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# Antenna Research Directions for 6G

## A brief overview through sampling literature

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***Abstract*—Antennas are a critical component in any wireless link. The significance of their role continues to grow, together with the rise of machine-to-machine (M2M) communications and telecommunications starting to move from the fourth generation (4G, or Long-Term Evolution, LTE) to the fifth generation (5G) and beyond 5G (B5G), and also due to the prominence of the convenience promised by the ubiquitous wireless communications. The antennas, or more precisely their large size and appearance, also become a subject of public debate, leading to the need for better antennas, which are can do both: provide high performance and offer visually attractive or nearly invisible/transparent designs. This work reviews several key research trends in antennas to fulfill these demands for the fifth generation of communications (5G) and beyond, especially 6G, and considers novel antenna techniques and designs needed to increase the smartness of the antenna systems and to provide improved beamforming and security.**

***Keywords—antenna, design, development, 5G, B5G, 6G, security, power, NOMA, hybrid beamforming, IoT, Reconfigurable antennas.***

## I. Introduction

The world demands more and more data, to support the opportunities brought by big data and new applications. The international telecommunications union (ITU) advises that the data traffic will continue growing at an exponential rate worldwide. In the context of enabling the population to take advantage of the fourth industrial revolution (4IR), people need to be connected to the Internet.

Antenna forms part of a wireless transmitting or receiving system that is designed to radiate or to receive electromagnetic waves. In considering the wireless link's balance for a typical wireless link, the antennas play a critical role [1].

Antennas are the key element of modern wireless telecommunications systems. Following the demand for speed and reliability, the physical communication link must support these requirements. The antennas used in mobile telephony networks (cellular) and Wi-Fi systems have gradually moved from simple patch and monopole antennas in the first few generations to advanced beamforming array antennas used in the multiple-input multiple-output (MIMO) systems in the fourth (4G) and the latest fifth (5G) generations of wireless technologies. The growth in the machine-to-machine (M2M) and device-to-device (D2D) communications, further escalated by the rise of the Internet of Things (IoT) is also introducing billions of new communicating entities, each requiring at least one antenna. Even though the standardisation work in 5G has just been completed and only the first deployments have been started, the research community has already started with the research towards the next generation of telecommunications, 6G, pushing the already hard performance requirements further.

As the antennas became arrayed, i.e., require multiple radiating elements, their physical size grows and sometimes becomes a visual disturbance. The growth in the use of the Internet and the rise of IoT applications will continue to drive the densification of networks and demand more wireless applications and thus antennas. Antennas need to support faster speeds, become even smarter and more compact, better aligned with the existing urban and rural environment, able to support localization/positioning services. This work presents an overview of existing antenna designs and how these existing antenna designs can be improved for the 5G and beyond antenna applications. These techniques are needed to increase the smartness of the antenna system and will include improved beamforming and perhaps security.

The rest of the paper is arranged as follows: the next section reviews some well-known but highly relevant facts about the interconnection between the different parts of the link and Shannon equations and control offered through appropriate antenna design. Section III offers a brief overview of some of the key trends in techniques for antenna design, and an in-depth discussion follows in section IV. The last section provides a summary of the paper.

## II. Significance of Antennas in the Link Budget

The link balance, which may for example be written as

$$P_{RX} = P_{TX} - L_C + G_{TX} - L_P + G_{RX} \quad (1)$$

and includes multiple variables: transmit power $P_{TX}$ (dBm), cable losses $L_C$ (dB), transmit antenna gain $G_{TX}$ (dBi), propagation attenuation/loss $L_P$ (dB), receive antenna gain $G_{RX}$ (dBi) as well as the Shannon's theorem considerations of capacity $C$ (b/s) being a function of external interference power $I$ (W), channel bandwidth $B$ (Hz) and margins such as the minimum required signal to interference and noise ratio:

$$C = B \log_2(1 + SINR), \quad (2)$$

where the signal to interference and noise ratio ($SINR$) is

$$SINR = S / (I + N). \quad (3)$$

Assuming the noise to be purely thermal noise, its power is

$$N = kTB, \quad (4)$$

with Boltzmann's constant $k$=1.38×10$^{-23}$ (J/K), temperature $T$ (K), and system bandwidth $B$ (Hz), which is considered to be the same as the channel. It is worth mentioning that the selected frequency of operation plays a critical role, as it defines the physical size of the antennas and is closely linked to the regulations. The transmit power is usually restricted by regulations [2]. [2] also calculated the maximum range with the maximum transmit-power limits which are permitted by the South African national regulations. As the 600 MHz TV band has 20 dB lower propagation loss in free space, the 12 dB higher-power 5.8 GHz Wi-Fi has only 4 dB of actual distance advantage. Also, the 5.8 GHz Wi-Fi can tolerate about 8 times less propagation loss than communications in the TV band.

Power consumption is another important aspect. The base stations are not heavily loaded for most of the day and thus do not need to transmit much data during light load periods. However, they have to transmit synchronisation signals at full power all the time. The overall energy consumption for base stations is thus affected by the minimum transmit power needed to achieve sufficient coverage.

Few of the variables can be controlled easily, e.g., the cable losses can be minimized by placing the power amplifier close to the antenna port and using low-loss cables. The propagation losses are defined by the environment. According to Shannon's theorem, the system bandwidth is effectively related to both the channel capacity and thermal noise at the receiver and is thus linked to the required throughput. The throughput is determined by the bit error ratio and modulation rate, where these are tightly coupled with the minimum required signal to noise and interference ratio (SINR), which makes it difficult to realize the high throughput without both a high order modulation and high SINR.

On the other hand, depending on the antenna's gain, the transmit and receive antennas together typically define up to 60 to 80 dB of the link balance, often the largest controllable portion of the link equation. The antenna gain pattern providing the ability to focus on the desired signal and the ability to form nulls and thus reject undesired signals are subject to antenna design. The direction of the maximum gain and nulls and overall shape of the antenna's radiation pattern may be controlled. The following sections review some recent advancements in the related design techniques.

## III. Brief Overview of Advanced Antenna Designs and Techniques

**Analog versus digital beamforming**: Beamforming, as discussed by authors in [3], helps to achieve a narrow beam with high gain, while also helping to form nulls and reject interference. The narrow beam helps to focus the energy thus also reduce power consumption. Rumyancev and Korotkov [3] discussed three beamforming techniques, namely digital, analog, and hybrid beamforming. Digital beamforming consists of a digital signal processing (DSP) based beamformer, $N$ RF chains, and $N$ antenna elements. The DSP affords high flexibility and full control but at expense of higher power consumption and a limited dynamic range. Analog beamforming typically consists of an RF chain, $N$ antenna elements, and an analog beamformer. An analog beamformer (except for aerial analog beamformers) consists of $N$ modules and each module contains a phase shifter and attenuator.

The phase shifter and attenuator discussed in [3] are used to control the phase and amplitude of the transmitted signal of each antenna element. Analog beamforming is cheaper than digital beamforming, can handle a higher dynamic range, and more energy effective due to the low power consumption of the phase shifters and attenuators. However, because analog beamforming only consists of one RF chain, this suggests that only one beam can be transmitted/received at a time. Hybrid beamforming is a beamforming technique that combines digital and analog beamforming and can combine some of the advantages of both methods.

**Low-resolution ADCs**: Hybrid beamforming was also discussed by authors in [4] and [5]. Authors in [4] stated that the hybrid and digital beamforming techniques with low-resolution analog to digital converters (ADCs) reduce the power consumption in 5G antennas. Evaluation results in [4] further showed that low-resolution ADC beamforming systems may be more energy-efficient than hybrid beamforming systems. Whereas, authors in [5] proposed a low-complexity hybrid beamforming design for multi-antenna communication systems. The authors stated that the hybrid beamformer consists of a constant modulus analog beamformer in the RF part of the system and a baseband digital beamformer.

**MIMO, filtering**: The payback for being able to form a narrow antenna beam is in the need to use multiple antennas, like array antennas, with a high number of antenna elements, which translates into the proportionally increased size of the antenna. Also, both tracking a user with a narrow beam and usage of the MIMO [6] techniques require digital signal processing, which together with the having to send additional channel information (to allow adopting to the channel), cancels some of the power consumption benefits brought by the narrow beams. MIMO techniques help to use spatial diversity and push the throughput up, in proportion to the number of antennas. The current research trends around hybrid beamforming methods are power-hungry digital beamforming with slightly more limited in functionality [7]. Some research looks to integrate hybrid beamforming with massive MIMO [8]. Considering the need to support multiple users, antennas are also used as both spatial and frequency filters [9] and they may also assist frequency selectivity desired in cognitive radio systems. These systems are allowed to operate in a very wide frequency range, such as television white spaces (TVWS) [10].

The latest generations, e.g. 5G cellular and Wi-Fi start to use multiple antennas at millimeter waves [11] (with the millimeter waves usually defined for the frequencies 30 GHz to 300 GHz). The study in [12] shows that there are attempts to try using full-duplex techniques in millimeter-wave communications.

**Beamformer for mm-wave**: [26] proposed large-scale antenna systems with hybrid beamforming structures in the mm-Wave band. The study in [26] investigated optimal designs of hybrid beamforming structures by focusing on a (the number of transceivers) by (the number of active antennas per transceiver) hybrid beamforming structure. Studies in [26] also analysed the energy and spectrum efficiency of the beamforming structure; including their relationship at the green point on the energy efficiency-spectrum efficiency curve. The green point is the point with the highest energy efficiency. Also analysed was the impact on the energy efficiency performance at a given spectrum efficiency value, and the impact on the green point energy efficiency. A reference signal design for the hybrid beamform structure was also presented by authors in [26]. The beamform structure proves to achieve better channel estimation performance than the method solely based on analog beamforming.

Studies in [27] proposed a delay-aware scheme that has high energy efficiency. This scheme is utilized in resource management and energy conservation in the fifth-generation (5G) radio network architecture. Authors in [27] based their scheme on the outcome from comparing the delays of a radio's access points (AP) when a delay-sensitive transmission is required. This scheme results in the provision of an optimal TVWS through the use of a spectrum broker. The use of the spectrum broker is to manage the consumption of energy in a 5G communication network which takes into account, the delay-aware scheme and the evaluation of the queuing delays that are being compared.

**Adding NOMA**: Several studies have proposed the combination of the above-mentioned techniques with non-orthogonal multiple access (NOMA) [13], [14], and [15]. Scaling up the number of users, improving user fairness and, enhancing the spectral efficiency in wireless networks can be made possible by non-orthogonal multiple access (NOMA) [13]. NOMA achieves this by allowing more than one user within the network to share one wireless resource. Authors in [13] further stated that it is possible to combine NOMA with many existing and emerging wireless technologies like multiple-input multiple-output (MIMO), massive MIMO, cognitive and cooperative communications, physical layer security, etc. Vaezi et al. further stated that it is advantageous to combine NOMA with the above-mentioned technologies in wireless network communications. Some of the advantages include an increase in spectral efficiency, scalability, efficiency, and greenness of future communications networks.

**Hybrid beamforming with NOMA**: Studies in [14] proposed a low-complexity and energy-efficient sub-connected structure (SCS) hybrid beamforming (HBF) The studies also proposed Fully-connected structure (FCS) HBF for non-orthogonal multiple access (NOMA) systems that operate under the line of sight (LOS) and non-line of sight (NLOS) millimeter-wave environments. Authors in [14] formulated a mathematical model that maximizes the sum-rate and energy efficiency of the two HBR-NOMA configurations to further substantiate their simulation results. Furthermore, Badrudeen et al. [14] respectively used successive interference cancellation-zero forcing (SIC-ZF) and phased-zero forcing (P-ZF) schemes to maximize both the sum rates and energy efficiency of the SCS-HBF-NOMA and FCS-HBF-NOMA systems. Authors in [14] further stated that the introduction of a 3-bit quantization is can optimize the sum-rate for energy-efficient finite resolution HBF-NOMA systems. They also advised that the number of users per cluster should be delicately selected for the maximum performance of HBF-NOMA system.

**Physical layer security**: Furthermore, trust and security are becoming major considerations in wireless systems, with research [18] and [19] starting to pay extra attention to the physical layer transmissions. Authors in [18] stated that transmit beamforming and artificial noise-based methods have been utilized to achieve physical-layer (PHY) security but stated that the above-mentioned approaches usually fail to provide the required secure performance. This can occur if the channels of a legitimate user (LU) and eavesdropper (Eve) are highly correlated as this usually occurs in the case where LU and Eve are close. The study in [18] aims at addressing the PHY security challenges for proximal LU and Eve in millimeter-wave transmissions of which the authors proposed a novel frequency diverse array (FDA) beamforming approach. The FDA beamforming approach deliberately introduces a couple of frequency offsets across array antennas which decouples the highly correlated channels of LU and Eve. The FDA beamforming can degrade Eve's reception by exploiting the decoupling capability and this eventually enhances the PHY security. Furthermore, authors in [18] aimed to maximize the secrecy rate by jointly optimizing the frequency offsets and the transmit beamformer and this was achieved by leveraging on FDA beamforming.

Authors in [19] stated that physical layer security protocols are derived from the intrinsic channel characteristics of the communication media for the key generation, randomness extraction, and sharing. The above-mentioned protocols seek to exhibit low computational complexity and energy efficiency. They are also able to maintain unconditionally secure communications. Bottarelli et al. in [19] presented a comprehensive quantization scheme for physical layer security focusing more on key performance metrics and intrinsic channel characteristics.

**Dielectric antennas for size reduction**: Antennas used in 4G, 5G, and beyond have improved directivity and can provide better coverage and connection speed to their users. However, the current designs of the 5G antenna are quite bulky and take a considerable amount of space, and often visually unappealing.

There is likely a significant potential in exploring dielectric antennas to reduce their size [20] and [21] and maybe even changing the very way a cellular system operates, i.e., taking advantage of overlapping antenna beams.

The studies [22] focused on providing a strong beamforming signal towards desired users and at the same time, reducing the effects of interference on the signal. The proposed design will require an antenna that can transmit equal beamforming signals in all directions. The antenna will also need to be omnidirectional with an enhanced gain to ensure accurate beamforming. [22] defined beamforming as the ability achieved by SAs to increase the range and capacity of a transmitted signal and the resultant signal has an improved SINR. In an antenna array, the system which is usually used to derive beamforming is the beamformer. The beamformer receives the desired signal, which is beamed from a specific direction and attenuates or nulls signals originating from other directions. [22] proposed that the gain of the antenna can be enhanced by introducing a constant to the adaptive RLS algorithm. The studies focused on providing a strong beamforming signal towards desired users and at the same time, reducing the effects of interference on the signal.

**Index modulation applied to a reconfigurable software-defined metasurface**: Index modulation (IM) techniques shows a promise in improving the energy and spectral efficiencies of high data-rate 5G wireless communications. This paper introduces a reconfigurable software-defined metasurface allowing implementation index modulation techniques in 5G transceivers. The work defines the implementation of spatial and subcarrier index modulations, including beam steering and phase modulation capabilities, and presents a metasurface aperture that can modulate and multiplex communications signals over the spectral, spatial, and temporal domains using space-time coding of unit elements.

**Having more antennas imply that less energy is required for transmission:** Studies in [24] also show that densification may allow using less energy for transmissions. The 5G network focuses on energy efficiency through the implementation of calibrating the efficiency mechanisms of all networking antennas.

**Sample of microstrip antenna design for 5G**: Authors in [25] presented a design of efficient microstrip linear antenna array for 5G communications systems. The antenna is made up of 16 elements having rectangular patches that are arranged in a linear configuration. The antenna operates at a frequency of 28 GHz. Saada et al. [25] further described their design stating that the single element comprises a gap-coupled feeder and the antenna is designed on low-loss Teflon-based RT/duroid 5880 substrates. The substrate also has a dielectric constant of 2.2 and the thickness of the substrate is 0.381 mm. The design in [25] employs a defected ground structure (DGS) which appears in the form of rectangular slots to reduce the effects of mutual coupling between adjacent elements. CST microwave studio was used to simulate the antenna and the results of the work in [25] showed that the 16-element array has a 10-dB bandwidth that exceeds a frequency of 2 GHz. The results also showed a maximum gain of 17.4 dBi at 28.4 GHz. These results show that the design satisfies the requirements of 5G communications systems; some of these requirements are high radiation efficiency, high gain, and sufficient bandwidth.

**Adaptive beamforming**: In recent times, adaptive beamforming has been having noticeable industrial significance as in the utilization of modern wireless communication systems. Studies in [28] provided an overview of the application of adaptive beamforming in cellular systems. This study further stated that adaptive beamforming is a breakthrough in emerging technologies like the long-range evolution (LTE) taking into cognizance the Nuevo 5G technology. Further literature in [28] discussed the relevance of massive and adaptive beamforming in 5G stating that 5G can accommodate an ever-increasing network service including the Internet of Things (IoT) and mobile broadband.

**Non-coherence SIMO**: Studies in [29] presented a new framework that utilized a noncoherent and non-orthogonal massive single-input multiple-output (SIMO). This framework deploys a large number of antennas which creates high spatial diversity which enables ultra-reliable communications. Noncoherent and non-orthogonal multiple access techniques on the other hand are applied to significantly reduce the effects of latency at the physical and data link layers. To elaborate the important design principles of their framework, Chen et al. [29] took into consideration a two-user IIoT system. In this system, two controlled nodes (CNs) send their signal to a managing node (MN) and this transmission is carried out using a shared time-frequency resource block. The MN uses the noncoherent maximum likelihood detector to get back the transmitted symbols of both CNs from the received sum signal. Simulation results of the study [29] showed that their design has a smaller error probability when compared to other designs.

**IoT-specific designs**: There are numerous antenna designs for IoT, e.g. [16] proposed a circularly polarized loop-type ground radiation antenna that makes use of a ground mode tuning (GMT) structure. On the other hand, a circularly polarized loop-type antenna discussed in [16] is designed to stimulate two orthogonal modes that are of equal magnitude on the ground plane. Zahid et al. [16] further stated that the GMT structure comprises an inductor and a metallic strip that has been installed at the edge of the ground plane. The reason for this is to get a 900 phase shift between the two ground modes. The antenna proposed in [16] produces “left-hand” circularly polarized waves in the  direction and right-hand circularly polarized waves in the  direction. Simulation results from the studies in [16] showed that a measured -6dB bandwidth of the circularly polarized antenna was 150 MHz and the axial ratio bandwidth which was referenced at 3dB was 130 MHz and the above result demonstrated a coverage of 2.4-2.48 GHz of the frequency band.

A 2.4 GHz directional pattern-reconfigurable slot antenna was presented in [17]. It stated that the slot antenna can provide three evenly-separated directional patterns and an omnidirectional pattern. It further stated that the presented antenna is suitable for the integration in IoT base solutions, with the antenna able to increase the communication range and reduce packet collisions.

**Non-coherent detection in SIMO for IoT**: An energy-based modulation constellation design framework for noncoherent detection in massive single-input multiple-output (SIMO) systems was developed by authors in [30]. This design is aimed at facilitating an ultra-reliable low-latency wireless communication essential for an Industrial IoT. The authors further assumed that a single antenna transmitter is linked to a receiver module that is made up of a large number of antennas passing through a Rayleigh fading channel and the receiver, in turn, decodes the transmitted information after each symbol is terminated. Authors in [30] proposed a fast noncoherent decoding algorithm of which a closed-form expression of its symbol error probability (SEP) is determined for a SIMO system with non-negative PAM modulation. The system energy efficiency was then enhanced by Gao et al.in [30]. The enhancement was achieved when the optimal PAM constellation that reduces the exact SEP was derived. The authors in [30] further derived the closed-form upper and lower bounds related to the optimal SEP. These derived bounds provide a basis for the unique expression for coding the gain of the most important term of the SEP. The coding plays an important role in optimizing the massive SIMO system.

**Multi-band MIMO for IoT**: Similarly, authors in [31] presented a novel compact single-substrate planar multiband five-element multiple-input multiple-output (MIMO) antenna system. The antenna system derived in [31] is required for an IoT environment. The design comprises a two-element folded meandered MIMO antenna which is aimed at providing coverage for long-term evolution (LTE) frequency bands below 1 GHz. This coverage also includes radio frequency identification (RFID) bands which are between 2.4 GHz and 5.8 GHz. The design also has two-element compact MIMO antennas that operate at frequencies that range between the following bands: 754-971 MHz, 1.65-1.83 GHz, 2.-3.66 GHz, and 5.1-5.6 GHz. Jha et al.[31] further stated that the proposed antenna elements are superimposed with a wideband sensing antenna. The sensing antenna is required for spectrum sensing between frequency ranges of 0.668-1.94 GHz and 3-4.6 GHz. The sensing antenna also serves as the ground plane utilized by MIMO elements in a cognitive radio environment.

**Hybrid beamforming-based NOMA analysis**: Similarly, the authors in [32] analyzed the effect of beam misalignment on the rate performance of the downlink hybrid beamforming-based non-orthogonal multiple access (HB-NOMA) systems. Almasi et al. [32] initially introduced an HB-NOMA framework in the context of multiuser millimeter-wave communications and then formulated a sum-rate maximization problem for the framework. Authors in [32] finally introduced an algorithm to design digital and analog precoders and power allocation. The entire process brings about the derivation of a lower bound for the obtainable rate of a perfectly aligned LOS channel. Analysis in [32] show that a large misalignment can degrade the sum-rate remarkably.

Studies in [32] proposed a circularly polarized loop-type ground radiation antenna that makes use of a ground mode tuning (GMT) structure. This study is aimed at developing IoT devices. The circularly polarized loop-type antenna is designed to stimulate two orthogonal modes that are of equal magnitude on the ground plane. Zahid et al. [32] further stated that the GMT structure comprises an inductor and a metallic strip that has been installed at the edge of the ground plane. The reason for this is to get a 900 phase shift between the two ground modes. The antenna proposed in [32] produces "left-hand" circularly polarized waves in the direction and right-hand circularly polarized waves in the direction. Simulation results from the studies in [32] showed that a measured -6dB bandwidth of the circularly polarized antenna was 150MHz and the axial ratio bandwidth which was referenced at 3dB was 130 MHz and the above result demonstrated a coverage of 2.4-2.48 GHz of the frequency band.

**Antenna for IoT in close-to-metal applications**: Koga et al. in [33] presented a compact antenna for IoT applications operable even close to metal surfaces. The compact antenna is made up of a double folded loop (DFL) antenna which can operate the frequency band of 2.4 GHz. There are connection terminals at the quarter wavelength that come from the feed point of a DFL antenna. The connection terminals of the DFL antenna are connected between the inner and outer loop of the antenna. A dielectric substrate that passes through holes bends the DFL antenna; this process is used to create the compact antenna. Authors in [33] stated that the compact antenna can operate even when metal is close to the antenna irrespective of its position. They further stated that the radiation efficiency of a DFL antenna when compared to the half-wavelength dipole antenna close to metal, exceeds 6 dB in signal strength.

**Directional pattern-reconfigurable slot antenna**: A directional pattern-reconfigurable slot antenna was presented in [34]. The presented antenna operates at a frequency of 2.4 GHz. Authors in [34] stated that the slot antenna can provide three evenly-separated directional patterns an omnidirectional pattern. They further stated that the presented antenna is suitable for the integration in IoT Base solutions; this property makes the antenna able to increase the communication range and reduce packet collisions. These studies in literature create a platform for the proposed antenna design for 5G and beyond.

## IV. Discussions

In the battle between analog and digital beamforming, the combination of the two is emerging as the likely winner. More research into combining inexpensive low-resolution ADC techniques seem to offer additional benefits.

Reconfigurable antennas able to change both the direction and frequency band of operation, including acting as filters, are continuing to rise in several applications. At the same time, reconfigurable reflective surfaces seem to gain unworthy attention as their practical usage will likely require controlling multiple elements and hence substantial power.

Most of today's networks use orthogonal multiple access (OMA). NOMA allows some degree of multiple access interference at receivers and promises 5-9 times improvements for the number of users and up to 100% more efficiency [35]. The work on antennas supporting non-orthogonal multiple access (NOMA) is on the rise.

Mm-wave is receiving significant attention and, due to the size and accuracy constraints, seems to be a separate area of research. Antennas in lower bands receive attention in terms of size reduction.

Physical layer security offers an additional layer of protection and may be considered a viable addition to 6G.

Much of the work is being devoted to IoT applications and specialized antennas are likely to continue being a trendy topic for many years to come.

## V. Summary

The paper considered several trends related to antenna design for communication, including analogy, digital and hybrid beamforming; reconfigurable antennas; antennas supporting NOMA; physical layer security based on using antennas; and IoT-specific antennas. Reduction in the power consumption and size, increase in physical security level, increase in performance through using NOMA and support for mm-wave and IoT applications seem to be the key themes in today's antenna design challenges.

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