On-the-fly Adaptation of Backscatter Modulator Impedances Using Digitally-Tuned Capacitors

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***Abstract*—We present a fully-digital backscatter communication circuit that uses digitally-tuned capacitors (DTCs) to optimize the backscatter modulator impedances across variations in antenna impedance and incident carrier wave power. The circuit transmits 1 Mbps single sideband frequency-shift keying backscatter modulation in the 915 MHz and 2.4 GHz industrial, scientific, and medical (ISM) bands. By using DTCs to optimize the backscatter modulator impedances, the desired sideband power was increased by 1.45 dB at 915 MHz and 2.7 dB at 2.4 GHz while the undesired sideband power was reduced by 2.88 dB at 915 MHz and 4.72 dB at 2.4 GHz.**

Backscatter, communications, internet of things (IoT), RFID, wearable electronics.

I. Introduction

Backscatter communication offers ultra-low power data uplink capability to energy constrained electronics. It achieves power consumption that is orders of magnitudes lower than conventional active radios like Wi-Fi (IEEE 802.11) and Bluetooth Low Energy, enabling novel applications of wireless sensing like *in vivo* neural recording from a dragonfly [1]. High energy efficiency is achieved by repartioning the RF carrier wave source and RF amplifier to an external carrier wave source, as shown in Fig. 1 (a-b). The backscatter communication system transmits data deliberately introducing an impedance mismatch at its antenna to reflect the carrier wave with a specific amplitude and/or phase. Changing the apparent impedance to the antenna requires very little power, but the energy savings come at a cost. The carrier wave must make a two-way trip from the carrier wave source to the backscatter sensor and back to the receiver, resulting in a less favorable link budget compared to conventional active radios [2].

The choice of impedances for reflecting the carrier wave is critical for maximizing the performance of a backscatter communication system. To this end, we have explored the use of digitally-tuned capacitors (DTCs) (Fig. 1(c-d)) with RF switch-based modulators as a way of developing low-loss, easily configurable backscatter systems [4]. For this work, we consider the situation where a backscatter sensor is used with an antenna whose characteristic impedance is changing, for example to operate in a different frequency band or due to physical deformation of the antenna, e.g. bending, in the case of wearable electronics [5].

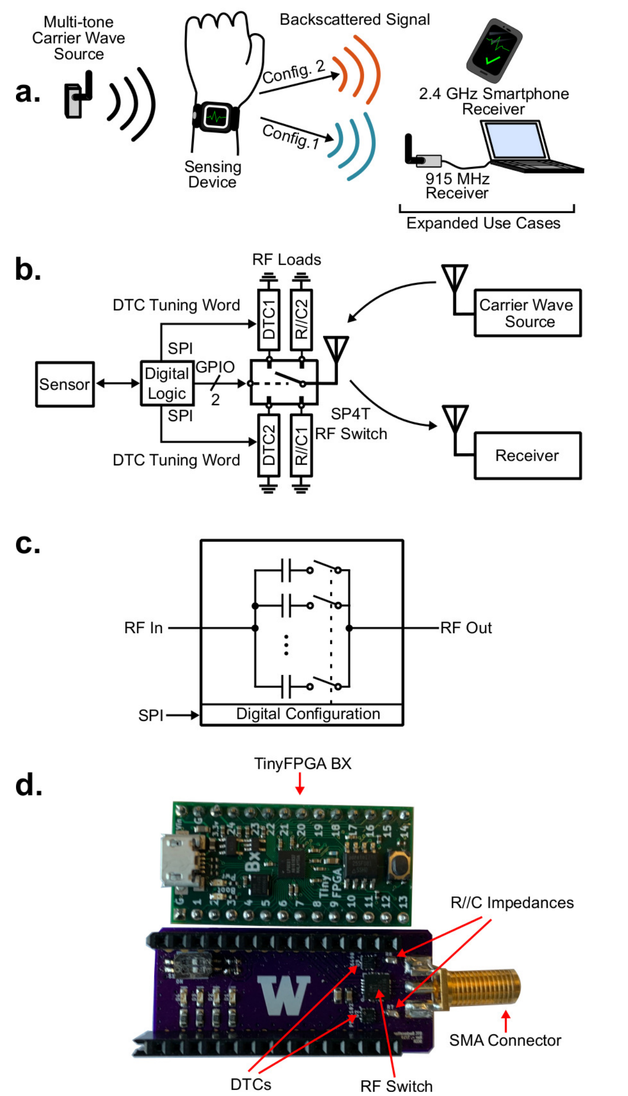

Fig. 1. (a) Application of multi-tone low power backscatter communication, (b) Block diagram of a digitally-tuned adaptive modulator to improve the backscattered signal spectrum, (c) Diagram of a digitally-tuned capacitor (DTC) (adapted from [3]), (d) Photo of the TinyFPGA BX circuit and the prototype backscatter modulator.

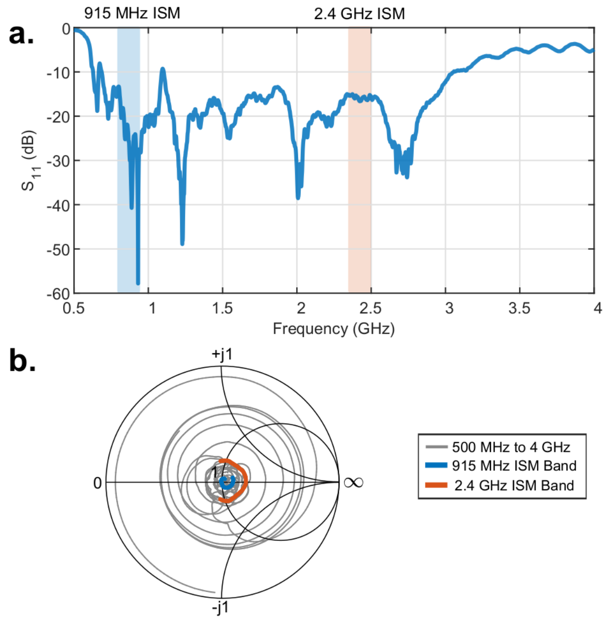

Fig. 2. Sample measurement of S_{11} for a wideband antenna. As seen from the log-magnitude plot (a) and Smith chart (b) the antenna's input impedance changes over frequency.

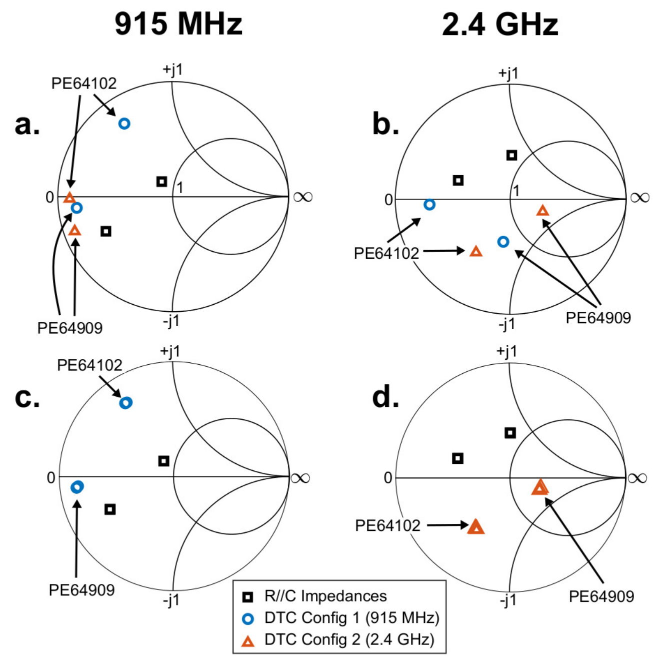

Fig. 3. Smith chart of the measured modulator impedances at 915 MHz and 2.4 GHz. Configuration 1 is the optimal DTC tuning for 915 MHz and Configuration 2 is the optimal tuning for 2.4 GHz. (a-b) Overlaid measurements showing how DTC Configurations 1 and 2 vary across frequency. (c-d) Measurements of the reflection coefficients as power was swept from -30 dBm to 0 dB. Negligible variation is observed.

II. Backscatter Modulator Design

A. Theoretical Overview

The received signal strength from a backscatter communication system can be determined based on the link budget equations presented in [2]. A key component of the backscattered link budget is the differential radar cross-section (DRCS), which depends on

$$\mid \Gamma_i^* - \Gamma_j^* \mid^2 \tag{1}$$

where $\Gamma_{i,j}^*$ is the conjugate match reflection coefficient

$$\Gamma_{i,j}^* = \frac{Z_a^* - Z_{i,j}}{Z_a + Z_{i,j}} \tag{2}$$

for a complex resonant antenna impedance Z_a and complex load impedances $Z_{i,j}$ [6]. The conjugate operator in Eqn. 2 is a non-linear operator, indicating that magnitude and phase of the conjugate match reflection coefficient, and thus the DRCS, will vary non-linearly with changes to Z_a. Practically, this means that the optimal choice of backscatter modulator impedances is likely to change as the antenna's impedance changes. These changes can affect not only the strength of the backscattered signal, but also the spectral performance like sideband suppression ratio for higher-order backscatter modulations [7].

B. Design Example

Multi-band backscatter communication is an example where one might need to design a backscatter modulator for different antenna impedances. Impedance measurements of an L-Com wideband log-periodic antenna (L-Com part number HG72710LP-NF) are shown in Fig. 2. The figure shows how the antenna impedance varies across different frequencies, including the 915 MHz and 2.4 GHz industrial, scientific, and medical (ISM) bands where many backscatter tags operate.

In addition to the antenna's impedance, the conjugate match reflection coefficient is also sensitive to parasitics of the complex load impedances, which can vary significantly across operating frequencies. This is demonstrated using the prototype circuit of Fig. 1(b) and (d), which implements an FPGA-based single sideband frequency-shift keying (SSB FSK) backscatter communication system using a single-pole-four-throw (SP4T) RF switch that can connect the antenna between two DTCs (Peregrine Semiconductor PE64909 and PE64102) or two resistor/capacitor pairs.

The DTC impedance configurations were chosen by sweeping through all possible control words and using the configuration which maximized the Eqn. 1 averaged across the four impedance states. Fig. 3 shows calibrated vector network analyzer (VNA) measurements of the backscatter modulator at 915 MHz and 2.4 GHz. In Fig. 3(a) and (b) it can be seen that the optimal DTC configuration for 915 MHz does not maximize the geometric distance between all the reflection states at 2.4 GHz and vice-versa.

III. Experimental Validation

Spectral measurements were performed to validate the performance improvement granted by using DTCs to achieve the optimal modulator impedance at a given frequency band. A digital design was written in Verilog was programmed onto a TinyFPGA BX open-source FPGA (Fig. 4(a)). The design

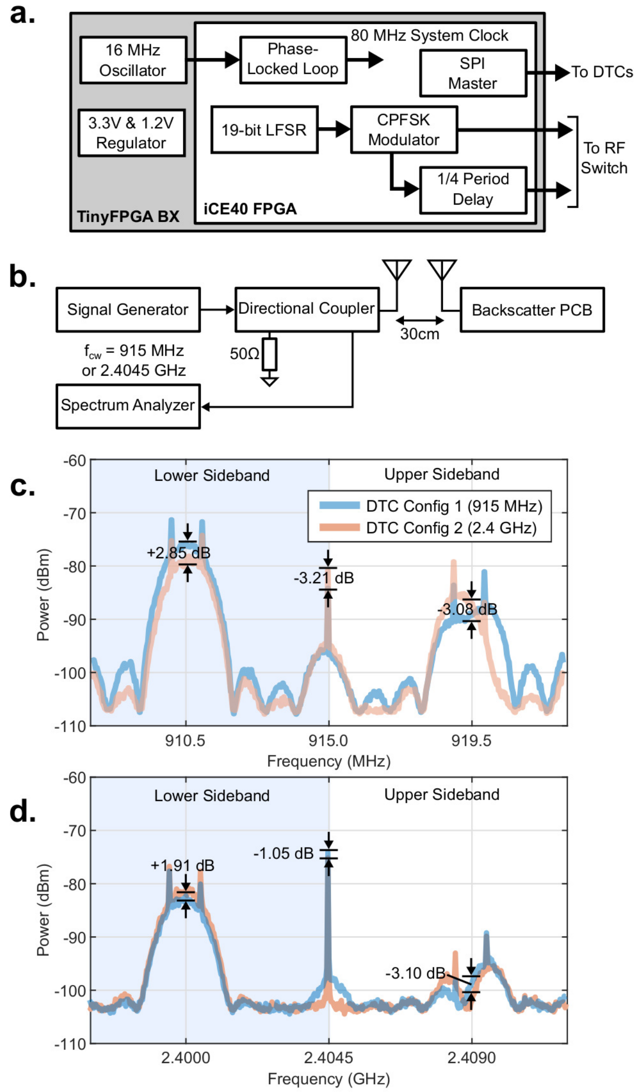

Fig. 4. (a) Digital design used to evaluate the DTCs (b) Setup for measuring the backscattered signal power in the (c) 915 MHz ISM band and (d) 2.4 GHz ISM band. In (c) DTC Configuration 1 is optimal and in (d) DTC Configuration 2 is optimal. For this experiment, the modulation was setup such that the lower sideband was desired and the upper sideband was undesired.

generated pseudo-random stream bits at 1 Mbps and used Single sideband continuous-phase FSK modulation (CPFSK) with subcarrier frequencies of 4.0 MHz and 5.0 MHz. The lower sideband was selected as the desired sideband for this experiment. The FPGA and backscatter PCB were joined and connected to a signal generator and spectrum analyzer via coaxial cables and a directional coupler (Fig. 4(b)). The backscattered spectrum was then measured for a carrier wave frequency of 915 MHz and 2.4045 GHz, as shown in Fig. 4(c) and (d), respectively. The measurements showed that by tuning the DTCs to achieve the optimal impedance states, the desired sideband power was increased by 1.45 dB at 915 MHz and 2.7 dB at 2.4 GHz. Similarly, the undesired sideband power was reduced by 2.88 dB at 915 MHz and 4.72 dB at 2.4 GHz.

IV. Conclusions & Future Work

We present analysis and measurements of a fully-digital backscatter communication system that uses DTCs to optimize its modulator impedances. The measurements demonstrate that using DTCs can improve the strength of the backscattered signal by several decibels, which could be a significant benefit for link budget-limited backscatter applications. Additionally the RF switch-based architecture was found to be resilient to variations in the incident carrier wave power at both 915 MHz and 2.4 GHz, which suggests that this is a useful architecture for applications experience a high dynamic range of carrier power. Future work will seek to quantify the performance of the system in a rel event use-case, e.g. uplinking data from a wearable wireless sensor.

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