mmWave/5G RFID Systems for Long-Range Wireless Sensing and Remote Localization Applications

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I. Introduction

In recent years, the tremendous growth in the demand for consumer electronics combined with the advances in the area of millimeter-waves (mmWave) has enabled great improvement in the field of Internet of Things (IoT), which is consequently paving the way for our societies to make the idea of *Smart Cities* possible. Some applications that lie under the 'Smart Cities' scope include structural health monitoring, ubiquitous biochemical and health monitoring, positioning and localization applications, as well as low-cost energy harvesting devices. In addition, the realm of virtual reality (VR) has also drawn tremendous attention among regular consumers, increasing the need for improving our current technologies related to digital twins in order to map physical objects into the digital world.

In this regard, Radio Frequency Identification (RFID) based technologies represent an adequate solution to satisfy the needs brought by the advances in IoT applications, as they allow to wirelessly read multiple sensor nodes in a highly- efficient manner. Particularly with backscatter RFID, a user is capable of communicating with a sensor tag using minimal amounts of power, as the tag uses the signal sent by the reader to operate and communicate back. In addition, RFID technology allows one to construct a network of multiple sensor tags than can be continuously monitored for a wide range of applications. On the other hand, additive manufacturing (AM) represents a key role for the development of these types of devices, as it enables highly versatile, low-cost and rapid fabrication processes that can satisfy the increasing demand for IoT devices. And as 5G capabilities become more available, it is possible design miniaturized RFID tags that operate at mmWave frequencies. In this paper, we briefly summarize some of the most recent advances in wireless sensing and remote localization applications that operate at mmWave frequencies.

II. Remote Localization and Orientation Sensing for VR scenarios

Utilizing RFID based technology for localization and orientation sensing has been explored previously, however the majority of this work operates in the Ultra-High Frequency (UHF) spectrum. These low frequency RFID systems are inherently limited in terms of localization as the bandwidth utilized for interrogation is directly proportional the ranging resolution and accuracy of the ranging estimation. Additionally, the wireless components of the UHF localization systems are bulky limiting the form-factor and deploy-ability for wearable or gesture recognition in VR applications.

Our lab aims to solve this by utilizing millimeter-wave identification (mmID) for the frequency of operation. Furthermore, with recent advances in wireless technology, mm-Wave radar systems have become highly affordable as well as benefiting from compact form factors as well as operating over a large continuous bandwidths enabling high fidelity localization. In [1-3], we demonstrate the use of miniaturized 60 GHz and 24 GHz mmIDs and frequency modulated continuous wave (FMCW) radar for localization and orientation sensing. The 60 GHz system takes full advantage of the compact reader and mmID architecture with the reader having an antenna-on-package form and is displayed in Figure 1a. The ranging error of this system is displayed in Figure 1b and highlights the high-fidelity localization capabilities the 60 GHz localization system with the bounded ranging error of 2 cm up to 50 cm away from the radar module. The whole system at scale would retail for ~$25 establishing the affordability of the proposed mm-Wave mmID localization system. Thus, there is a massive potential for short range localization for motion capture applications to be integrated with future gesture recognition and VR applications.

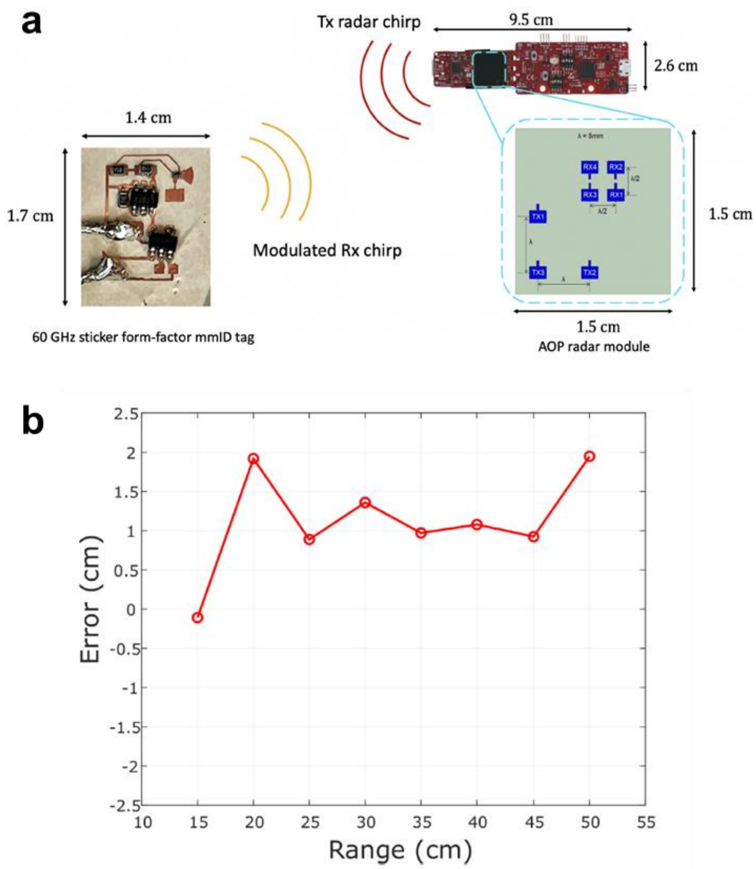

Figure 1. (a) FMCW radar and mmID system measurement diagram [2], and average error from the true value over the measurement range for the mmID tag [1].

Using this same wireless interrogation framework with an FMCW and mmID components, we created an orientation sensing mmID [4]. This mmID is comprised of four sub-elements each divided in the amplitude, spatial, and frequency domains to encode orientation information of the mmID itself. The mmID layout is displayed in Figure 2 with the dimensions labeled. The current work for orientation sensing was done through training on the amplitude information of each of the four elements to detect the yaw orientation of the mmID. This amplitude information was then the input into a supervised learning model to estimate the current orientation of the mmID. The mmID was then rotated about the z-axis in front of the radar and a plot of the true angular orientation of the mmID versus the estimated orientation of the mmID from the kNN (k-nearest neighbor) model is displayed in Figure 2. The plot highlights the high accuracy of orientation sensing with angular error of 0.051° over the ± 90° angular space. Thus, a compact, affordable orientation and localization mmID system can be envisioned for future highly immersive experience in a wide variety of VR applications.

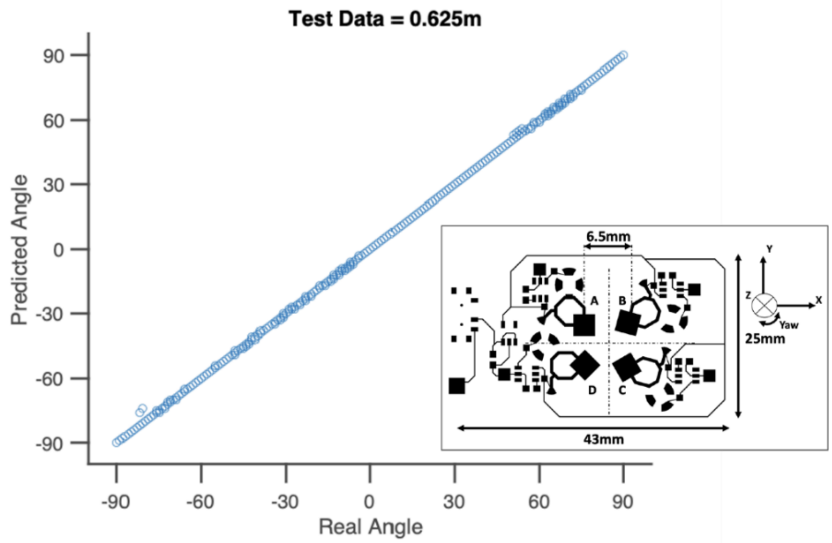

Figure 2. Predicted vs. real angle results for the mmWave backscatter RFID for rotational sensing after training with kNN model at 0.625m range. The inlet shows the tag architecture [4].

III. Long-Range Environmental Wireless Sensing

Environmental monitoring is one of the most beneficial applications for IoT systems. Wireless sensor networks can be deployed in multiple scenarios for continuous environmental monitoring, for instance, smart agriculture, air and water quality control, and toxic gas detection are some of the applications with most interest, where the parameters to be monitored include temperature, humidity, pH levels, carbon dioxide and other air pollutant concentrations, water salinity, among others.

Our group has built expertise in the development different varieties of sensors over the last decade. For instance, we have worked with different gas sensors such as ammonia (NH3) [5], carbon dioxide (CO2) [6], toxic nerve agent gases [7], [8], as well as temperature [9] and humidity sensors [10]. Depending on the target analyte, different types of solutions can be formulated in order to achieve high sensitivity and selectivity and to formulate inkjet-printable inks. Common material used for sensing applications include carbon nanotubes (CNT) and graphene functionalized with different molecules depending on the target agent. Figure 3 presents some examples of inkjet-printed gas sensor architectures on flexible substrates such as polyimide and LCP substrate.

In order to integrate the sensing elements into a RFID sensor node that operates at mmWave frequencies, our group has previously demonstrated the use of fully-printed and energy-autonomous retrodirective antenna arrays that can achieve ultra-long-range performance, namely Van-Atta arrays, by maximizing the antenna gain and achieving ranges in the order of 80m [9–11]. These sensor nodes are composed of the antenna array, the low-cost mm-wave switches for backscatter modulation, an energy harvesting circuit such as a solar cell or a rectenna circuit, and the fully printed sensing element connected to a microcontroller unit (MCU), which can be replaced by virtually any type of gas sensor depending on the desired application (Figure 3f). As presented in Figure 3g, the interrogation of these type of sensor nodes allow to detect a change in the backscatter modulation frequency with rapid response times and at multiple angles of interrogation (about ± 40° angular coverage), a particular feature of the Van-Atta array [9-11].

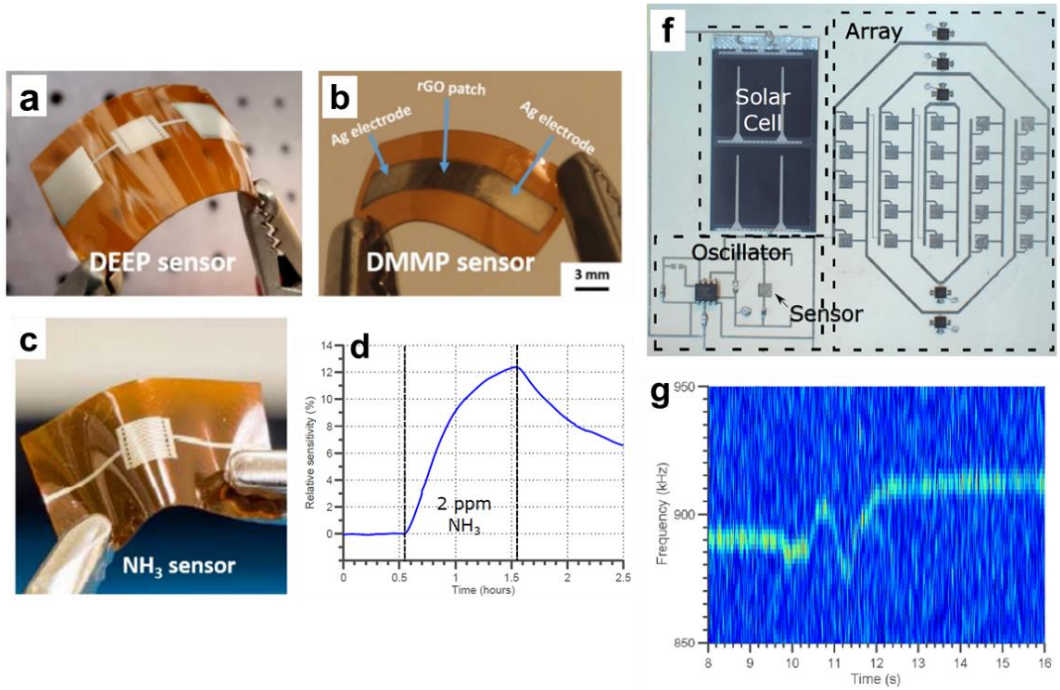

Figure 3. Samples of chemi-resistive gas sensors developed in our group: (a) nerve agent simulant (DEEP), (b) nerve agent simulant (DMMP) [5], (c) NH3 sensor [12] and its response (d) [11]. A fully printed and energy-autonomous Van-Atta array integrated with a NH3 sensor is shown in (f) and its frequency response upon exposure to NH3 is shown in (g) [11].

IV. Structural Health Monitoring and Smart Skin Applications

A technology that has particularly benefited from the advent of IoT is structural health monitoring (SHM), an emergent diagnostic tool for continuous monitoring of structural failure, compressive and tensile stress, vibrations, humidity, and temperature of large structures. Civil and aerospace engineering are two examples of areas that can be greatly benefited from the advances in SHM, by continuously monitoring the aforementioned parameters and predicting possible performance failures. However, this is not only reserved for large structures, as it can be implemented in virtually any kind of electronic devices for security applications and for *Smart Skin* (SS) applications.

Our group has multiple works on the development of low-power and even fully-passive wireless modules for different types of strain, temperature and humidity sensing that are suitable for SS and SHM applications [9–11], [13–15]. As described in the previous section, RFID tags consisting of Van-Atta arrays offer a great solution to overcome the potential path loss due to the use of mmWave frequencies due to their retrodirective performance, which enables longer ranges for wireless interrogation. The size and operating frequency of the Van-Atta array can be adjusted to any particular needs and can be easily tuned to use frequencies in the mmWave/5G+ spectrum. Moreover, fully passive chipless RFID tags for temperature, humidity or strain sensing can be designed based on the substrate properties, and they can even be embedded inside a matrix for improved performance [9,10]. Figure 4a shows an example of a fully passive temperature sensor for Smart Skin applications utilizing a Van-Atta array operating at 23.26 GHz as well as its performance [9]. Van-Atta arrays can also be utilized for strain sensing, as a change in the position of the antenna elements will induce a shift in the resonant frequency, hence being able to map a change in strain to a change in frequency.

A different type of strain sensor is presented in Figure 4b, where a change in resistance between opposite electrodes can be detected when the structure is subject to bending, allowing to predict the bending radius of the structure by using a machine learning model to use the results for phase array calibration [14]. A similar strain sensor design could be used in other applications as presented in [15], where the authors propose a 60 GHz RFID tag that maps the resistance change due to bending to a change in the modulating frequency of the tag, allowing to have a very low-power strain sensor that also allows to detect the localization with sub-cm resolution.

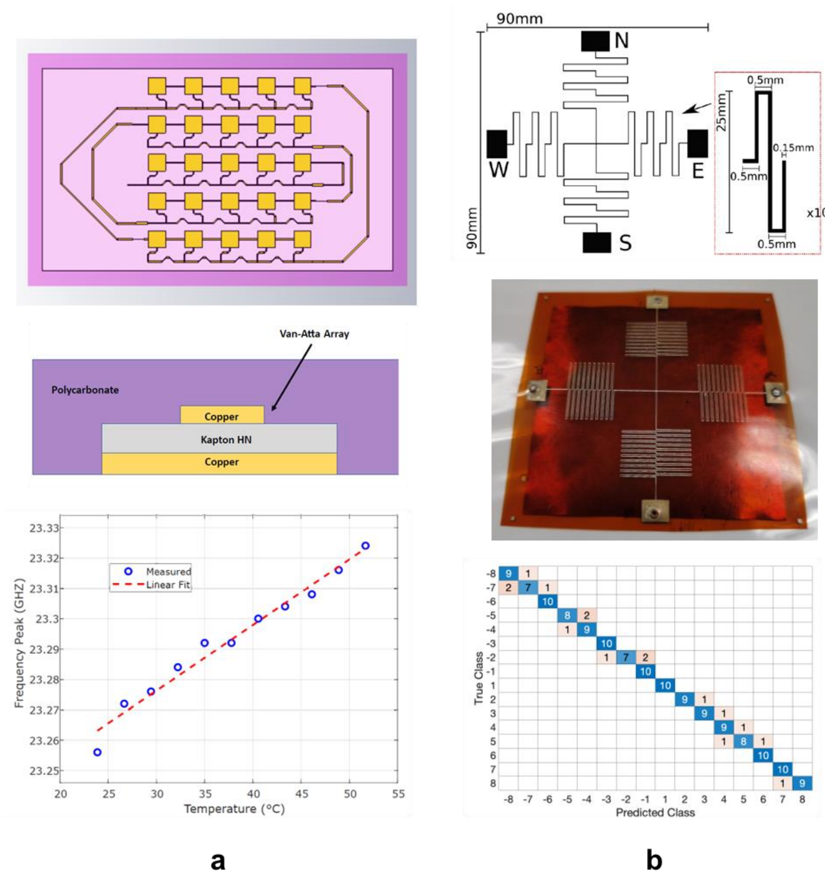

Figure 4. (a) Van-Atta RFID sensor tag embedded in polycarbonate for temperature sensing. The top and middle images show the tag design, and the bottom figure shows the frequency response due to temperature changes [9]. (b) Strain sensor based on resistance changes in a meandered conductive trace. The top and middle images show the sensor design whereas the bottom shows the comparison between predicted and true bending radii [14].

V. Conclusion

This paper showcases some of the most recent advances in fully printable mmWave/5G RF modules for wireless sensing applications that operate at frequencies up to 60 GHz. The works here presented range from fully passive tags to energy-autonomous long-range RFID systems and low-cost miniaturized tags for orientation and rotational sensing with great potential for use in VR systems. It is clear that the advances in mmWave technologies are producing a great impact in the field of IoT and have the potential to satisfy the demand for ubiquitous environmental sensing, smart skins, and structural health monitoring in a low-cost fashion due to the benefits of additive manufacturing. As these technologies continue to grow, we are getting steps closer to achieving the full potential of smart cities.

VI. References

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