Transparent Antennas for 5G Wireless Connectivity: Bridging Aesthetics and Performance

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***Abstract*—Transparent antennas integrate seamlessly with surfaces such as glass, offering aesthetic and functional benefits. However, there is a gap in the literature regarding their practical evaluation when integrated into an end-to-end 5G system. To bridge this gap, we demonstrate the performance of a transparent dipole antenna on glass compared to a conventional antenna in the C-band. We establish an end-to-end link in controlled 5G tests using OpenAirInterface5G as the gNB and a 5G Commercial Off-the-Shelf (COTS) User Equipment (UE). Physical layer metrics such as Received Signal Strength Indicator (RSSI) and Reference Signal Received Power (RSRP) as well as application-layer metrics such as uplink and downlink throughput demonstrate performance comparable to conventional antennas.**

I. INTRODUCTION

Achieving consistent network access for Internet of Things (IoT) devices in smart cities, or ensuring reliable communication between users and fixed 5G infrastructure, requires significant advances in antenna design. The growing deployment of IoT devices requires higher data rates and more ubiquitous networks, challenges that 5G technology is designed to address. Smart cities depend on increased communication density and speed between interconnected smart objects integrated into urban infrastructures. However, the high frequency bands used in 5G result in shorter transmission ranges and increased weather dependency, often creating network dead zones.

Transparent antennas, seamlessly integrated into windows, offer a promising solution to increase the density of access points and signal repeaters without compromising urban aesthetics. In addition, base station antennas can be concealed as part of building windows, allowing dense and high-performance 5G networks to blend into elegant urban architecture.

Despite their advantages, transparent antennas face challenges due to their low gain. Their transparent conductors, such as Indium-doped Tin Oxide (ITO), exhibit a trade-off between optical transparency and electrical conductivity, increasing losses and reducing antenna gain.

This demo highlights the potential of transparent conductive materials for invisible antennas on glass to support reliable 5G communications. Using a private 5G testbed with OpenAirInterface [1], we demonstrate their performance, focusing on both physical and application-layer metrics.

II. TRANSPARENT ANTENNA TECHNICAL DESCRIPTION

In our previous work, we have demonstrated an autonomous IoT system that integrates a single transparent antenna on a glass window [2], [3]. Using various Transparent Conducting Oxide (TCO) materials, including ITO and Gallium-doped Zinc Oxide (GZO), and advanced patterning methods such as lithography and inkjet printing, we developed a communication module operating at 2.4 GHz. This module supports Bluetooth Low Energy (BLE) and Wi-Fi for transmitting sensor data, including illumination, temperature, and photovoltaic energy levels. The prototype and its components are illustrated in Figure 1. Building on this foundation, in the current study we adapted ITO-based transparent antennas patterned by lithography for 5G FR1 Rx/Tx communication. These antennas achieved a minimum S_{11} reflection coefficient at 3.7 GHz and an impedance (Z_{11}) of 95 Ω [2], [3].

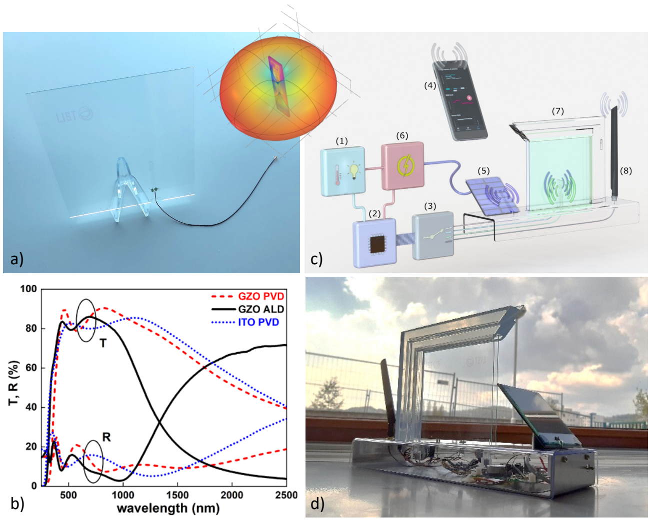

Figure 1. Our own autonomous IoT smart glass window prototype [2], [3]: (a) Isolated glass window with a patterned and connected transparent antenna made of TCO materials; (b) Optical transparency validation in transmittance and reflectance of the TCO thin films used to process transparent antennas (ITO, GZO); (c, d) Conceptual view and assembled autonomous IoT smart glass window prototype, respectively.

III. INITIAL RESULTS

We conducted indoor 5G trials in C-band TDD mode to compare the performance of the transparent antenna with a conventional antenna – 5G Omni Antenna AZ7795G – under similar RF conditions. Leveraging our licensed 5G frequency, we used an open-source Software-Defined Radio (SDR) implementation of the 5G Radio Access Network (RAN) protocol stack OpenAirInterface5G [1]. We established end-to-end connectivity between the Commercial Off-the-Shelf (COTS)

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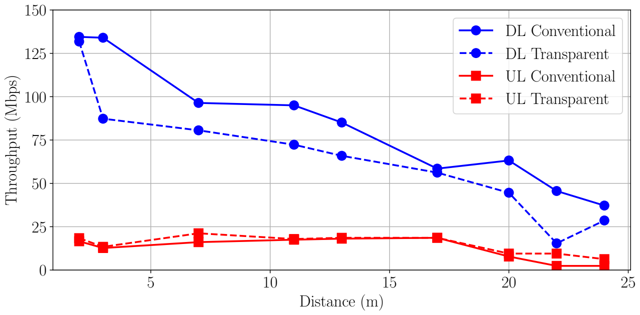

Figure 2. Comparison between transparent and conventional antennas in terms of measured application layer throughput.

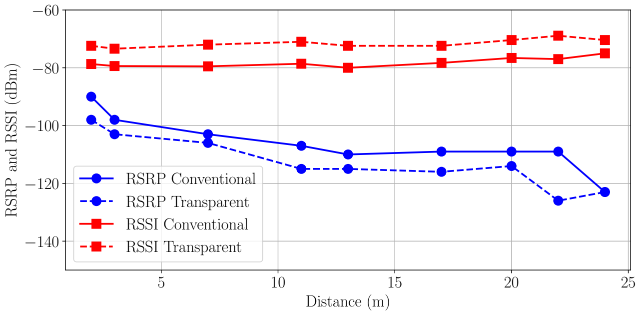

Figure 3. Comparison between transparent and conventional antennas in terms of measured RSRP and RSSI at the UE.

User Equipment (UE), Apple iPhone 16, and the 5G gNB. The gNB operated with one transmit and one receive antenna over a 40 MHz bandwidth, using a 30 kHz sub-carrier spacing (numerology 1) and a TDD slot format of `[DDDDDDDFUU]`. This slot format, being downlink intensive, is well suited for scenarios with high downlink traffic demands, but it can also be configured for uplink intensive requirements. We conducted `iperf` tests to measure application-layer throughput for both uplink and downlink. Simultaneously, several key physical layer metrics such as Reference Signal Received Power (RSRP) and Received Signal Strength Indicator (RSSI) were collected on the UE side.

The experiments were conducted in an indoor office environment, with the gNB fixed at a single location and the UE placed at different distances from the gNB. The results for downlink/uplink throughput are shown in Figure 2, while the RSRP and RSSI are shown in Figure 3. Initial results indicate that the transparent antenna is comparable to the dipole antenna in almost all scenarios. It also seems that the transparent antenna generally underperforms in the downlink but outperforms in the uplink, compared to the conventional antenna.

IV. DEMO DESIGN

This live demonstration will use OAIBOX [4], which provides a user-friendly interface for configuring the gNB parameters and monitoring/logging results at both the gNB and UE, in addition to automating the tests. Both transparent and conventional antennas will be connected to the 5G gNB SDR via a programmable RF Switch [5]. The RF Switch will allow switching between the transparent antenna and the conventional antenna for comparison purposes. An Apple iPhone 16 will be used as the 5G UE. To comply with local spectrum regulations, the experiments will be performed inside a Faraday cage [6] as shown in Figure 4.

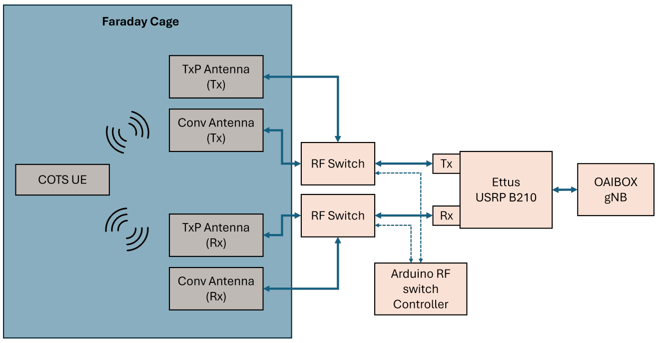

Figure 4. Live demonstration setup. All the radiating elements are placed inside the Faraday cage.

During the demo, an end-to-end connection will be established between the 5G gNB and the COTS UE, and common tests such as `iperf` and web-browsing will be initiated on the UE side. Hands-on silver mesh gloves and the illuminated viewing window of the Faraday cage will make it easy for users to operate the COTS and run the above applications. Key performance metrics, including signal strength, data rates, and network stability, will be evaluated to demonstrate the practical viability of the transparent antenna compared to the conventional antenna.

V. CONCLUSION

This demonstration highlights the potential of transparent antennas to deliver seamless, high-performance connectivity while aesthetically blending into urban environments. Suitable for dense 5G networks and IoT applications, these antennas perform comparably to conventional antennas in most scenarios, making them ideal for smart cities and next-generation wireless networks.

ACKNOWLEDGMENTS

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