A Dual-Band Approach for Backscattering Modulation

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***Abstract*—In typical passive UHF RFID systems, tags rely on backscattering, where they modulate a reflected signal by switching impedance states, powered solely by the reader's RF signal. In contrast, active RFID tags offer enhanced communication capabilities but require an internal power source. This work introduces a novel hybrid approach that combines electromagnetic energy harvesting and backscattering, utilizing two distinct carrier frequencies. A 2.45 GHz transmitter powers a rectenna and encodes a frequency sweep from 20 kHz to 100 kHz using a simple mixer. After energy harvesting, the device modulates its 5.8 GHz backscattering antenna with the down-converted signal. This results in a backscattered 5.8 GHz signal that is easily distinguishable from the transmitter signal owing to the introduced frequency offset. This method enhances the reliability and modulation options of passive RFID tags. Finally, a fully passive, batteryless remote control application is explored to demonstrate the potential of this approach.**

***Index Terms*—RFID, Backscattering, Modulation, Low-cost, batteryless, IoT.**

I. INTRODUCTION

The last decades, radio-frequency identification (RFID) has become a vital part of many modern industries. In retail, cost-effective RFID tags can be embedded in products to prevent loss and theft [1]. Furthermore, some stores have started implementing this technology in automated checkouts, saving costs and increasing customer convenience [2]. The vast scale of today's logistics and inventory management also greatly benefits from these tags, allowing goods to be identified, tracked and monitored at all times [3].

There are several frequency bands in which RFID applications typically operate [4]. At lower frequencies, tags rely on inductive coupling, as is the case for near-field communication (NFC). However, this only supports readouts up to maximally one meter. To increase the range, ultra-high frequency (UHF) tags are used, typically operating between 860 MHz and 960 MHz. Since the antennas operate in their far field, the path loss is very large and the power received by the tag is minimal. To enable communication at these low power levels, backscattering is employed, diminishing the need for a complex RF transmitter in the tags. The tag receives the, generally amplitude or phase modulated, signal from the transmitter, and either stores this information or responds to the message. By switching the RFID antenna between different loads, the tag is able to respond to the reader by backscattering its signal. This amplitude load modulation usually operates at a sub-carrier of the incoming data signal [5]. Yet, the sensing capabilities and range of entirely passive RFID tags remain very limited. Alternatively, surface acoustic wave (SAW)-based filters [6] have demonstrated a significantly extended range due to their independence from integrated circuits (ICs). However, this simplicity limits their functionality, typically restricting them to basic tag identification or simple sensing tasks. Active RFID tags do enable more complicated sensing applications and can achieve a significantly greater communication range compared to passive UHF tags [7], making them an attractive option for the internet of things (IoT). But, in contrast to the passive backscattering tags, active tags rely on a battery or an external power source.

Recently, energy harvesting has been explored for batteryless IoT applications [8]. Solar panels, kinetic movement or thermal differentials are currently being used to power sensing applications or perform low-power tasks [9]–[11]. These external sources could eliminate the need for batteries in active RFID tags or significantly extend their lifespans. However, they are all reliant on light, movement or heat, respectively, limiting their feasibility in certain environments and applications. As an alternative, electromagnetic energy harvesting or wireless power transfer (WPT) has long been explored at microwave frequencies [12]. Since ambient RF sources are generally too weak to power any circuit, the rectennas must be intentionally irradiated, of which the effective isotropic radiated power (EIRP) is limited by regulations. Hence, as is the case for passive RFID tags, the extremely low received power levels have largely hindered advanced applications and a simple backscattering modulation remains the best option. Furthermore, the power required to activate the circuit means that the range of the WPT is again extremely limited, maximally achieving a few meters.

In this work, we propose a new approach to these long-standing problems by combining the strengths of wireless power transfer with backscattering at two separate microwave frequencies. The technique is aimed at enabling simple passive RFID tags or batteryless IoT applications that can communicate with significantly lower power levels, thereby increasing the range of such tags. By transmitting a modulation signal to the wireless node and modulating the backscattering at another frequency, the circuit can operate without ICs.

In contrast to other dual-band approaches that aim to increase the bandwidth [13] or support multiple communication protocols [14], our system focuses on maximizing communication range using entirely passive hardware. Compared to harmonic backscattering [15], our method allows for encoding

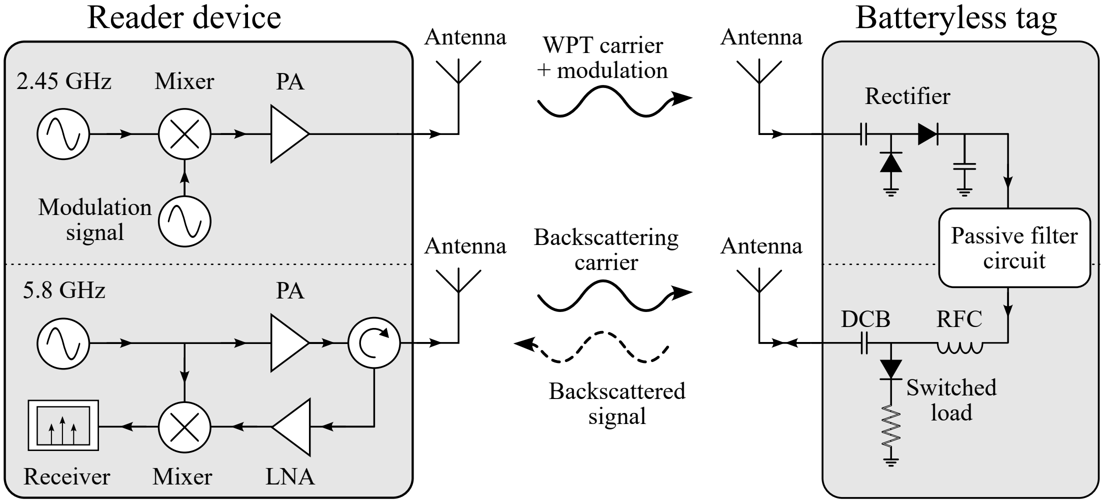


Fig. 1: Block-schematic overview of the proposed communication technique between the reader and passive batteryless device.

more information passively, as the modulation signal is swept over a broad frequency span rather than being restricted to harmonic frequencies. Furthermore, the reader device will suffer from significantly less interference by its own harmonics. Though backscattering sensors that modulate the harmonics through vibrations have been proposed [16], these still rely on mechanical energy harvesting. Our system eliminates this dependency by introducing a second carrier frequency. This operating principle is further explained in detail in Section II. Afterwards, Section III demonstrates the feasibility of this modulation technique in a proof-of-concept measurement and a conclusion follows.

II. OPERATING PRINCIPLE

A block-schematic overview of the proposed technique is shown in Fig. 1. The operation relies on two separate carrier frequencies, the first of which is used for wireless power transfer and sending a modulation signal to the receiver device. The second frequency offers a means for the passive device to respond to the reader by modulating and backscattering its signal. In this paper, two microwave frequencies, at the 2.45 GHz and 5.8 GHz ISM bands, are selected as they are internationally available. However, any pair of sufficiently spaced carriers could be used, depending on the application.

Starting from the top left in Fig. 1, the first carrier of 2.45 GHz is generated. This carrier is then mixed with a modulation signal, which in this application will typically be a frequency sweep. The frequencies in this sweep must be sufficiently low, such that the first order mixing products remain in the two selected frequency bands. After mixing, this signal is then amplified by a power amplifier (PA) and transmitted by the reader's antenna. Since this is the signal responsible for WPT, the output power should be maximized within the given regulations to achieve the maximum range.

This modulated WPT signal is then received by the batteryless node and rectified. In the current representative implementation, a voltage doubler rectifier is employed as it is known to achieve a good power conversion efficiency (PCE) [17]. Though any rectifier topology could be used, its PCE will have a direct impact on the range of the wireless link. Note that custom CMOS rectifiers could achieve a higher performance by exploiting synchronous rectification [18]. The rectifier, being optimized around the 2.45 GHz band, will rectify the carrier frequency to a DC voltage. However, the comparatively low-frequency modulation signal will not be filtered. Hence, the resulting output is a pulsed DC signal at double the modulation frequency.

Next, the harvested power is exploited to respond to the reader. Typical energy harvesting devices would use this power to charge a supercapacitor and perform some operation once sufficient charge has accumulated. Here, in contrast, we propose to directly use the pulsed DC voltage for backscattering. Moreover, an entirely frequency-selective circuit can be conceived, allowing only pulses from a specific modulation frequency to pass or be blocked. In a remote-control application [19], this circuit could be comprised of simple push buttons that connect certain filter components, each responsible for a different bandpass frequency. However, other low-power or passive sensors could also be used to manipulate these filters. For example, a thermistor-based filter could enable an entirely passive and batteryless remote thermometer.

The now filtered modulation signal is used to switch a load connected to a 5.8 GHz antenna to enable backscattering, hereby mixing the modulated signal with the backscattered 5.8 GHz carrier. As shown in the overview of Fig. 1, this continuous-wave carrier is also generated at the reader side, where it is amplified and transmitted to the tag. On the batteryless tag side, the antenna load is switched using a diode, switching the antenna between a complete mismatch (open) and a matched load, though alternative topologies can achieve similar results. Importantly, an RF choke (RFC) should be used to prevent the 5.8 GHz signal from interfering or getting influenced by the rest of the tag's circuit. Similarly, depending on the antenna type, a DC-block (DCB) capacitor may be

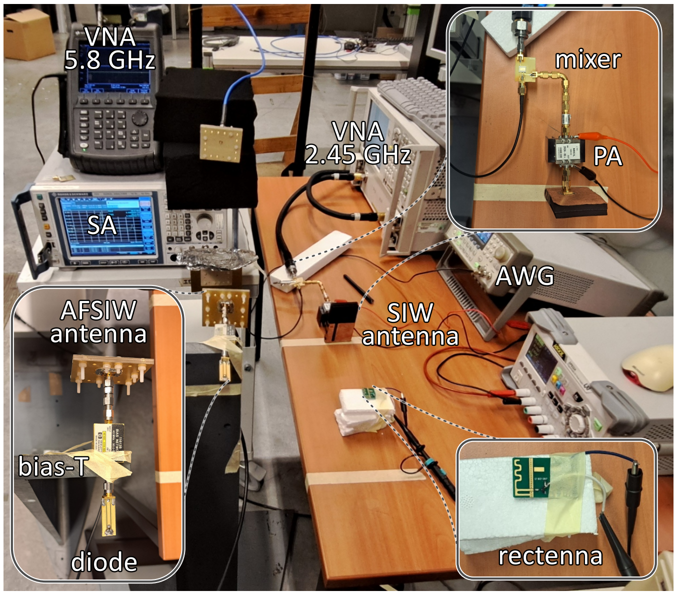
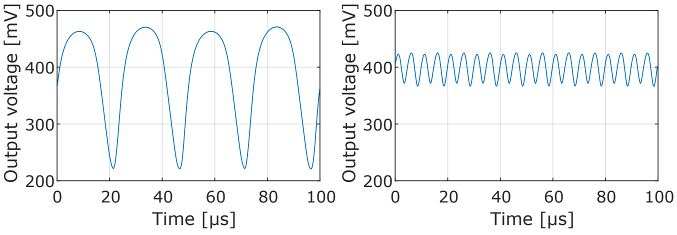
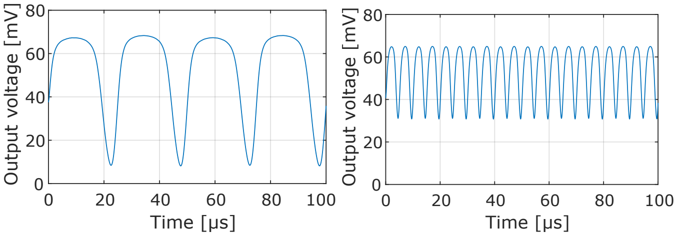


Fig. 2: Overview of the experiment setup.



(a) $f_{mod} = 20\,\text{kHz}$, unloaded. (b) $f_{mod} = 100\,\text{kHz}$, unloaded.



(c) $f_{mod} = 20\,\text{kHz}$, loaded. (d) $f_{mod} = 100\,\text{kHz}$, loaded.

Fig. 3: Pulsed-DC output voltage of the 2.45 GHz rectenna.

necessary to prevent the modulated signal from getting shorted by the antenna.

Finally, the backscattered signal is received by the reader, either via a separate antenna or by relying on a circulator to separate the transmitted and received signals. The received signal is then typically fed into a low-noise amplifier (LNA) and mixed with the 5.8 GHz carrier frequency to obtain the modulated signal. Depending on how the tag's filters are configured, the received modulation frequency will be modified, carrying the information.

III. PROOF-OF-CONCEPT MEASUREMENT

To validate the proposed modulation technique, an experimental mock-up setup is built utilizing testing and measurement laboratory equipment, as illustrated in Fig. 2.

First, to emulate the reader, a Keysight PNA E8364B vector network analyzer (VNA) is configured as a 2.45 GHz carrier source emitting 10 dBm. To obtain a modulation signal, a sine wave of [20-100] kHz, 1 Vpp is generated by an Agilent 33250A arbitrary waveform generator (AWG). Next, a MAC 60+ double balanced mixer module by Mini-Circuits upconverts this modulation signal onto the 2.45 GHz carrier before amplifying it to 16 dBm using a ZRON-8G+ PA by Mini-Circuits. This modulated WPT signal is then transmitted by a 4.8 dBi substrate integrated waveguide (SIW) antenna [9]. The second carrier frequency of 5.8 GHz at 9 dBm is generated by a Keysight fieldfox VNA and fed directly into a 6.6 dBi air-filled SIW (AFSIW) antenna [20]. To receive the backscattered signal at the reader, an identical AFSIW antenna is connected to a Rohde & Schwarz FSV 40 spectrum analyzer (SA), which directly monitors the signal and its modulated mixing products.

To realize the batteryless remote device, a compact and efficient 2.45 GHz rectenna [21], featuring an antenna gain of 0.2 dBi, was exploited to harvest the wireless power and to down-convert the modulation signal embedded in the received 2.45 GHz carrier. Another 6.6 dBi AFSIW antenna, identical to the one deployed at the reader, also serves as the 5.8 GHz backscattering antenna. The load-switching was performed using a single SMS7630 diode by Skyworks, which was connected to the antenna using a bias-T, acting as both DCB and RFC. On the DC-side of the bias-T, the pulsed-DC modulation signal is connected, thereby mixing with the 5.8 GHz backscattered signal. Note that, in this proof-of-concept experiment, only the backscattering modulation technique is demonstrated and no filters for manipulating the data are implemented yet. Furthermore, since the mock-up by no means represents a final product, the system and its components are far from optimized and the functional range is limited. Therefore, the measurement setup uses a spacing just 30 cm for the 2.45 GHz WPT and 50 cm for the 5.8 GHz signal, such that the measurements are clearly visible. In the future, however, a well optimized custom PCB is expected to achieve a range of at least several meters.

To demonstrate the concept, a frequency sweep from 20 kHz to 100 kHz is configured on the AWG. Consequently, a frequency that is double the original modulation frequency can be observed at the output of the rectenna, as shown by the example oscilloscope measurements presented in Fig. 3. Mostly independent of the mixing frequency, the average unloaded output voltage of the rectifier at this distance is approximately 400 mV, whereas it is only 54 mV when loaded with the unoptimized backscattering diode. Yet, this remaining small signal suffices to change the diode impedance and thereby modify the backscattering antenna's load. The modulated backscattered signal can then be observed on the SA. Fig. 4 demonstrates the resulting modulated frequency sweep by combining multiple screenshots. The resulting received power of the mixing products is -67 dBm, in comparison to -28 dBm leaking from the

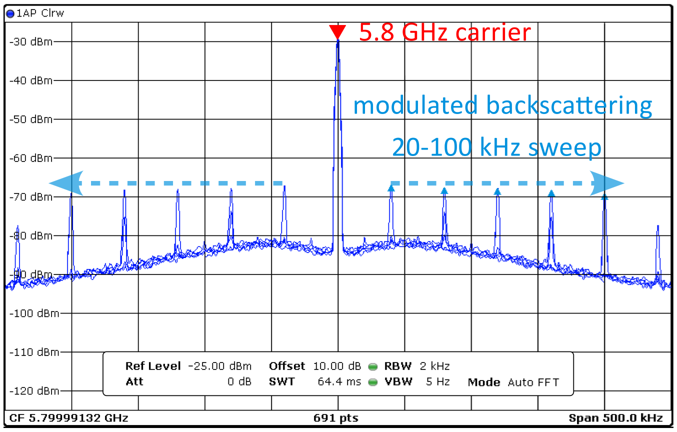


Fig. 4: Combined received output spectra showing the backscattered frequency-sweeping modulation signal.

carrier frequency. However, in the future, a complete system with a circulator would significantly improve the isolation. When the pulsed-DC modulation signal is disconnected from the backscattering antenna, the mixing products in the output spectrum disappear, conclusively proving that the received modulated signal is indeed generated by the proposed entirely passive backscattering system.

IV. CONCLUSION

In this work, a dual-band approach for backscattering modulation was proposed and successfully demonstrated. Measurements show how the modulated signal is clearly observed in the output spectrum with a signal strength of -67 dBm, proving the validity of this concept. Currently, the range remains limited, with the mock-up measurement demonstrating a WPT distance of just 30 cm. In the future, however, a completely optimized custom design should greatly improve this range up to several meters. Finally, this technique enables simple and entirely passive RFID tags or IoT devices, without the need for any ICs. Therefore, the proposed method has the potential to offer an increased readout range compared to other electromagnetically-powered devices.

V. ACKNOWLEDGMENT

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