5.8-GHz Low-Power Tunnel-Diode-Based Two-Way Repeater for Non-Line-of-Sight Interrogation of RFIDs and Wireless Sensor Networks

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***Abstract*— The efficacy of the deployment of backscatter networks in sensor networks and the internet of things has been severely limited by the maximum read range of backscatter radio frequency identification (RFID) tags. The work presented here demonstrates a low-power two-way repeater architecture capable of increasing the read range and extending the coverage of tags to non-line-of-sight (NLOS) scenarios. This is achieved through the use of a two-way frequency divided tunnel diode-based reflection amplifier optimized for use in backscattering channels. The system reports a more than 2X increase in the read range of a semi-passive RFID tag at 17 dBm output power. The work presented here shows a system capable of giving a comparable performance with the state of the art while consuming up to 1000X less power in a simple single-component front end.**

***Index Terms*— Backscattering, Internet of Things (IoT), negative differential resistance, radio frequency identification (RFID), repeaters, tunnel diode.**

I. Introduction

COMMUNICATIONS by means of reflected power or backscatter communications, as it is more commonly known, is not a new concept. Having been developed in the 1940s [1], this technology has seen a steady increase in its deployment in the following decades in an array of modern applications most notably in radio frequency identification (RFID) within the ultrahigh frequency band (UHF). These applications commonly consist of a single transistor or a switch and an antenna. These devices are able to be activated using only the RF power from an illuminating continuous wave signal and thus can be operated without any external source of energy. In modulated backscattering, a radio frequency (RF) tag is illuminated by an interrogating signal and the tag reflects the impinging signal back toward the transmitter with a reflection coefficient that is varied as a function of the load presented to the terminals of the antenna. The high energy efficiency of the modulated backscatter RFID scheme has made it a strong candidate for implementation in the exponential growing Internet of Things (IoT) and wireless sensor networks (WSNs) that is proposed to have an estimated 50 billion connected devices by the year 2030 [2].

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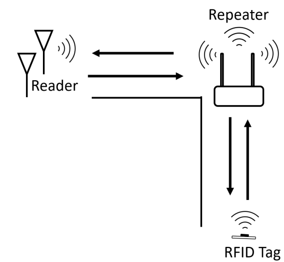


Fig. 1. Proposed repeater architecture in the non-line-of-sight base case of a single bistatic reader (co-located TX/RX), tag and repeater.

Despite the high-energy efficiency of modulated backscattering, the read range of the tags suffers from limitations owing to the fairly expensive link budget required. This is a result of the fact that the received signal power decays to the fourth power of the distance between the reader and the tag; thus, there is a demonstrated need for a cheap, low-cost manner to extend the range of the link for networked implementations in line with the IoT and WSN.

There have been a variety of reported efforts exploring means to improve the read range of RFIDs. The authors in [3] propose the use of a carrier emitter that is detached from the reader in a bi-static configuration, however, this implementation while successful would require the use of RF emitters consuming tens of milliwatts depending on desired output power. In [4] a repeater system is proposed using high gain antennas and a low noise amplifier to improve the link budget in the forward path from the reader to the tag such that more power can be delivered to the tag for a given distance. This presents an effective solution for the passive RFID tags, however, this form of amplification becomes expensive from a cost and power consumption perspective.

Tunnel diodes have been reported for use in the development of low power consumption long range RFID tags [5]–[7]. A tunnel diode-based carrier emitter was presented in [8] which introduces a low power solution where the tunnel diode was used to synthesize a carrier signal for backscatter networks, however, the achievable range of this method was limited by the power output from the emitter. Additional efforts demonstrating the utility of repeater nodes for increased coverage of RFID tags however power consumption of the proposed repeaters prove to be a limitation [4], [9]–[12].

In this effort, the authors present a pair of ultralow power tunnel-diodes-based frequency divided reflection amplifiers for use as repeater nodes that enable the increase of radial coverage and extension of the read range for backscattering 5.8 GHz semi-passive RFID tags, particularly in applications where the reader may not always have a line of sight path to the tags or it is preferable to have a centralized reader and distributed tags. This is a low-cost, low power consumption solution to improve the feasibility of dense and networked implementation of RFID-based sensors in the 5.8-GHz frequency regime.

II. System Components

The proposed system involves the use of a pair of tunnel diode reflection amplifiers to improve the link budget in a backscattering RFID channel as well as improve its coverage by allowing a multitude of tags to be interrogated, especially when a line of sight path from the tag to the reader does not exist.

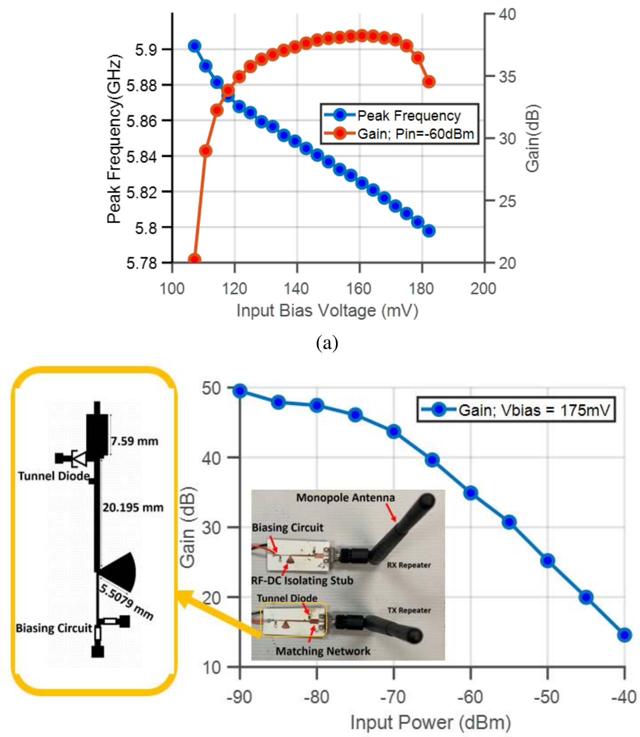
A. Tunnel-Diodes-Based Repeater

The repeater is made up of a tunnel diode reflection amplifier matched to an antenna of choice. In this work, a quarter-wave monopole antenna is chosen for its near-isotropic radiation properties. Tunnel diodes when properly biased are able to present themselves as negative resistance to the terminals of an appropriately matched antenna at a frequency of interest. The negative resistance yields a reflection coefficient that has a magnitude greater than 1 which results in the amplification of an incident signal in reflection. The amplification realized is dependent on the bias voltage and input power into the device. Each reflection amplifier features a tunnel diode (MBD2057 is chosen in this work), stub matching network, and a biasing circuit. The amplifier is characterized by a variety of input powers and bias voltages the results of which are shown in Fig. 2(a) and (b).

The proposed reflection amplifiers are frequency multiplexed such that the operating frequency where the device realizes its best performance in the transmitting and receiving channels are different. This is done by taking advantage of the relatively linear relationship between the applied bias voltage and frequency of operation as shown in Fig. 2(a). The frequency division of the TX/RX channels allows for good isolation between the two closely spaced repeaters and mitigates the potential for oscillation with the only constraint now being the chosen modulation frequencies of the RFID tags being interrogated. The repeater in the transmit path operates at 5.766 GHz with a bias voltage of 166 mV and the receive link repeater is tuned to 5.7 GHz with a bias voltage of 150 mV. The pair of the fabricated repeaters are shown as an inset in Fig. 2(b). The low bias voltages are a feature of the tunnel diodes and highlight the low power consumption of the repeater with each one consuming merely 20 μW.

B. 5.8-GHz Semi Passive RFID Tag

In order to evaluate the proposed system, a 5.8-GHz semi-passive tag is designed and characterized. The tag consists of an antenna, single-transistor switching front end and oscillating circuitry. A quarter-wave monopole antenna is chosen for



(a)

(b)

Fig. 2. Reflection amplifier characterization. (a) Peak frequency versus input bias voltage and gain versus input bias voltage. (b) Gain versus input power.

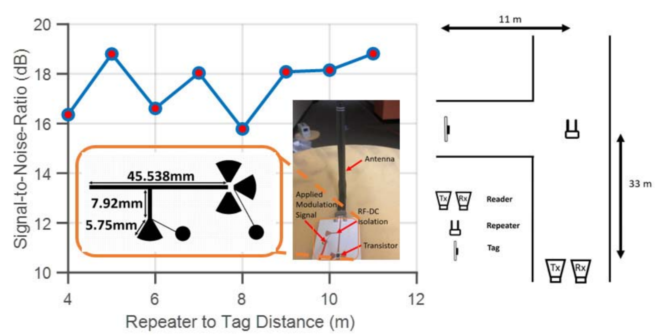


Fig. 3. SNR variation over tag-repeater distance.

simplicity and isotropic radiation in the tag design while the low input gate capacitance of the CE3520K3 transistor makes it suitable to ensure the switch is low power. An image of the fabricated tag is embedded in Fig. 3

To set a baseline for subsequent measurement comparison, this tag was moved away from the reader until a consistent signal to noise ratio of about 10 dB was observed. This was recorded to occur at a distance of about 18 m with 36 dBm output from the transmitting antenna.

III. System Evaluation

To show that the developed system was capable of extending the range of a semi-passive RFID tag while simultaneously enabling non-line of sight interrogation of a multitude of tags, the system was evaluated in a series of non-line of sight (NLOS) conditions with varying distances and transmit power levels in order to show its performance in both single and multitag setups. The measurement setup was comprised of a pair of 9 dB gain horn antennas to transmit and receive, the USRP N210 software-defined radio to synthesize the transmitting signal, and a Tektronix RSA 3408A spectrum analyzer to observe the received signals. The software defined radio was unable to realize more than an 8 dBm output so in order to use the full available power, the SKY66288-11 power amplifier that features a gain of 28 dB at 5.8 GHz was added to the transmit link. The GVA-8+ gain block with 12.5 dB gain was added to the receive link to improve its sensitivity.

A. Single Tag

The first scenario measured involved a single semi-passive tag placed in front of the repeater and the reader placed in front of the repeater around a corner from the tag. The reader was moved to a distance of 33 m to the repeater and the tag was stepped in 1 m increments from 4 m to 11 m away from the repeater. The EIRP for this measurement scenario was 17 dBm which corresponds to only 1.25% of the allowable EIRP specified by the FCC. The sampling rate on the spectrum analyzer was 200 kHz. The SNR of the signal received by the receiver over the different tag-repeater distances is shown in Fig. 3 for the same output power from the transmitter. The plot shows that for this transmit power, the SNR remains relatively constant as the tag was moved further away. This can be explained by the performance of the tunnel diode reflection amplifier where there is an increased gain at lower input power due to saturation of the tunnel diode at higher input power levels as shown in Fig. 3. These results showed the capability of the system to not only extend the range of the semi-passive RFID tag but also extend the visibility of the RFID tag to the reader as is moved further away NLOS.

B. Two Tags Co-Located

In this multitag configuration, the setup was fairly similar to that described for the single tag scenario but a second tag modulating at a slightly different was added to aid discrimination in the resultant spectrum. The addition of a secondary tag at a different frequency necessitated an increase in the sampling rate of the spectrum analyzer up to 500 kHz for this measurement cycle. The measurements were performed maintaining a distance of 33 m between the reader and the repeater and 11 m between the reader and the tag. A series of five measurements were taken for each setup of interest and then averaged. Measurements were taken in four scenarios: both tags active, tag 1 only active, tag 2 only active, and a no tag scenario. The measurements shown in Fig. 4 indicate that the repeater channel was able to adequately amplify both tag responses simultaneously. The region in the middle of the spectrum is the reflection amplifier functioning as an undisciplined oscillator as the input power from either tag was too low to lock onto but the channel spanning the operating bandwidth of the tunnel diode was amplified.

C. Two Tags Separated

In the final configuration, the measurement setup was changed so that the tags were separated from each other. Tag 1 was kept at a distance of 2.3 m to the repeater and tag 2 was kept at a distance of 14 m to the repeater while the reader was located 11.2 m line of sight from the repeater. Similar to the results from the previous setup, the repeater channel was able to amplify the responses of both tags but not lock to either one as shown in Fig. 5. This was important in this configuration as it showed the system does not suffer from the near-far problem and lock onto the nearer tag while disregarding the tag further away. However, it may be advantageous to have the repeater lock onto a single injected signal to further extend the read range by providing additional gain. This was verified by turning off tag 2 and increasing slightly the input transmit power until the repeater locked onto the desired signal. For the same distance, there was an increase of 22 dB in the signal-to-noise ratio for the locked tag as shown in Fig. 5. This opens up the potential for the use of time-multiplexed RFID tags operating at a similar frequency where each tag is activated in turn for a short period of time and can be locked onto to gather information.

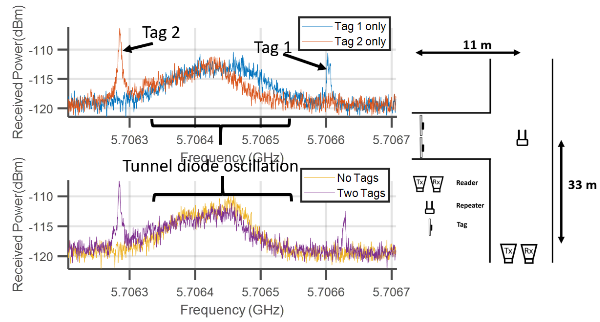


Fig. 4. Received signal power versus Frequency for two co-located tags.

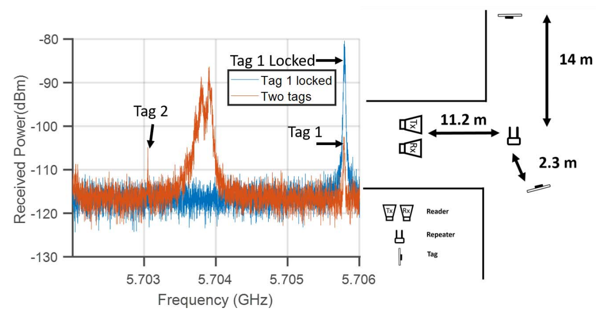


Fig. 5. Received signal power versus Frequency for two separated tags.

TABLE I
REPEATER POWER CONSUMPTION COMPARISON

	Repeater Power Consumption	Operating Band
This work	40 µW	5.8 GHz
[4]	9300 mW	900 MHz
[10]	240 mW	2.4 GHz
[12]	270 mW	2.4 GHz

IV. CONCLUSION

In this effort, the authors show a system that presents low power low cost range and coverage extension capability for RFID networks. The system is able to improve coverage and readability for multiple tags in NLOS scenarios while extending the read range by more than 2X for 17 dBm transmitter output power and consuming up to 1000X less power than competing technologies as shown in Table I. It is implemented in a minimal single-component low-cost architecture. It is easily inferred that the range and visibility of the RFID tags can be extended much more when transmitting the maximum EIRP. The reported system shows great potential for extension to multirepeater, multiple time multiplexed tags/WSNs, and multiple reader networks for smart city, IoT, smart inventory, and smart agriculture use cases.

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