

Design and Development of Compact Ultra-Wideband Millimeter-Wave Planar Antennas for Next-Generation Wireless Communication Systems: A Comprehensive Review

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Abstract- The emerging sixth-generation (6G), beyond-fifth-generation (B5G) and fifth-generation (5G) wireless systems are rapidly developing, which has led to the need for antennas that are compact, have wide impedance bandwidth, and have adequate gain and reliable radiation. The planar antennas are desirable for their lightweight, low-profile, economical, and printed circuit manufacturing compatibility. This review reflects recent advances in planar UWB and mmWave antenna research, with a focus on the topics of bandwidth extension, miniaturization, gain enhancement, band-notched, MIMO, wearable applications, choice of substrate, and the design through Artificial Intelligence (AI). The following are major methods: Slot loading, defected ground structures (DGS), coplanar-waveguide (CPW) feeding, parasitic elements, fractal geometries, engineered electromagnetic surfaces and antenna arrays. The literature shows that hybrid configurations can yield good balance in performance, but bandwidth/ gain/efficiency/size/c Fabrication Tolerance are still interdependent. Key research areas include low loss and low-cost substrates, optimization that is tolerant of the substrate, repeatable measurements, multifunctional integration, and AI models that are more transferable. These directions are applicable to future communication and sensing platforms in practice, featuring high-performance antennas.

Keywords-Ultra-Wideband (UWB), millimeter-wave (mm Wave), planar antenna, DGS, CPW, MIMO, 5G, B5G, 6G, artificial intelligence.

1. INTRODUCTION

Wireless communication systems are heading toward a network which is required to enable a combination of high data rates, low latency, dense device connectivity, reliable links and accurate sensing. These requirements are found in Internet of Things (IoT) devices, autonomous systems, industrial automation, wearable electronics, radar, localization and high capacity backhubs. Both UWB and mmWave technology can offer very high speed short-range communications and can be used for very high accuracy ranging, but mmWave technology can also provide access to huge spectral resources [1] and [3].

Applications for these include planar antennas where the radiating conductors can be made directly on the dielectric material. These are thin, light and can be integrated into RF front ends and printed. Recently, characteristic mode analysis has been applied to gain insight in the modes that contribute to radiation from planar elements [2]. A conventional patch, however, is typically narrowband and the issue is challenging if compactness or higher operating frequencies are needed.

Modification of radiator, feed or ground plane is the most common way of bandwidth enhancement. Slots provide additional resonances, increase the surface-current paths, and change the ground-current distribution; DGS can be used to manipulate the ground-current distribution; CPW feeding can be used for compact broadband implementations; parasitic or engineered electromagnetic elements can provide additional control [6] and [12]. Measured performance at mmWave frequencies [7]–[10] can be greatly affected by surface roughness, connector transitions, dimensional tolerance, and accuracy of assembly.

This review thus focuses on the design mechanisms and not just the numerical values reported. Recent papers (2022-2026) from planar antennas (UWB, mm Wave), miniaturization, gain, MIMO, wearable applications, substrate and fabrication issues, band notched and AI optimization are discussed.

2. LITERATURE REVIEW

2.1. Wideband and Ultra-Wideband Planar Antennas.

UWB antennas are good to use if a single radiator has to be able to communicate, localize, measure range, sense, and be used in wireless sensor networks over a wide frequency range. The primary design goal is to achieve an acceptable level of matching of the input over the desired band without wasting the efficiency or pattern too much [1]. This can typically be accomplished in planar

structures through the addition of extra resonant paths and through the manipulation of the coupling between the radiator, feed, and ground.

One of the easiest methods is the slot loading technique. A slot disrupts the normal path for current and causes current to take a longer path. Depending on the size and location of the slot, its effect is to reduce the first resonance or to add an extra one, or to enable the neighboring resonances to overlap. The U-, C-, circular-, and rectangular-shaped slots have thus been extensively studied [5], [6]. The improvement is not automatic; the length, width, orientation and feed distance of the slots must be chosen to ensure that the modes in the desired band add together constructively.

Another bandwidth control technique that is important is DGS. By removing selected portions of the ground plane, the return-current path and equivalent reactive behavior are changed. Surface-current distribution and proper impedance matching can be affected by positioning the defects. The method is appealing for printed fabrication as normally the alteration of the ground can be achieved in the same printed process. Too much ground disturbance, however, can change their radiation pattern or increase the integration difficulties of a ground array.

CPW is a feeding arrangement where the feed and ground conductors are placed on the same substrate surface. This can make the manufacturing easier and remove some of the limitations related to the via. CPW geometry is also advantageous in controlling the feed-to-radiator coupling characteristic in compact UWB antennas. However, the selection of conductor width, feed gap, substrate thickness and the geometry of the transition is not independent but should be optimized with the full antenna.

Research has lately begun to merge multiple mechanisms. A slotted radiator can be used with a modified ground and optimized feed to have multiple resonances within a small ground area. Zhu et al. reported a strip-loaded slotted circular patch which shows the importance of multimode excitation and current-path engineering in broadband mmWave operation [6]. The literature on the general subject of UWB enhancement also classifies UWB enhancement into four categories: radiator modification, ground plane engineering, feed optimization, and electromagnetic configurations [12].

2.2. Millimeter-Wave Planar Antennas for 5G and Beyond

A key challenge with mmWave systems is that they provide significant spectral resources with higher propagation loss, thus the need for gain and directional control. Multiple elements can be

implemented as a single radiator, MIMO array, phased array, leaky-wave antenna or lens inspired structure on small size substrates with planar technologies.

This diversity is reflected in recent work. Ahmad et al. has reported a tri-band wearable antenna for mmWave 5G [3]. A wearable design for Vivaldi that considers body-related effects and is designed to operate at 28/30 GHz has been addressed [7]. The use of parasitic isolation structure to minimize inter-port coupling in a quad port 28/38 GHz design was presented [8]. An additional example of high gain, directional radiation, which can be obtained in planar architecture without restricting the patch to a conventional rectangular shape, is offered by leaky-wave and flat Luneburg-lens designs [4, 5].

In the case of these frequencies, the selection of substrates is especially critical. FR-4 is inexpensive, but it might have more loss and material variations for cheap prototypes. The microwave (high frequency) behavior of low-loss laminates is generally superior and is a generally higher cost. Thus, substrate type, thickness, loss tangent, connector and fabrication process must always be taken into account alongside reported gain and bandwidth.

2.3. Compact Antenna Miniaturization Techniques

Handset, sensor node, wearable and space-constrained RF modules all need compact antennas. Obstacle of miniaturization is that an electrically small radiator has less physical area to support a broadband current distribution. Minimizing size will reduce radiation resistance, bandwidth and the relative contribution of dielectric losses and conductor losses.

Slots are popular because they 'shorten' the effective electrical length, without reducing the external length. Folded or meandered current path can change the resonance to a lower frequency and keep a small footprint. Several resonant modes can be supported in the same slot, resulting in the possibility of slot loading both for multiband and UWB. Electric length is similarly increased in a compact volume for fractal geometries such as Koch, Sierpinski, and Minkowski type contours. The downside of their disadvantage is that they have a higher geometric complexity and are sensitive to fabrication errors.

Another way to control the electromagnetic environment around the radiator is achieved by using metamaterial-inspired structures and metasurfaces. Phase, current distribution, surface waves, matching, gain, or miniaturization can be affected by engineered inclusions or periodic surfaces.

However, very precise designs might lose their broadband characteristics, and exactly small geometrical features can be hard to accurately fabricate at mmWave frequencies.

Hybrid miniaturization: Hybridization of complementary mechanisms. A parasitic element can recover gain, a slot can reduce the resonant frequency and a DGS can tune the ground response. The benefit is increased design flexibility, but so do the number of parameters and sensitivity of the resultant structure. Some comparisons are therefore useful which include electrical size, operating band, efficiency, gain, the properties of the substrate and whether dimensions cover the feed region or not.

2.4. Gain Enhancement and High-Gain Planar Structures. Gain Enhancement and High-Gain Planar Structures.

Propagation loss is a design consideration that may decrease link margin as frequency is increased, therefore gain enhancement is important. One element can focus the radiation using parasitic directors, reflectors, resonant loading or engineered surfaces. Position and spacing of parasitic elements must be optimized; greater coupling may be beneficial in improving directivity and adversely affect impedance matching.

Arrays are a more systematic way to high gain. Controlled spacing multiple elements with designed feed network can provide increased effective aperture and can be used for beam steering and spatial multiplexing. Both linear and planar arrays were examined by Jabbar et al., with the tests conducted both in the laboratory and in an over-the-air environment, highlighting the importance of a full evaluation of the array and feed network system [9]. The consequences of this are that the footprints are bigger, the feed is more complex and the measurement is more demanding.

With high gain mmWave antennas, simulated performance should not be considered as the final criterion. Gain may be less than measured due to connector transitions, conductor roughness, substrate variation, assembly tolerances and feed losses. Hence, it is recommended that both simulated and measured characteristics should be reported in practical antenna research, wherever possible.

2.5. An introduction to MIMO and Wearable Integration.

Wide impedance bandwidth is not sufficient for MIMO antennas. Elements that are spaced very close together may exhibit high mutual coupling, influencing isolation, efficiency, correlation and active impedance. Parasitic strips, neutralization paths, DGS, spatial separation, and engineered surfaces can be used as decoupling methods. Ahmed et al. achieved parasitic isolation in a compact configuration of 28/38 GHz quad-port [8] and Abbasi et al. highlighted the importance of high isolation in an eight element 5G mm-wave array [10].

Wearable antennas cause body loading due to lossy and dispersive nature of body tissue. The body can vary the resonant frequency, can change the impedance, change the radiation pattern and decrease efficiency. This is an illustration of why body-oriented validation is required, as pointed out in the Vivaldi MIMO work in [7]. Therefore, representative installation conditions should be considered for a wearable antenna assessment and not only free space simulations.

2.6. Design of Planar UWB Antennas having Band-Notch Characteristics

The large bandwidth of the UWB antennas can overlap other existing narrowband services. A WLAN or WiMAX or satellite signal that is strong in the vicinity of the UWB receiver can interfere with the receiver. Band notched antennas are designed to overcome this issue by creating a notch in the passband to reject radiation in the narrow region while still maintaining an acceptable passband response [12].

One way to do this is to cut a resonant slot into the radiator. Current flows around the slot near the unwanted frequency, and the resonant path acts as a trap. The notch frequency can be controlled by varying the notch length, width, position and coupling. Other approaches include parasitic strips, resonant stubs, complementary split-ring resonators and split-ring-inspired resonators and ground-plane defects.

If more than one narrowband service needs to be rejected, there can be several notches. Each additional resonator, however, adds another coupling path and adds sensitivity to fabrication variation. A good band-notched design should therefore include notch center frequency, rejection depth, notch bandwidth, passband bandwidth and frequency stability. The radiation pattern and efficiency around the notch should also be taken into account since a high $|S_{11}|$ does not always mean a good antenna response.

For portable and wearable systems, there is a possibility for change of notch near components and body loadings. Tolerance analysis and tunable or reconfigurable notch mechanisms are thus good avenues of research. The selection of the notch technique should depend on the bandwidth of rejection desired, available space, number of unwanted services and complexity of the design.

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2.7. Key E-field and System-Level Parameters

Reporting must be uniform to be a fair comparison. The size of the whole board, the size of the radiator, the thickness of the substrate, and the electrical size should be separated and a small radiator mounted on a large ground plane should not be seen as a very small antenna! Impedance bandwidth should be specified according to the reflection-coefficient criterion, together with the frequency limits.

The fractional bandwidth can be written as $FBW = 2(f_H - f_L)/(f_H + f_L)$ where f_H is the upper frequency in the Band and f_L is the lower frequency in the Band. Bandwidth is useful to accompany realized gain and radiation efficiency because a good impedance match does not mean an efficient radiator. Dielectric and conductor losses may be appreciable at mmWave frequencies. Besides S_{11} , it is important to consider isolation and envelope correlation coefficient for a MIMO system. If the application requires broadband communication and/or sensing, the radiation pattern must be evaluated at multiple frequencies due to the band dependence of beam shape, nulls, or polarization. The fabrication tolerance should be evaluated by varying the critical dimensions (CD), the dielectric properties, the feed alignment, and the connector conditions within realistic ranges.

2.8. AI-Assisted Antenna Optimization

When there are many geometrical variables to explore a full-wave simulation becomes quite expensive. By learning a surrogate relationship between the antenna parameters and resonance, bandwidth, gain, $|S_{11}|$, etc., AI can alleviate this burden. After the learned design space, optimization algorithms can search the design space before final electromagnetic verification.

Artificial neural networks, deep learning, genetic algorithm, particle-swarm optimization, Bayesian optimization, and Gaussian-process regression are some of the possible approaches. They are successful based on the quality and amount of training data. A model trained on one topology might not be applicable to a different one, or to a different substrate, or to a different frequency domain [13]–[15].

To achieve a reliable AI workflow, one should use electromagnetic reasoning, data generated through simulation, surrogate optimization, full-wave verification, and prototype measurement. Normalized electrical dimensions, material parameters of the substrate, coupling distance, and modal information are examples of physics-related inputs which can enhance the transferability. Errors on significant resonances should be checked and not just a simple average of prediction accuracy.

3. COMPARATIVE ANALYSIS OF RECENT PLANAR ANTENNA APPROACHES

The reviewed studies address different frequency ranges, applications, substrates, and performance objectives. Consequently, a direct numerical ranking is not appropriate. The comparison below is qualitative and emphasizes the primary design contribution, operating context, and main practical limitation reported or implied by each study.

Table I. Qualitative comparison of representative recent planar antenna studies.

Ref.	Antenna / Architecture	Band / Use	Main Technique	Primary Contribution	Main Limitation
[3]	Tri-band wearable planar antenna	mmWave 5G / wearable	Multi-band planar radiator	Compact multi-band operation with wearable integration	Body loading, conformability, and efficiency
[4]	Flat Luneburg-lens antenna	mmWave / high gain	Engineered lens / dual polarization	High-gain dual-polarized radiation with	Phase control and fabrication complexity

Ref.	Antenna / Architecture	Band / Use	Main Technique	Primary Contribution	Main Limitation
				reflection cancellation	
[5]	Planar leaky-wave antenna	mmWave	Leaky-wave radiation	Wideband fixed-beam radiation with controllable direction	Directional feed and transition design
[6]	Strip-loaded slotted circular patch array	mmWave UWB	Slots, strips, multimode excitation	Broadband behavior from multiple coupled modes	Several geometric parameters require optimization
[7]	Four-element Vivaldi MIMO	28/30 GHz / WBAN	Vivaldi elements and MIMO integration	Low-profile MIMO with body-oriented validation	Isolation, body detuning, and wearable constraints
[8]	Quad-port cross-shaped MIMO	28/38 GHz / 5G	Parasitic isolation strip	Compact multi-port layout with improved isolation	Coupling and fabrication tolerance
[9]	8- and 32-element arrays	26.5–29.5 GHz / FR-2	Array and controlled feed network	High-gain measured array operation	Feed and OTA measurement complexity
[10]	Eight-element high-isolation array	5G mmWave MIMO	Compact array / isolation engineering	Low-form-factor array with high isolation	Element coupling and array footprint
[14]	Shared-aperture microwave/mmWave MIMO	Multi-band 5G/6G	Shared aperture and integrated MIMO	Multiple functions in one planar region	Cross-band coupling and calibration

3.1. Comparison by Design Mechanism

The table below illustrates that none of the architectures is the best-suited solution for all the requirements. Slot loaded radiators are especially useful for bandwidth and multimode excitation, and DGS is suitable if ground current control is desired. The feeding of CPW is appealing for small size printed implementation. Arrays are able to give a higher effective aperture for the same feed complexity, and parasitic elements can increase gain or isolation. Engineered surfaces and shared-aperture structures can be designed and optimized for added functionality, but usually demand a more focused approach.

The next step in a practical design sequence is to determine the dominant restriction (by current, field or modal analysis) and then use the simplest mechanism that meets it. New features should only be added if they address a defined secondary problem. This can help to minimize the number of unnecessary parameters and enhance the robustness of the fabrication process.

3.2. The considerations for using substrate and fabricating include the following:

The dimensions, impedance, loss and bandwidth are strongly affected by the properties of the substrate. The guided wavelength and physical size depends on the dielectric constant and the loss tangent affects dissipated power. A change in thickness will change the impedance, bandwidth, surface-wave behavior, and mechanical strength. Two antennas, which are geometrically similar, but built on different substrates should not be compared unless these parameters are taken into account.

Nearly any narrow slot, small gap, via, placement of connectors, soldering or multilayer alignment may cause large deviations at mmWave frequencies. The fabrication method and the data of the material, the model of the connector and the arrangement of measurement should be described in a strong study, so that the differences between simulation and measurement results can be interpreted.

3.3. The use of MIMO, Wearable, and Shared-Aperture Integration.

The use of multifunctional compact antennas is becoming more common. A number of communication bands, sensing functions, and spatial streams can have to share in a limited spatial region. Shared-aperture architectures are based on multiple functions or multiple radiators being allocated to one physical space to decrease the size of the hardware. This approach is demonstrated in recent work on integrated microwave/mmWave circuits [14] with cross-band coupling and port isolation being important design challenges.

Current generated by one element can excite other elements and the common ground in a compact MIMO antenna. This coupling has an impact on S-parameters, efficiency, radiation pattern and diversity. Therefore the design of a MIMO should be considered as a single multi-port electromagnetic system at the very start of the design, and not as a set of separate antennas grouped together at the end of the design.

When the human body is added by wearing a system, this is called "wearable systems. The resonance can change with tissue loading, and there can be further variation due to mechanical bending. Wearable antennae should therefore be tested in typical body configurations with representative body loss. This approach to validation is shown to be important in the Vivaldi MIMO study in [7].

3.4. AI's contribution to the Comparative Design Process. How AI plays a role in the Comparative Design Process.

AI is at its best when it decreases re-simulation but still maintains electromagnetic validation. A realistic approach starts with physical architecture selection and feasible ranges of parameters. Based on full-wave simulations, a representative set of data is then created, an AI model is trained to map the relationship between the parameters and the performance, and an optimizer is used to find candidate solutions. The re-simulation of final candidates is required and if possible, fabrication and measurement of the final candidate is required.

Physics-informed features can enhance model utility. The model does not only rely on raw dimensions but can also feature normalized electrical dimensions, substrate properties, coupling distances or modal indicators. These factors can contribute to the transferability of a model across frequencies and corresponding topologies.

Evaluation should not be limited to just the average prediction error. Worst case errors about narrow resonances and notch frequencies may be important. The most important test that an AI-based design passes is that it is validated by independent electromagnetic testing and fabricated.

4. SYNTHESIS OF REVIEWED TECHNIQUES

There are five common design principles that can be seen throughout the literature. One of the most common ways of getting broadband behavior is to arrange several resonances close together so that they overlap. Secondly, to improve compactness, the electrical path length must be made longer or the electromagnetic surroundings must be changed, which can increase the loss and fabrication sensitivity. Third, high mmWave gain is typically achieved with arrays or parasitic elements, or engineered surfaces. Fourth, isolation and correlation control are needed in addition to impedance matching in MIMO. Fifth, while AI can help expedite design space exploration, it is still reliant on representative data and physical verification.

The preferred balance is determined by the requirements of the application. Wearable antenna puts emphasis on body loading, conformability, efficiency, and safety. A base-station array focuses on the aspects of gain, beam control and calibration. Cost, size and reasonable efficiency may be important concerns for an IoT node. Multiple bands and calibrated multi-function operation, as

well as stable patterns, can be needed for an integrated sensing and communication platform [11,15].

5. DESIGN GUIDELINES FOR COMPACT UWB AND MMWAVE ANTENNAS

The communication requirement is a useful starting point for a design workflow: operating frequency range, bandwidth, gain, polarization, number of ports, available volume, substrate restrictions and installation environment. Then the designer is to determine which electromagnetic limitation is dominant. A slotted or multimode radiator might be a better choice if bandwidth is the primary concern; DGS is a possibility if the concern is ground-current control; parasitic elements or arrays would be better choices if the bandwidth is not enough, but extra slot complexity is desired.

Sensitivity analysis is done next. Prior to final optimization, critical dimensions should be perturbed and parameters with high influence should be identified and prioritized. This is particularly crucial at mmWave frequencies where slight changes in dimension can alter resonance. Last but not least, instead of minimum $|S_{11}|$, multi-objective optimization should take into account bandwidth, realized gain, efficiency, size, isolation, cost, and robustness.

6. RESEARCH GAPS

6.1. Bandwidth-Gain Trade-Off

One of the recurring challenges is to achieve a very broad impedance bandwidth and high realized gain in a compact, single-layer design. Slots and DGS work very well for bandwidth and arrays and directive elements tend to work better for gain. They can enhance overall response when used together, but may also result in increased loss and sensitivity due to additional geometry. Bandwidth and realized gain and efficiency should be reported in future studies.

6.2. Compactness Versus Efficiency

Physical miniaturization may result in higher stored reactive energy, and sensitivity to material loss. A small antenna can then have a good reflective characteristic and have a lower radiation power. Radiation and total efficiency should be included in comparative studies and gain should be separated in the simulated from the measured gain.

6.3. In addition to the cost of the substrate, there is also a loss due to mmWave.

It is possible to use low loss microwave materials to enhance efficiency in mmWave applications, but their cost may make them prohibitive for mass-market applications. Further controlled studies are required, with the same topology being reproduced in low cost, low loss substrates, under similar measurement conditions. This type of work would isolate the geometry effect from the material effect.

6.4. AI Generalization and Reproducibility

There are numerous AI based antenna models, which are trained for a specific geometry and frequency range, and therefore cannot be reused. Surrogate modeling and physics-informed models, as well as openly documented datasets, might enhance generalization and reproducibility. Reporting procedures for data generation, parameter intervals, training/testing partitions and independent electromagnetic verification [13]–[15] should be reported in future studies.

6.5. It is a multifunctional and Shared-Aperture Integration. It is a multifunctional and Shared-Aperture Integration.

Future terminals can integrate UWB, 5G/6G, sensing, satellite and local area wireless capabilities. Shared-aperture and co-designed MIMO antennas have a high interference between different bands and calibration is challenging. New architectures that are more compact are needed that remain efficient when multiple ports and bands are used concurrently.

6.6. Experimental Validation

Results from simulation are not enough to prove the robustness of mmWave. Calibrated S-parameters, radiation patterns, realized gain, efficiency and MIMO metrics (if applicable) should be included when evaluating prototypes. Wearable antennas should additionally be tested under representative body loading. Record the uncertainty in measurement and the reasons for the difference between simulation and measurement.

6.7. Need for a Unified Benchmark

Because of the different definitions of size, bandwidth, gain and efficiency used by the authors, published results are difficult to compare. The dimensions, electrical size, substrate characteristics, frequency range, impedance criterion, realized gain, total efficiency, radiation-pattern characteristics, fabrication technique, and measurement status are all to be incorporated into a unified benchmark. Isolation, envelope correlation, diversity gain and active reflection should also be provided for MIMO.

7. CHALLENGES AND FUTURE DIRECTIONS

7.1. Low-Loss and Low-Cost Materials

The materials of future practical antennas should have the following characteristics: Low dielectric loss, mechanical stability, economic, and compatibility with standard PCB processing. Laminates that are engineered and process compatible can help close cost/performance gaps.

7.2. Reconfigurable and Adaptive Antennas

Multiple standards may make fixed-band antennas less desirable. Frequency, polarization or beam adaptation can be achieved by switches, tunable components and programmable surfaces. The key issue is that of reconfigurability without significant loss, added control complexity, or loss of reliability.

7.3. Meta surfaces, EBG, and AMC

Waves can be suppressed on engineered surfaces, manipulated in phase, and deflected. EBG and AMC structures are thus a promising choice for gain and isolation enhancement. Simplification of unit cells, and tolerance-resistant implementations, should be the focus on future work.

7.4. AI-Enabled Multi-Objective Optimization

Bandwidth along with gain, efficiency, size, isolation, cost and fabrication tolerance are likely to be taken into account in the optimization of the next generation of antennas. The final candidate can be validated electromagnetically, and surrogate-assisted and evolutionary approaches can limit the number of costly simulations.

7.5. The use of MIMO and Shared-Aperture Architectures. Use of MIMO and Shared-Aperture Architectures.

The size of the devices gets smaller, and several elements of the antenna have to fit in a small area. Mutual coupling can be mitigated using decoupling structures, characteristic-mode control, neutralization paths, and engineered surfaces. A particularly desirable feature of many shared-aperture designs is the ability to have more than one band or function in a single physical area. They are only successful in practice if they are able to be isolated, their feed networks can be controlled, and their feed is calibrated [10, 14].

7.6. With Sensing and 6G Integration

Integrated sensing and communications is likely to impact the 6G antenna requirements. The future antenna should also be able to handle the combination of communication and sensing, with stable phase response, calibrated channels, adequate angular coverage and controllable radiation patterns. This is a critical trend that has made the calibration of arrays, and the electromagnetic co-design of entire systems, even more important [15].

7.7. Sustainable and Manufacturable Design

Material use, fabrication yield, repairability and environmental considerations should also be increasingly taken into account for antenna research. Highly complex geometries can lead to good simulated performance, though can be challenging in terms of manufacturing. A more practical design with a slightly less optimized structure with strong dimensions and standard materials may be more suitable for deployment.

7.8. Beyond Conventional Planar Geometry

While planar antennas are still very appealing, 3D packaging, conformal substrates, metasurfaces, and heterogeneous integration are combinations that may be used in the future to provide systems with printed planar antennas. These techniques allow to retain the advantageous characteristics from planar processing and introduce extra freedom in beam control and miniaturization. The challenge is to m7.1. Low Loss and Low Cost Materials

Materials with low dielectric losses, mechanical strength, low cost and normal processing on PCBs is needed for future practical antennas. The adoption of engineered laminates and process compatible alternatives can help to bring the cost–performance gap closer.

8. PRACTICAL DESIGN WORKFLOW

Any practical workflow should begin with the system specification and not begin with a preferred shape of the antenna. First, the required frequency range, the direction of the link, the gain, polarization, the volume of the device, the substrate, the number of ports and the installation environment are determined. Both wearable and body loading systems will require both body loading and safety considerations, whereas base-station or backhaul systems can focus more on array gain and beam control.

The second step is the selection of the electromagnetic architecture. If the bandwidth and compactness are the focus, a single element with a slot is appropriate. CPW feeding can be used for simple printed implementations. Ground current behavior can be a limiting factor for matching; in such cases, DGS can be added. Instead of increasing radiator slots, a parasitic element or array might be more effective if the gain is still not enough.

The third step is the parametric sensitivity analysis. Before final optimization it is important to vary important dimensions to find the parameters which most affect the resonance, bandwidth, gain and isolation. This will decrease redundant computational effort and give helpful properties for AI-based surrogate models.

Multi-objective optimization is the fourth stage. Bandwidth, realized gain, efficiency, physical size, isolation, and robustness can be included in the objective, in addition to minimizing reflection coefficient. Then the Pareto-optimal candidates can be chosen based on the particular application. Fabrication and validation are the last two stages. Use definitions that are consistent with the simulation for prototype measurements. Connector modeling, uncertainty of substrates, dimensional tolerance and assembly effects are all methods of investigation into discrepancies. For mmWave arrays, calibrated radiation-pattern and gain measurements are important. Testing should be repeated for use in body related configurations for wearable antennas.

9. OVERALL DISCUSSION

The literature surveyed shows a trend from the optimization of individual antennas to system level design. Bandwidth, gain, compactness, efficiency, isolation, cost, and robustness are now being considered together. This is especially evident in the MIMO, shared-aperture, wearable and AI-aided architectures.

Perhaps the most important one is that an increase in the geometric complexity is not a requirement for a better antenna. The more slots, resonators, parasitic elements or engineered surfaces, the more freedom in the design but the more sensitive and complicated fabrication. Thus, the "most practical," as far as this is relevant to architecture, is not necessarily the architecture with the highest simulated bandwidth or gain, but rather the one that offers an appropriate balance for a given purpose.

The comparison also emphasizes the role of the measurement conditions. Large variations can be seen at mmWave frequencies due to the differences in the substrate, connectors, test setup, and fabrication tolerance. Reporting and experimentation is then essential to making meaningful research comparisons, therefore.

The future will probably be a mixture of compact planar geometry, reconfigurability, engineered electromagnetic surfaces, shared apertures, MIMO, sensing, and data-driven optimization. These types of systems will need more connections between electromagnetic theory, numerical optimization, manufacture and RF-system integration.

10. CONCLUSION

This review focused on the latest advancements in compact UWB and mmWave planar antennas for future wireless communication systems, highlighting the literature from 2022 to 2026. The analyzed works include the analysis of bandwidth enhancement, band-notched operation, minimization, high-gain structures, MIMO integration, wearable antennas, substrate selection, shared-aperture architectures, and AI-based optimization.

Other methods of enhancing the performance of antennas such as those mentioned above are complementary: Slot loading, DGS, CPW feeding, parasitic elements, arrays, and fractal geometries can be used. Arrays and parasitic structures are effective in the areas of gain and isolation, respectfully, whereas slot and multimode approaches are effective for broadband operation. Additional body loading and cross-band coupling considerations are needed for wearable and shared-aperture systems. While AI can speed up the process of exploring parameters, the outcomes generated must always be driven by electromagnetic reasoning and validated by outside tests.

It has also been revealed from the literature that the performance of antennas can't be assessed by a single criterion. The following are parameters that should be considered to achieve a useful

design: impedance bandwidth, realized gain, efficiency, radiation-pattern stability, physical size, isolation, cost, and fabrication robustness. Tolerances and material characteristics are significant at mmWave frequencies. Future studies should thus focus on low loss and economical substrates, strong geometry, common performance metrics, tolerance design and optimization, robust AI models, and multi-functional hardware designs that include communication and sensing.

Overall, planar technology is still a good platform for a compact antenna for 5G/B5G/6G applications due to its low profile, manufacturability, manufacturability, and design flexibility. The next generations of antenna research will focus on system-aware, multifunctional and technically robust solutions, not on optimizing a single electromagnetic parameter.

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