Miniaturized Millimeter Wave RFID Tag for Spatial Identification and Localization in Internet of Things Applications

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***Abstract* — In this paper, a miniaturized millimeter wave Radio Frequency Identification (RFID) system for the spatial localization and Internet of Things (IoT) applications is presented. The spatial localization of the RFID tags is enabled by the use of a Frequency Modulated Continuous Wave (FMCW) Radar as the reader. The radar is used to resolve the modulated backscatter signal returned by the RFID tags when interrogated by a Continuous Wave from the reader. The spatial information (range, angle with respect to the reader antenna) is contained in the returned signal's peak frequency and phase. The returned baseband signal is processed digitally in order to extract the required information regarding the spatial location of the RFID tag.**

***Keywords* — 5G, RFID, millimeter wave, internet of things, radar, FMCW, backscatter**

I. Introduction

Over the last few decades there has been an increasing interest in the use of Radio Frequency Identification (RFID) based technologies for a variety of applications. Owing to their relatively low cost of manufacturing, energy autonomy (battery-less), and general suitability for a multitude of wireless localization and sensing applications. A large amount of existing RFID technology applications is deployed in the Ultra High Frequency (300 MHz to 3 GHz) band. However power limitations, limited available bandwidth and a plethora of devices operating in this frequency band has encouraged research and exploration into the use frequencies of operation in the millimeter wave regime.

This creates a unique opportunity in conjunction with the advent of Fifth Generation (5G) wireless technology which seeks to connect a swarm of devices supporting high data rates whilst utilizing the readily available millimeter wave frequency bands. The proposed system operating in the 24 GHz Industrial, Scientific and Medical (ISM) band fits the bill for compatibility with 5G wireless technologies and increased available bandwidth. In addition, the use of millimeter wave frequency bands enables the development of a very low form factor RFID tag which makes this system suitable for ubiquitous dense implementations in an array of short-range identification and localization implementations.

The use of RFID to identify, track and localize objects in range has been achieved in different ways using two core principles namely round-trip time of flight (TOF) where the total time taken for a signal to travel between the reader and tag is used to estimate distance, and received signal strength where the loss in signal strength due to roundtrip propagation from tag to reader is used to calculate the distance. The system presented makes use of the round-trip time of flight principle via the use of a modulating backscatter RFID tag interrogated by a Frequency Modulated Continuous Wave (FMCW) radar [1]. There have been various efforts [2,3] reporting the use of FMCW radar-based detection with an active backscatter modulating RFID tag for localization and detection applications however the proposed systems have relatively high-power consumption (hundreds of milliwatts), large form factor tags (several centimetres thick) and bulky expensive readers. The authors present here a miniaturized ultra-low power, low cost millimeter wave RFID system for use in close range densely implemented spatial localization and identification applications for the Internet of Things. In Section II, the proposed RFID tag front end and baseband circuitry are described. Then, in Section III, the FMCW radar system used for interrogation and the post processing scheme used for the extraction of spatial information are described. Section IV presents the results obtained from the tests performed on the presented system. Finally, a conclusion is drawn in Section V.

II. Miniaturized RFID Tag

The adoption of millimeter wave frequencies (the 24 GHz ISM band in this work) enables the development of a smaller, lower profile tags compared to current widespread implementations at UHF bands. The proposed RFID tag is made up of two sections: the RF front end and the baseband circuitry. The RF front end is comprised of a rectangular patch antenna and a single RF transistor for backscatter modulation based on load switching. The baseband circuit includes a low power oscillator to generate the modulating signal, a low power consumption voltage regulator and an energy source.

A. RF Front End

The antenna is designed to operate at a center frequency of 24.125 GHz, so it is able to cover the available 250MHz of ISM allocated bandwidth from 24-24.25 GHz. The antenna is designed to re-emit the interrogating continuous wave signal after modulation in the cross polarization to what is received as suggested in the reflect array presented in [4]. When used with a similarly cross polarized transmitting and receiving antenna at the reader there is improved self-interference rejection which shows up as a gain in the signal-to-noise ratio (SNR).

The RF transistor used is the millimeter wave compatible low noise FET (CE3520K3). Based on an input signal on the gate of the transistor from the low power oscillator, the transistor switches from an open circuit to a short circuit load. The appropriate loads to enable switching are achieved through the use of quarter and half-wavelength stubs. This load switching modulates the reflection coefficient from 0 to +1 thus causing the interrogating 24GHz signal to be modulated by the signal from the oscillator.

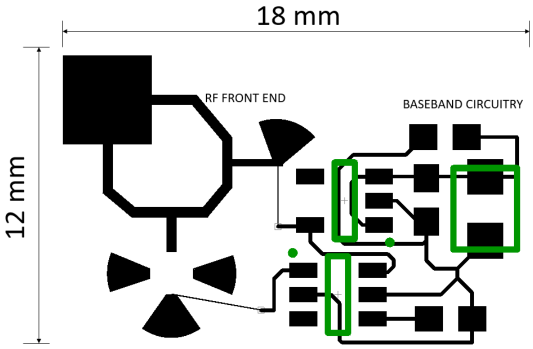

Fig. 1. Layout of the proposed RFID tag (18mm x 12mm) showing RF front end and baseband circuit components

B. *Baseband Circuit*

The baseband circuit comprises of an energy source, an ultra-low power consumption voltage regulator and the low power oscillator. The voltage regulator is used to maintain a constant bias voltage across the RF transistor so as to ensure consistent performance while consuming as little power as possible. The low power oscillator is a critical component of the active backscattering RFID tag. The LTC6906 oscillator is chosen for its low power and high stability. A less stable oscillator would degrade system performance due to high amount of phase noise generated by a jittery device. The frequency generated by the oscillator is determined by the R-C impedance of a fixed internal capacitance and a selected resistance value.

C. *Device Fabrication*

The RF Front End and Baseband circuitry are fabricated on a flexible Liquid Crystal Polymer substrate (ε =3.14, tanδ = 0.0025) with a thickness of 180µm. The fabrication is achieved via an inkjet masking procedure where Microchem SU8 is inkjet printed onto the copper clad surface of the Liquid Crystal Polymer. The SU8 acts similar to a positive photoresist where the portions of the copper covered by the SU8 remain insoluble and the rest of the copper is etched away using an Iron Chloride solution. The fully fabricated device is shown in Figure 2.

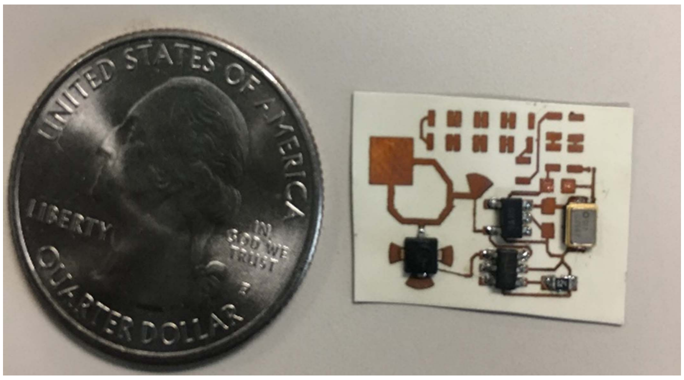

Fig. 2. Fabricated Miniaturized RFID Tag

III. READER AND POST-PROCESSING

A. *Reader System*

The reader used in this work is based on low cost readily available 24 GHz chipsets sourced from Analog Devices Inc. The integrated FMCW transceiver system consists of the ADF5901, ADF4159 and ADF 5904 which make up the transmitter, PLL and receiver. A convenient solution exists that integrates these three essential devices in the commercially available EV-RADAR-MMIC2 development board. The demodulated baseband signals from the four channels of the receiver are sampled using a Tektronix DPO 7454 Oscilloscope. The digital data is subsequently saved onto a flash drive and imported into an array in MATLAB for further processing. An integral component of the reader system is the custom made cross polarized antenna module which is fabricated on a Rogers RO4003 substrate having thickness of about 305µm. The antenna system consists of four linear antenna arrays in the receiving channel and two transmitting antennas in the cross polarization. The designed reader antenna system exhibits very high TX/RX isolation by virtue of the orthogonal polarizations in which they radiate.

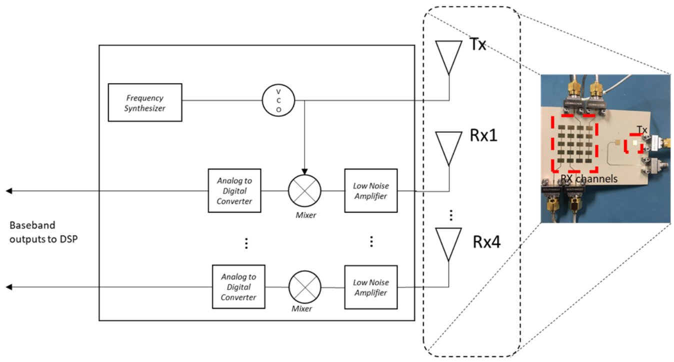

Fig. 3 Reader System Architecture

B. *Tag Identification and Detection*

The baseband signals are sampled by the oscilloscope at a rate of 200 kHz for a duration of 10 seconds yielding 2×10^6 samples for each of the four receiving channels in the timedomain. In order to detect the presence of the RFID tags, a simple Fast Fourier Transform (FFT) operation is performed too reveal the frequency content of the sampled baseband signal. After running this operation, a peak search algorithm is used to locate pairs of spectral peaks precisely centered around the modulating frequencies of the tags of interest. This means that the modulating frequency of an RFID tag in the field of view of the reader with no a-priori knowledge of the tag's characteristics with the only stipulation being that the antenna on the tag is tuned to that of the reader (24 GHz in this case).

C. Ranging

It is known that for round trip time of flight based radar detection systems such as the FMCW, the distance of a target relative to the reader is proportional to the generated beat frequency which is proportional to the round trip time delay experienced by the signal as it travels from the reader to the tag and back towards the reader [2,3]. When the delayed version of the interrogating signal is received on the RX channels, it is mixed with the signal that was sent in order to obtain a constant beat frequency which is representative of the total distance travelled by the signal. This is where the advantage in using an active backscattering system shows up because now, the signal of interest can be modulated away from any passive clutter around DC which yields a much higher signal to noise ratio and increased sensitivity. There is however a limit in the achievable range resolution which is inversely proportional to the available bandwidth and is given by equation 1 where c is the speed of light and B is bandwidth.

$$d_{res} = \frac{c}{2\,B} \tag{1}$$

Given that at the 24GHz ISM band there is 250 MHz of bandwidth available, the resolution limit of the system is calculated to be about 75cm, which would make the proposed system unsuitable for accurate densely deployable spatial localization. This limitation is overcome by taking advantage of the periodic nature of the interrogating FMCW signal by isolating all of the spectral peaks in the frequency response that are spaced evenly by the frequency of the FMCW signal. The isolation of these peaks enables the use of a spline based envelope interpolation across the magnitude of the spectral peaks present in order for the beat frequency to be more precisely determined. This inadvertently increases the range resolution achieved. It is important for a reference measurement to be taken first so that the delay added due to the coaxial cables and transmission lines can be de-embedded.

D. Angle of Arrival

Once the range and modulation frequency of the target has been determined, the final quantity required in order to get a full spatial picture of the deployed RFID tags is the angle in azimuth of the tag with respect to the reader. This is achieved by spatially sampling the received signal at the reader so that the angle of arrival is obtained as a function of the difference in phase between the signal received at each receiving antenna. This comes as a result of the extra distance that the signal travels to reach each antenna when the impinging direction is off boresight taking a point on the plane of the receiving antennas as a reference [2,3]. The angle of arrival is extracted by applying a second FFT but in this case it is applied spatially. There are only four receiving antennas however by zero-padding in space, more angular information can be recovered. The spatial FFT behaves like a sum beamformer, showing a coarse peak at the angle where the tag is located. It is important to note that due to the high clutter/multipath environment, the phase must be calibrated to a reference measurement first.

IV. RESULTS AND DISCUSSION

A variety of tests and configurations are run in order to demonstrate the ability of the RFID tag to be identified and localized in space. In the first measurement, a tag is placed at boresight a distance of 0.2 m from the plane of the reader antenna. One data set is taken for calibration/reference and two more to evaluate variability in the proposed method for the extraction of the range information. The data is collected and processed in MATLAB via the FFT methods described. Fig. 4 shows the identification of the tag with a center frequency at 40.413 kHz. The spectral peaks used for the interpolation process are shown in the upper right section of the figure and finally the interpolated spectrum used to determine the beat frequency is shown in the lower right of the figure.

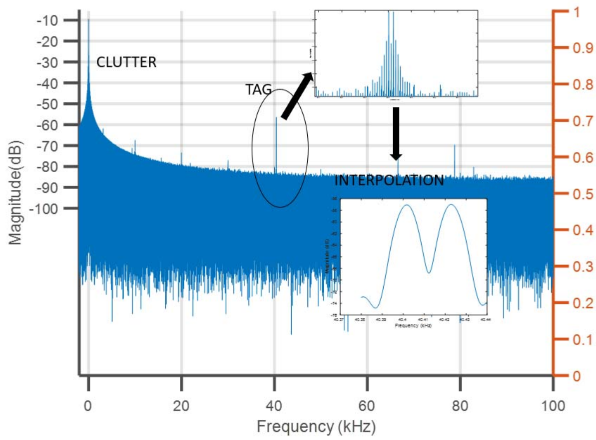

Fig. 4 Tag at Boresight, 0.2m from reader

Table 1 Range Measurements for 0 degrees

	Measured Distance (m)			
Real Distance (m)	**Trial 1**	**Trial 2**	**Trial 3**	**Mean**
0.200	0.200 (ref)	0.206	0.188	0.198
0.300	0.308	0.290	0.284	0.294

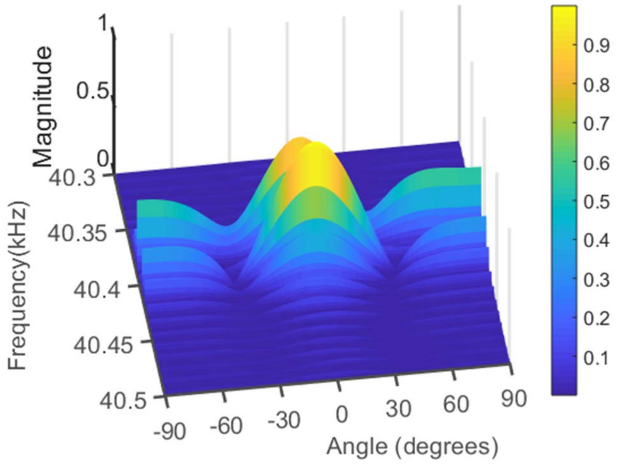

Fig. 5 Angle-Frequency plot for tag at 0 degrees w.r.t reader

The next set of measurements were taken at a distance of 0.3m between the tag and reader. Table 1 summarizes the results obtained from these measurements. From the table it is noticeable that there is low variation between trials and the mean across trials is within 5% of the real measured distance. For these measurements, the tag remained at the same azimuthal angle thus, a spatial FFT can be used to recover the required angular information. This is illustrated via the angle-frequency two dimensional plot in Fig. 5. The plot shows expected spectral lines centered about the identified modulating frequency with an angular peak in the boresight direction of 0 degrees.

In order to show full spatial localization capability, the tag is moved to a distance of 0.3m and oriented at an off boresight angle with respect to the plane of the reader antenna. Three sets of data are collected in this configuration to show the minimal variability and robustness of this processing scheme and the ability to detect the tag at an off boresight angle while maintaining reasonable accuracy in the range measurements.

Table 2 Range Measurements for off boresight angle

	Measured Distance (m)			
Real Distance (m)	**Trial 1**	**Trial 2**	**Trial 3**	**Mean**
0.300	0.311	0.293	0.323	0.309

The table shows agreeable results within 5% of the true measured value. Fig. 6 shows the two dimensional angle-frequency plot for the off boresight location of the RFID tag. The angular peak of interest occurs at approximately -50 degrees with respect to the plane of the reader antenna. The primary incidence is a result of line of sight between the tag and reader, the other peaks that occur at the frequency of interest can be attributed to multipath due to the high density lab environment in which measurements were performed.

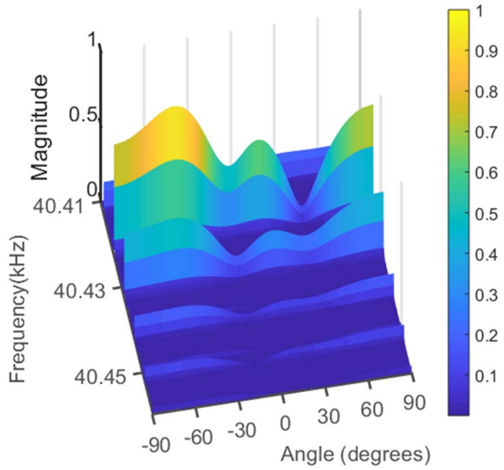

Fig. 6 Angle-Frequency plot for tag at -50 degrees w.r.t reader

V. Conclusion

In this effort, the authors present a first of its kind miniaturized millimeter wave RFID tag capable of unique identification and spatial localization. The millimeter wave compatibility of the proposed RFID tag makes it suitable for a variety of budding 5G and IoT topologies and architectures that require identification and/or localization. The very low form factor and ultra-low power consumption of the proposed device and makes it very suitable for a variety of low power sensing and detection applications. The use of an interpolation method on the frequency response obtained by the simple FFT in order to more precisely estimate the frequency content in between the evenly spaced spectral peaks improves the range resolution so that detection is possible for tags spaced more closely together. In addition, for a dense implementation the low bandwidth occupation (100s of Hz) of each tag indicates that a large number of tags separated in frequency can be uniquely identified and subsequently spatially located.

References

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