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5G/mm-Wave Next Generation RFID Systems for Future IoT Applications

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***Abstract*—With the promise of the massive deployment of 5G/mm-Wave technologies, low-maintenance and highly scalable wireless systems are desirable to meet the needs of the next generation IoT systems. Mm-Wave backscattering devices present great potential for IoT systems with their compact form factors, minimalist design, and available spectrum. This paper provides a review of the current state-of-the-art in semi-passive RFID/mmID tag technology, non-line-of-sight (NLOS) repeater architecture, and 5G/mm-Wave energy harvesting enabling low-latency wireless communication, precise localization, long-range capabilities, dense wireless sensor networks, and powering these next generation ultra-low-power RFID systems through the 5G wireless power-grid.**

***Index Terms*—5G, mm-Wave, RFID, mmID, ultra-low-power, IoT**

I. INTRODUCTION

With the recent widespread deployment of 5G and Internet-of-Things (IoT) technologies, there is a need for the future development of innovative, prolific wireless systems that require ultra-low manufacturing costs and limited servicing to provide ubiquitous operation of these future smart systems. A Radio Frequency Identification (RFID) tag, or backscattering devices, in particular present a desirable solution to the ever advancing 5G and IoT technologies. The design of such devices are both minimalist and cost-effective, enabling the mass-production and usage in future IoT applications ranging from wearable biomonitoring to smart city systems. From a maintenance perspective, these devices are superior to more complex wireless modules, in terms of power consumption, as they require only modifying an incident electromagnetic interrogating signal through changing the load connected to the RFID antenna, thereby removing the need for power-consuming high-frequency local oscillators and amplifiers in the wireless sensor node. In the use case of ubiquitous IoT applications, semi-passive to fully passive operation is desirable and the presented work will mainly focus on the ultra-low-power backscattering devices. The recent work and commercialization of backscattering devices mainly has focused on devices that operate in the Ultra-High Frequency (UHF) band. These systems provide both scalability and low-power consumption, however are limited in both available bandwidth and maximum range of operation, and require bulky system components. A natural solution that parallels the advances in 5G/mm-Wave systems is to design these backscattering systems at mm-Wave frequencies, enabling favorable form-factors, dense deployment of these devices, high-data rates meeting the needs for broad spectrum of IoT applications, while maintaining the required scalability and ultra-low-power consumption of these devices. This paper presents an overview of the state-of-the-art mm-Wave backscattering devices that are highly attractive in future IoT systems. Section II details the various mm-Wave backscattering modules for low-latency communication, precise localization, and ultra-long-range low-power devices. Section III presents a novel, ultra-low-power repeater architecture that could be utilized in distributed RFID sensor networks. Section IV describes the utilization of 5G/mm-Wave harvesting to enable the powering of these ultra-low-power devices for the next generation RFID systems.

II. ULTRA-LOW POWER MM-WAVE BACKSCATTERING MODULES

Backscattering based modules provide a highly attractive solution for future ubiquitous IoT applications due to their ultra-low-power consumption, minimalist design, and ultra-low-cost. A large majority of these RFID modules and systems operate in the Ultra-High Frequency (UHF) band. However, these UHF systems are hindered both in physical compactness and available bandwidth, thereby inherently limiting the form-factor, channel capacity, and fidelity in tracking applications when employing these systems in future IoT systems. Thus, a natural solution is to increase the operational frequency of these ultra-low-power systems up to the 5G mm-Wave bands to benefit from compact system components, high data rates, and precise tracking capabilities. In [1], the authors demonstrated backscatter communication operating at $24.5\,\mathrm{GHz}$ on the order of $1\,\mathrm{Gbps}$ with the ability of higher order modulation techniques such as QPSK and 16-QAM. Additionally, this backscattering module was fabricated utilizing Additive Manufacturing (AM) processes on the flexible, thin Liquid Crystal Polymer (LCP) substrate displayed in Fig. 1 allowing for wide

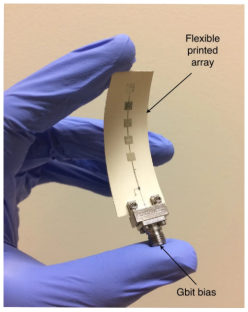


Fig. 1. Photo of the inkjet-printed, flexible 5x1 antenna array and front-end for high data-rate IoT applications [1].

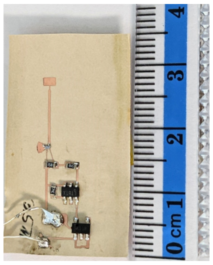


Fig. 2. Photo of the $1.5\,\mathrm{cm}\times3.5\,\mathrm{cm}$ sticker-like, wearable, ultra-low-power, semi-passive mmID [3].

range of IoT applications such as low-latency, ubiquitous, wearable, wireless biomonitoring applications.

Furthermore, these mm-Wave systems enable compact, high precision localization and tracking IoT applications due to the available bandwidth at these operational frequencies and wavelength of the interrogating system. The available bandwidth of these systems is inversely proportional to the range resolution and in phase-based tracking the sensitivity of these 5G/mm-Wave system is proportional to the free-space wavelength of the operational frequency ranging from tens of centimeters to a few millimeters. From the perspective of selecting an appropriate reader for Millimeter-Wave Identification (mmID) localization and tracking applications, a Frequency Modulated Continuous-Wave (FMCW) radar is a logical choice as with advances in RF design these radars have become commodities in today's market. In [2] and [3], the authors presented the combination of radar and mmID technology with an FMCW radar and a miniaturized, ultra-low-cost, ultra-low-power mmID tag utilized for spatial identification and localization. The compact 60 GHz mmID shown in Fig. 2 combined with the Antenna-on-Package (AoP) FMCW radar module displayed ultra-accurate ranging up to 0.5 m with a plot of the average ranging error at each distance measured shown in Fig. 3 [3]. With the maximum ranging error bounded to 2 cm, a continuous operational power consumption of 1.43 mW of the mmID, and a total system cost of 25$ at scale, the presented single-chip reader system exhibits great potential for future short range, wearable applications in Human Computer Interaction (HCI) and smart robotic applications.

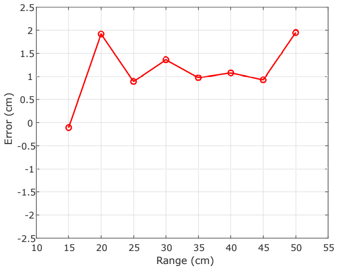


Fig. 3. Benchmark of ultra-accurate ranging of the single chip mmID localization system [3].

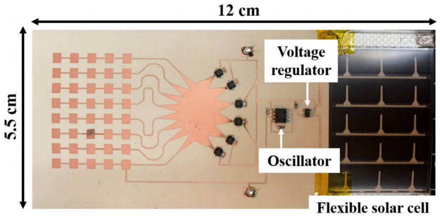


Fig. 4. Ultra-long-range, ultra-low-power 5G/mm-Wave Rotman lens-backscattering RFID [5].

While both of the presented works with mmID systems present high-data rate and precise localization, these systems are limited to an operational range of 0.5 m. This is mainly due to limited aperture of this mmID's single patch antenna. However, simply adding high-gain array to the mmID tag produces an orientation-dependent point-to-point link that requires proper alignment of the reader and the mmID. A solution that provides both a wide-angular coverage, while providing a high-gain structure, which not only compensate for the path loss but allow the extension of reading ranges relative to similarly-sized low-frequency antennas by focalizing the backscattered signal back in the direction of the reader [4]. In particular, the authors in [5] presented a Rotman lens-backscattering RFID shown in Fig. 4 operating at the 28 GHz 5G-band. A plot of the measured differential radar cross section (RCS) vs. incident interrogating angle is shown in Fig. 5 demonstrating a total angular coverage of 110 ° providing orientation-agnostic operation. Furthermore, with the maximum Equivalent Isotropic Radiation power (EIRP) of 75 dBm in the 5G-band, the estimated maximum reading range of the system is 1.8 km establishing the excellence of 5G/mm-Wave backscattering modules in ubiquitous, long-range sensing applications such as future smart city systems.

Thus, the presented mm-Wave backscattering modules offer desirable compact form-factors, ultra-low-power consumption, ultra-low-cost, high-data rates, precise localization, and long operational range making this technology applicable in a wide variety of IoT applications ranging from wearable biomonitoring to smart city applications.

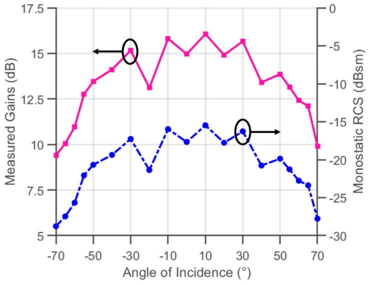


Fig. 5. Plot of measured differential RCS versus incident angles [5].

III. NEXT GENERATION, ULTRA-LOW POWER REPEATER SYSTEM

Despite the demonstrated high energy efficiency of the modulated backscatter RFID scheme, the read range of deployed RFID tags suffer from limitations that come from a fairly expensive round-trip link budget as the received signal power decays to the fourth power of the distance between the reader and the tag. There have been ultra-long-range RFIDs reported in literature having read range in excess of hundreds of meters however dense implementation of these tags for sensing applications become expensive due to the cost of the active element in use [6]. In [7], an ultra-low cost, low power repeater is presented. This device is able to amplify the interrogating signal travelling towards the tag as well as the modulated return scattered back from the tag. The repeater is frequency divided to mitigate self-interference and potential ringing between the two channels so that amplification is done in the up-link and down-link independently. This presents a low-cost, low power consumption solution that improves the feasibility of dense and networked implementation of RFID for sensing applications. This is of great benefit in applications where the reader may not always have a line-of-sight path to the tags, or it is desired to have a centralized reader and some distributed tags.

The repeater is made up of a tunnel diode reflection amplifier matched to an antenna of choice. When tunnel diodes are biased in a particular region, they are able to present themselves as a negative resistance to the terminals of an appropriately matched antenna at some frequency of interest. This negative resistance results in a reflection coefficient that has a magnitude greater than 1 so that any incident signal is amplified in reflection. Characterization of the repeater gain performance and its architecture is shown in Fig. 6. Notable here is the very low biasing voltage of $175\,\mathrm{mV}$ required to achieve a very high gain. The device features a total power consumption over $1000x$ less than competing technologies at a meager $40\,\mu\mathrm{W}$ and operating voltage more than 90% less and still producing a similar gain performance. This opens the door for energy autonomy and presents a stride forward in the realization of ubiquitous sensing utilizing RFIDs. All of this is presented in a minimal, single component low-cost architecture suitable for deployment in dense wireless sensor network implementations. Figure 7 shows the results of non-line-of-sight interrogation in a muti-tag configuration. The spectrum of the received signal in the different tag states is shown.

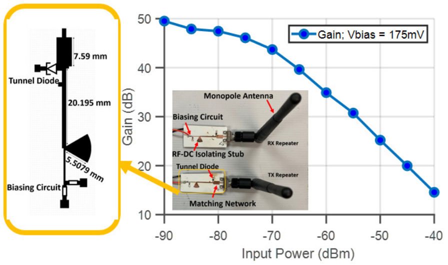


Fig. 6. Repeater architecture and gain versus input power characterization [7].

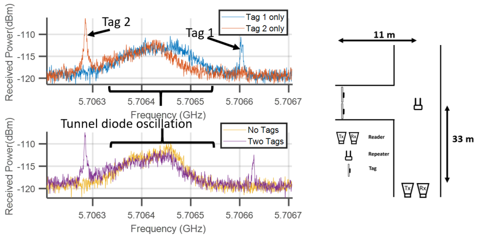


Fig. 7. Non-line-of-sight interrogation of multiple tags [7].

IV. POWERING NEXT GENERATION RFID SYSTEMS WITH 5G MM-WAVE HARVESTER

Backscatter-communication-enabled front-ends, with their remarkably low power consumption levels while transmitting—especially long-range retrodirective mm-Wave implementations—lend themselves perfectly for integration alongside energy harvesters into ultra-low-cost battery-less passive systems. In particular, the Rotman lens-backscattering RFID tag presented in section II demonstrated an overall power consumption of $2.64\,\mu\mathrm{W}$, fully supplied by the flexible attached solar cell under indoor light conditions [5]. While the aforementioned structure is semi-passive in its current form, the 5G powering technology presented in this section triggers the emergence of fully-passive ultra-long-range backscattering RFID tags, based on the concept of extending the role of 5G/mm-Wave networks from data providers to combined data and power providers. Mm-Wave transmitters, equipped with large-aperture, high gain-radiators are capable of focalizing the electromagnetic energy to create highly efficient wireless links for wireless power transfer. However, this beneficial high-gain feature becomes a curse for large-aperture passive receivers requiring an orientation-agnostic operation. The technology presented here describes a solution that breaks the usual paradigm, imprisoned in the trade-off between rectenna angular coverage and turn-on sensitivity. The concept relies on the implementation of a Rotman lens, a passive type of beamforming networks (BFNs), between the antennas and the rectifiers, as shown in Fig. 8. Using this architecture, the

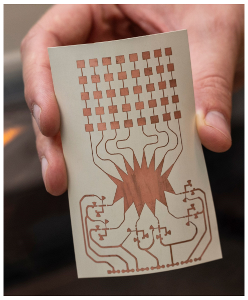


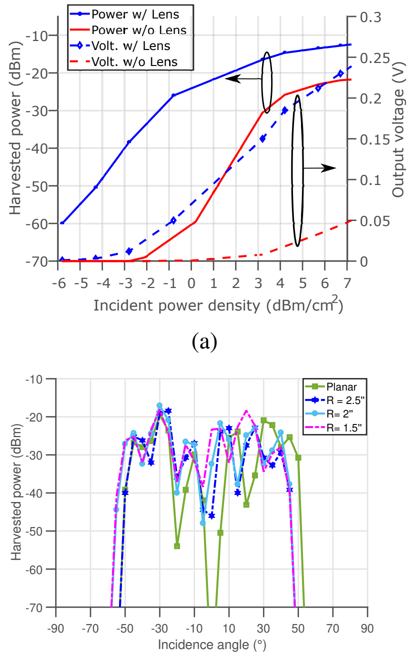
Fig. 8. Photo of the fully-printed planar Rotman lens-based harvester.

signals are received from any direction, combined internally inside the lens, and focalized to one beam port where a rectifier is connected. The incorporation of the lens does not only cover a wide angular coverage of 120°, but also provides—through combining—the maximum at the input (and, therefore, the maximum possible conversion efficiency) of a specific rectifier, depending on the direction of the incident signal.

The superiority of the Rotman lens-based rectenna over a lensless rectenna was demonstrated with the design, fabrication, and testing of both structures with respect to incident power densities and angles of incidence [8]. The plot shown in Fig. 9a, displaying the measured harvested powers and output voltages of the two structures with and without the lens, demonstrates the ability of the Rotman lens to increase the rectenna's turn-on sensitivity and rectification efficiency. Moreover, the structure was fabricated on a thin and flexible Liquid Crystal Polymer (LCP) substrate with a full ground plane, allowing its deployment on metallic surfaces and in bent configurations. The structure's robustness to folding was characterized by placing it on cylinders with different bending radii. Fig. 9b shows the measured harvested powers with respect to incident angles for different curvatures, displaying an unprecedented stability in the system's power collection and rectification abilities with minor attenuation observed at the edges. Using this innovation, IoT devices will be powered and be capable of passively communicating information (as mmIDs) at distances exceeding $180\,\mathrm{m}$ using 5G base-stations transmitting the full $75\,\mathrm{dBm}$ EIRP allowable by the FCC in the 5G/mm-Wave bands [9].

V. CONCLUSION

This paper has reviewed the state-of-the-art backscattering 5G/mm-Wave technologies including various ultra-low-power mm-Wave tag designs for low-latency communication, precise localization, and ultra-long range interrogation, an ultra-low-power NLOS repeater architecture for widely dispersed wireless sensor networks, and a 5G/mm-Wave harvester enabling ubiquitous operation of the presented technologies. These advances in mm-Wave backscattering systems present immense potential in shaping the next generation mmID systems utilized in IoT applications.



(a)

(b)

Fig. 9. (a) Plot of the measured voltages and output powers versus incident power density for the rectenna with and without the Rotman Lens [8] and (b) measured harvested powers versus incidence angles for different curvatures [9].

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