The breakthrough in technology and the partnership approach to design is essential to the performance barriers. One technological method usually compromises other measures (like band-width or profile) to optimise a specific measure (like gain). Research has shown that functional complementarity may be achieved effectively by incorporating technologies in an organic integration with varying physical mechanisms. These composite design approaches indicate a paradigm shift in antenna design practices, that are based on single performance optimisation, to multi-performance synergistic trade-offs.

The foundation of the high-frequency and high-performance technology lies in materials and manufacturing processes. Finally theoretical performance of antennas is limited by the materials and processes deployed to bring them into reality. In 5G/6G high-frequency (especially millimetre wave) operation, high dielectric constants and low loss (albeit lose) of microwave dielectric ceramics (e.g. Al_2O_3 and AlN) and their ability to form (e.g. gel casting and tape casting) plays a critical role.

Nevertheless, there are numerous problems in this area, which still have not been resolved despite improvements. Any materials which are used in high-frequency bands (millimetre wave/terahertz) have significant losses, hence require a high level of uniformity of substrates as well as manufacturing accuracy. There are inherent trade-offs between the two or more optimisation goals where the algorithms require large computational efforts and cannot operate in real-time. Also, in severe cases of integration (wearables and on-chip antennas) thermal management and electromagnetic compatibility are still not tackled.

In the future, when 6G is available, high-gain microstrip antenna technology will further develop in the following aspects. The main problem with static optimisation is that it becomes difficult to adjust to the dynamic environment; therefore, the active components will be integrated into the reconfigurable intelligent surfaces (RIS) and become the focus of research. The antenna will be an intelligent front-end, incorporating sensing and computing functionality, and research is underway to have integrated arrays that are able to process both communication signals and environmental perception signals, which can be done simultaneously and efficiently, to aid the ubiquitous intelligence of 6G. It is hoped that this review and outlook serves to go on and further innovate in this area.

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