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State-of-the-Art Antenna Technology for Cloud Radio Access Networks (C-RANs)

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Abstract

The cloud radio access network (C-RAN) is one of the most efficient, low-cost, and energy-efficient radio access techniques proposed as a potential candidate for the implementation of next-generation (NGN) mobile base stations (BSs). A high-performance C-RAN requires an exceptional broadband radio frequency (RF) front end that cannot be guaranteed without remarkable antenna elements. In response, we present state-of-the-art antenna elements that are potential candidates for the implementation of the C-RAN’s RF front end. We present an overview of C-RAN technology and different types of planar antennas operating at the future proposed fifth-generation (5G) bands that may include the following: (i) ultra-wide band (UWB) (3–12 GHz), (ii) 28/38 GHz, and (iii) 60-GHz radio. Further, we propose different planar antennas suitable for the implementation of C-RAN systems. We design, simulate, and optimize the proposed antennas according to the desired specifications covering the required frequency bands. The key design parameters are calculated, analyzed, and discussed. In our research work, the proposed antennas are lightweight, low-cost, and easy to integrate with other microwave and millimeter-wave (MMW) circuits. We also consider different implementation strategies that can be helpful in the execution of large-scale multiple-input multiple-output (MIMO) networks.

Keywords: 5G antennas, 28/38 GHz antennas, 60 GHz radio, cloud computing, green RAN
plane etched oppositely onto the dielectric substrate of the printed circuit boards (PCBs). In some configurations, the ground plane may be coplanar with the radiator. The radiators can also be fed by a microstrip line or coaxial cable [9].

Numerous microstrip UWB antenna designs have been proposed [10–15]. For instance, a patch antenna has been designed as a rectangular radiator with two steps, a single slot on the patch, and a partial ground plane etched on the opposite side of the dielectric substrate. It provides a bandwidth of 3.2–12 GHz and a quasi-omni-directional radiation pattern [10]. Moreover, a clover-shaped microstrip patch antenna has been designed with a partial ground plane and a coaxial probe feed. The measured bandwidth of the antenna is 8.25 GHz with a gain of 3.20–4.00 dBi. In addition, it provides a stable radiation pattern over the entire operational bandwidth [11]. Another design is a printed circular disc monopole antenna fed by a microstrip line. The matching impedance bandwidth is from 2.78 to 9.78 GHz with an omnidirectional radiation pattern, and it is suitable for integration with PCBs [12]. In addition, several elliptical shaped-based antennas have been designed. For example, three printed antennas have been designed starting from the elliptical shape, namely the elliptical patch antenna, its crescent-shaped variant, and the semielliptical patch [13].

Another type of printed antenna is the UWB-printed antenna fed by a coplanar waveguide (CPW). For example, one trapezoidal design and its modified form cover the entire UWB band (3.1–10.6 GHz) and have a notch for the IEEE 802.11a frequency band (5.15–5.825 GHz). The frequency notch function is obtained by inserting different slot shapes into the antenna. The notch frequency can be adjusted by varying the slot’s length. The antennas show good radiation patterns as well as good gain flatness except in the IEEE 802.11a frequency band [14]. Another kind of radiating element considered suitable for phased arrays is the class of Vivaldi antennas, also known as quasi-end-fire nonresonant radiator or tapered slot antennas (TSAs) [15]. However, the element is normally fabricated by cutting a notch in a metal plate and backed by a quarter-wave cavity behind the feed point to improve its forward gain. A few examples of designed and fabricated UWB monopole and directional antennas are shown in Figure 2.

The next generation of ongoing wireless revolution with the growing demand of wireless facilities in mobiles, the millimeter-wave (MMW) frequency band appears to be a strong candidate for future radio access technologies. In addition to UWB, MMW technology (30–300 GHz) allows the developing of miniaturized and compact antenna sensors to be used in the RF front end, thus reducing the overall size of the system [16–19]. Compared to lower frequency signals, MMW signals can propagate over shorter distances due to their larger attenuation. Therefore, the development of MMW antennas with high gain performance for wireless access networks has attracted the interest of many researchers. In order to improve the spectral efficiency and exploit the benefits of spatial multiplexing, MMW antennas are expected to be used for large-scale MIMO (i.e., massive MIMO) systems. Therefore, it is important that improving a single parameter of an individual antenna will significantly improve the overall performance of a MIMO system, since each branch of the MIMO system will find at least one of them. The following are some well-known architectures and packaging techniques for improving the performance of MMW radios in terms of bandwidth, gain, and directivity.
Figure 2. Different types of UWB antennas (a) conical antennas, (b) planar monopoles, (c) planar monopoles with band stop filters, (d) Vivaldi antennas and (e) spiral antennas [9].
Vettikalladi et al. [20] explained the significance of the addition of a superstrate on an aperture-coupled antenna at MMW frequencies. It can be seen that with the addition of a superstrate, the bandwidth is noted to be \( BW = 58.7\text{–}62.7 \text{ GHz} \) (i.e., 6.7\%) with a maximum gain of 14.9 dBi. A new dual-polarized horn antenna fed by a microstrip patch operating in the Ku band was proposed in Ref. [21]. The patch and horn were designed separately and then assembled together. The horn antenna had a reflection coefficient of less than −10 dB and a port isolation greater than 30 dB over 14.6–15.2 GHz and a gain of 12.34 dBi and 10-dB beamwidths of 87° and 88° at 14.9 GHz. The final structure had a gain of 12.34 dBi. The authors in Ref. [22] presented a wideband transition from CPW to horn antenna (CPWHB) based on the slot-coupled stacked-patch antenna technique, while those in Ref. [23] presented a wideband high-efficiency 60-GHz aperture superstrate antenna. It is found by measurement that by using a superstrate above the aperture antenna, we can improve the gain up to 13.1 dBi with a wide bandwidth of 15\% and an estimated efficiency of 79\%. This good result is higher than that of a classical 2 × 2 array, on an RT Duroid substrate, with a gain of 12 dBi and an efficiency of 60\%. In Ref. [24], a new concept of a directive planar waveguide (WG) antenna array for the next generation of point-to-point E-band communication was presented. The proposed antenna consisted of two major parts: first, the array of Gaussian horn radiating elements, and second, the mixed feeding rectangular WG network. A high-gain slot-coupled circular patch antenna with a surface-mounted conical horn for MMW applications at 31 GHz was proposed in Ref. [25]. The design adopted microstrip/conical horn hybrid technology for a 6-dB enhancement over the conventional circular patch antenna. A novel micromachining approach for realizing 60-GHz foam aperture-coupled antennas was presented in Ref. [26]. The foam is indeed an ideal antenna substrate, as its electrical properties are close to those of the air. High-gain compact stacked multilayered Yagi designs were proposed and demonstrated in the V-band in Ref. [27]. This novel design showed for the first time an antenna array of Yagi elements in an MMW-stacked structure. The measured Yagi antenna attained an 11-dBi gain over a 4.2% bandwidth with a size of 6.5 × 6.5 × 3.4 mm². Efficient and high-gain aperture-coupled patch antenna arrays with superstrates at 60 GHz were studied and presented in Ref. [28]. The maximum measured gain of a 2 × 2 superstrate antenna array was 16 dBi with an efficiency of 63\%, 4 dB higher than that of a classical 2 × 2 array at 60 GHz.

In order to meet recent requirements of designing large-scale MIMO wireless communication systems, conformal antenna technology enables the development of compact antenna arrays [29, 30]. Moreover, to create high-capacity MMW-MIMO systems, conformal antenna structures can be integrated with modern beam-switching technology, resulting in a data rate of several gigabytes. In cases in which the line-of-sight link is blocked, beam-switching technology allows the dynamic control of the antenna’s main beam in order to find the received signal with the highest power. Several antenna arrays with beam-steering and beam-switching capabilities have been developed in Refs. [16, 31, 32]. Recently, a beam-switching conformal antenna array system operating at the 60-GHz mm-wave frequency band offering 1.5-GHz bandwidth was reported in Ref. [33]. However, the size of the developed switched beam array system was 31 × 46.4 mm² rounded around a cylinder with a radius of 25 mm. Second, the simulations resulted in a gain value of 16.6 dBi.
3. Design of planar antennas for C-RANs

Among various devices, C-RANs have a good number of highly efficient antennas integrated with their RF front ends. In order to make these antennas more adaptable and fulfill the telecom vendors’ requirements, they are expected to operate in one of the future proposed 5G bands: (i) UWB (3–12 GHz), (ii) 28/38 GHz, or (iii) 57–64 GHz suggested for system design and implementation. In this work, we will design, model, and optimize state-of-the-art antenna elements operating over the proposed frequency bands that can be considered suitable candidates for the implementation of a C-RAN’s RF front end. The proposed antennas are designed to be efficient, moderate in size, low-profile (i.e., can be implemented using conventional fabrication processes), and cost-effective. In addition, the designed antennas’ key parameters such as reflection coefficient, gain, radiation pattern, dispersion effect, radiation efficiency, and pattern stability are calculated and optimized to achieve the C-RAN’s high data rate requirements. The following are the design details of our proposed antenna elements suggested for the implementation of the C-RAN’s front end.

4. UWB antenna element

In this section, we present antipodal tapered slot antennas (ATSAs) with elliptical strips termination modified with elliptical-shaped edge corrugations. The proposed corrugated antenna uses elliptical slots loading to improve the gain by up to 1.9 dB over an operational bandwidth of 0.8–12 GHz. It also improves the front-to-back lobe ratio. The designed ATSA exhibits minimum distortion to ultra-short pulses of 50 ps covering the 3–12-GHz frequency band.

4.1. Antenna design

The antenna element shown in Figure 3(a) is a traveling wave ATSA developed on Rogers 5880 substrate having dielectric constant \( \varepsilon_r = 2.2 \) and thickness \( h = 1.574 \text{ mm} \). The size of each antenna is \( 160 \times 120 \text{ mm}^2 \).

The ATSA-EC contains strip conductors on both sides of the substrate. In order to have impedance matching over a bandwidth of more than 10:1, the tapered slot is designed by following the guidelines in Ref. [35]. The exponential taper \( C_g \) is used for the ground in order to achieve the broadband microstrip to parallel plate transition. The tapered curve \( C_g \) is defined as

\[
C_g = W_y - 1 + 0.1 W_y e^{\alpha \frac{w_x}{W_x}}
\]

where \( \alpha \) is the rate of transition for the exponential curve defined as follows:

\[
\alpha = \frac{1}{1.92 W_x} \ln \left( \frac{W_y + 0.1 W_f}{0.1 W_i} \right)
\]

where \( w_x \) is the \( x \)-directed length of the curve with \( w_y \) and \( w_f \) being the \( y \)-directed initial and final points, respectively. The variation of impedance bandwidth and radiation characteristics
against different geometrical parameters of proposed ATSAs are analyzed by full-wave simulation software CST Microwave Studio [36]. Table 1 presents the geometry of the ATSA, which results in 182% impedance bandwidth with the required radiation performance.

![Figure 3](image)

**Figure 3.** Layout diagram of (a) antipodal tapered slot antenna with elliptical-shaped edge corrugation (ATSA-EC) and (b) photograph of fabricated antenna [34].

| $R_{s1}$ | $R_{s2}$ | $D_w$ | $w_x$ | $w_y$ | $w_z$ | $w_1$ |
|---------|---------|-------|-------|-------|-------|-------|
| 32.5    | 42.25   | 65    | 8     | 43.85 | 35    | 5.95  | 6.12  |

Table 1. Optimized geometrical dimensions (mm) of ATSA.

In order to improve the radiation characteristics, elliptical edge corrugations are applied to the ATSA, as shown in Figure 3(a). At each edge of the antenna, unequal half-elliptical slots (UHESs) are loaded with the period $C_s = 17$ mm. The largest UHES having minor axis and major axis radii $R_{s1} = 15$ mm and $R_{s2} = 8$ mm, respectively, is placed at the center of the elliptical fin. Conversely, the major axis radii of the other UHESs are decreased linearly by the factor $C_r = 0.7$ having the constant ellipticity ratio $e_r = 0.533 = R_{s2}/R_{s1}$.

4.2. Results and discussion

The photograph of the fabricated ATSAs is shown in Figure 3(b). The measured return loss of the fabricated ATSA-EC is compared with the simulation results, as shown in Figure 4.
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