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Single-Layer Dual-Band Satellite-IoT Terminal Antennas with Increased Beamwidth

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Abstract
In this Vision, we present an idea for a low-profile cost-effective, dual-band antenna with a small frequency ratio and enhanced beamwidth, suitable for dual-band bidirectional IoT satellite networks. A broader antenna beamwidth increases the number of Low-Earth-Orbit satellite contacts and decreases the IoT system latency. The proposed patch antenna uses a slot to enable the dual band operation and a set of parasitic elements to modify the radiation pattern in both frequency bands. We present an example operating in L band to illustrate the potential of this idea. The enhanced HPBW is on average 140° over the two frequency bands and all angular planes, which is an improvement of 41° in comparison to the same antenna without parasitic elements.

Key terms
IoT; Satellite IoT; LEO Constellations; Broadbeam microstrip antennas

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1. Introduction

The satellite Internet of Things (IoT) is witnessing a rapid expansion, with both traditional satellite providers and new companies offering or announcing services for global coverage and connectivity in world's most remote areas [1]. Market studies estimate the number of Satellite-IoT connections will surpass 10 million by 2025, triggering a demand for efficient low-power Satellite-IoT terminals [1], [2]. Although it was estimated that the satellites served only 5% of total IoT/machine-to-machine (M2M) connections in 2016 [3], their unique value proposition is that they are the only platform offering a truly global coverage. Since the IoT/M2M applications addressable by satellite are primarily narrowband, Mobile Satellite Service (mostly in L band) dominate with a 93% share of all units (almost 3 million devices in 2015) [4].

The size of the Satellite-IoT terminals will often be dictated by the antenna, inferring that new cost-efficient antenna designs are required. Beside the low complexity and cost, a good antenna performance at low elevation angles is essential for IoT applications for the purpose of increasing the number of satellite contacts and reducing the overall system latency. In addition, to enable a bi-directional, full-duplex communication, antennas also need to cover two frequency bands, often with a small frequency ratio (FR) [5]. Existing L-band, circularly polarized (CP), dual-band solutions with a FR in the range of 1.05 include high-profile helix antennas [6] or complex multi-layer structures, such as stacked-patch [7], or ring-patch structures [8].

This paper presents simple methods of obtaining a cost-efficient low-profile CP dual-band IoT terminal antenna and improving its beamwidth – a key requirement for Satellite-IoT applications. Emphasis is placed on simplicity and antenna profile, while improving the radiation characteristics in both frequency bands. A dual band design with a small FR is obtained with a simple modification of a conventional CP single-fed patch antenna in Section II. The radiation beamwidth in both bands is improved in Section III by adding a set of co-planar parasitic elements, and the design tradeoffs are discussed in Section IV.

2. Dual Band CP element

In conventional single-fed patch antennas, circular polarization is generated by a small frequency offset between two orthogonal degenerate modes of the patch resonator, using various geometric asymmetries (trimmed corners, diagonal slots, etc.). When carefully tuned, the broadside axial ratio (AR) is minimal (close to 0 dB) in a single frequency point between the mode resonances, with the antenna well matched in a bandwidth of several % around this frequency. To provide impedance matching at two closely separated frequencies, the geometric asymmetry can be further increased until the antenna resonances are separated to cover the two desired bands. Although this simple modification compromises the antenna's AR, it enables impedance matching with an arbitrarily small frequency ratio and zero increase in complexity. Other dual-band antenna geometries with closely spaced frequencies either require a multi-layer structure [8] or have a limited achievable frequency ratio [9]. It is important to note that this approach is applicable only to single-fed patch antennas.

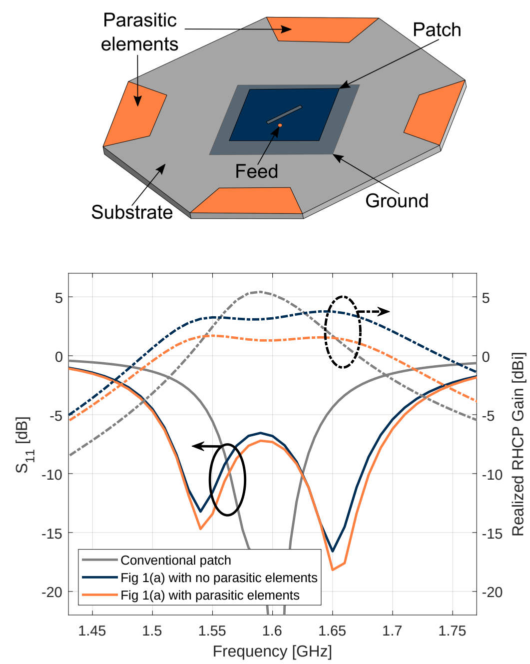

Figure 1: (a) Proposed antenna geometry: (b) Simulated (solid) S11 parameter and (dashed) broadside realized RHCP gain of (gray) a conventional patch antenna (not shown here), and the proposed antenna: (blue) without and (orange) with parasitic elements.

To demonstrate the principle, a CP patch antenna is designed on a low-permittivity substrate ($\varepsilon_r = 3.66$, $\tan\delta = 0.003$, $h = 3$ mm) and tuned to the mobile-satellite frequencies of 1.54 and 1.64 GHz. The antenna geometry, its S_{11} parameter and broadside CP realized gain are shown in Figure 1. The choice of substrate permittivity and thickness will affect the impedance-matching bandwidth per band, maximum gain, and pattern beamwidth, as with conventional patch antennas. The results are obtained using ANSYS Electronics Desktop [10].

The resulting antenna exhibits a dominant CP component and a realized gain of several dBi in broadside at both frequency bands. In spite of a high AR of ∼10-18dB, the antenna exhibits an excellent compromise of a wide RHCP gain and low complexity, and cost. The higher AR values do not pose a problem for low-bandwidth Satellite-IoT applications, as the antennas on the satellite side typically radiate pure CP. Therefore, the link does not experience large signal drops due to polarization losses, that are typically 1.5 dB. When compared to a conventional linearly polarized (LP) patch antenna, the proposed antenna shows at least a 1-dB gain improvement at low-elevation angles, despite the high AR.

The antenna inherently exhibits broadside radiation and stable radiation patterns in both bands. The following section describes another modification that improves the antenna beamwidth at both frequency bands.

3. Beamwidth improvement

An approach to increase the antenna beamwidth is to improve the radiation in lateral directions. Demonstrated methods include ground-plane reduction [11] or adding parasitic elements such as other patches [12], rings [13], [14], annular parasitic strips [15], higher-order-mode rings [16], or other complex structures [17]. In [15], beamwidth is improved in two separate frequency bands by using two sets of parasitic strips, each set being dominantly excited at the corresponding frequency.

The radiation pattern of the proposed antenna must be improved in both frequency bands and all azimuth angles. For a CP antenna, the main difficulty lies in the excitation of both orthogonal components of the radiated field at low elevation angles. This can be achieved by adding parasitic elements, but only if all the elements are excited at both frequencies. For the closely spaced frequencies of the antenna from Section II, it is shown here that a single set of modified elements is sufficient for CP pattern control in both bands.

Coplanar elements with a trapezoidal shape are added on the top layer of the patch substrate. The elements are placed with a 45° angular offset with respect to the two degenerate modes of the patch element. This arrangement allows each of the patch modes to efficiently couple to all parasitic elements, similarly as a single feeding pin excites both modes in the patch itself. In addition, this coupling slightly improves the antenna matching at both frequency bands, as seen in Figure 1b.

The pattern of the parasitic elements increases the antenna radiation at lower elevations, compared to the standalone dual-band patch antenna. The antenna beamwidth is determined by the shape and size of the elements, as well as their distance from the patch, which are optimized to maintain beamwidth stability at two frequencies, necessary for an efficient two-way communication. As a rule of thumb, longer elements further away from the patch tend to generate conical radiation patterns, initially in the higher frequency band, significantly increasing the beamwidth. Any beamwidth larger than 160° is not practically useful, as the IoT terminals are usually not able to establish a link with the satellite at elevation angles lower than 10° above horizon. Therefore, a compromise between the total antenna dimensions, gain, and pattern improvement is established to keep the half-power beamwidth (HPBW) in the vicinity of 150°.

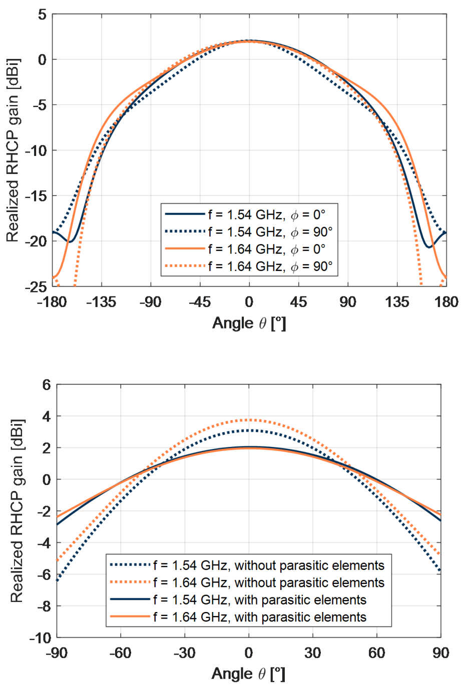

Figure 2: Radiation patterns of the (a) proposed antenna at two frequencies and angular cuts, and (b) comparison with the antenna without parasitic elements. Note the gain improvement of 1 – 2 dBi at angles 60°–75°.

Radiation patterns of the proposed antenna, both with and without the parasitic elements, are shown in Figure 2, and the HPBW for the two frequencies and angular planes is shown in Table 1. The beamwidth is enhanced significantly with the addition of parasitic elements. The average HPBW over all angular planes is 133° and 146° at 1.54 and 1.64 GHz, respectively. It is critical to carefully tune the two resonances created on the patch by the presence of the slot to achieve a stable pattern and beamwidth in both frequency bands. Adjusting the length and shape of the parasitic elements also helps to reduce the discrepancy between the two bands.

4. Discussion

In this Vision, we present a simple technique to design cost-efficient dual-band patch antennas with a small frequency ratio and a dominant CP sense, for modern Satellite-IoT networks. The slot of the conventional rectangular CP patch antenna is elongated to further separate the two orthogonal patch resonances and enable dual-band operation with zero increase in complexity. The AR of the proposed design deteriorates with the increase of frequency spacing of the two resonances. Therefore, this technique is only suitable for dual-band CP communication systems with a small FR between bands.

Frequency	1.54 GHz		1.64 GHz	
Angle φ	0°	90°	0°	90°
Without parasitic elements	99	97	99	96
With parasitic elements	148	160	128	148

Table 1: Antenna beamwidth (in degrees).

In addition, a set of four coplanar parasitic elements, placed around the patch antenna, significantly improves the antenna beamwidth at both frequency bands and all angular planes. The shape, size, and position of the parasitic elements is optimized to achieve a desired compromise between pattern stability and overall antenna dimensions. The presented example, with an average HPBW of 140° for the given antenna geometry, illustrates the capabilities of the proposed patch-antenna modification. The same principle can be applied to patch antennas having different substrate properties, further improving the beamwidth.

One of the main advantages of this principle, in addition to their broad beamwidth and dual-band operation, is its mechanical simplicity. However, antenna placement and its integration with the IoT terminal must be carefully addressed. A broader beamwidth and the lack of ground plane below the parasitic elements could potentially lead to the perturbation of the antenna nominal operation, depending on the antenna placement. To address this limitation in the future, parasitic elements with a ground plane could be used. Alternatively, parasitic elements can be placed above the plane of the patch. The latter approach could allow an integration of the elements with a custom antenna radome.

The proposed idea is presented as a response to a growing need for antennas with a wide beamwidth in the field of full-duplex dual-band IoT satellite communication. Beamwidth improvement of such antennas allows for a reduction of time between satellite contacts and consequently, an improvement of the IoT message latency. A low profile of the presented design makes it especially interesting in the Satellite-IoT domains where terminal aerodynamics are crucial, such as commercial fleet management for land transport (cars, vans), and tracking of drones.

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