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Enhanced FSK-modulated Ambient Backscatter Communication System

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***Abstract*—Backscatter communication (Backcom) technology is rapidly developing for deployment in Internet-of-Things (IoT) applications due to its low cost and potential for battery-free operation. In this work, we show that with proper processing at the Backcom receiver the performance of ambient Backcom, with frequency-shift-keying (FSK) based modulation, can be significantly improved compared to the current state of the art. Employing existing ambient radio frequency (RF) signals like TV, FM, Wi-Fi, cellular, etc. as carriers to eliminate dedicated carrier generator, namely ambient Backcom, can massively reduce system costs. However, this compromises to link performance, e.g., data rates and communication range, can be significant and therefore limit its application. Our proposed system is validated using ambient FM signals and 40 kHz bandwidth digital signals in both simulation and experimental environments, achieving zero-error communication with 4m distance between tag and receiver at 200 bps.**

***Keywords*—Ambient carrier, backscatter, FSK, signal processing**

I. INTRODUCTION

Backscatter communication (Backcom) technology is preferred for Internet-of-Things (IoT) devices thanks to its potential for low power. Data transmission is achieved by passively and dynamically reflecting/modulating incoming wireless signals rather than actively generating local radio frequency (RF) signals to convey information. Therefore, the backscatter tags consume much less power, of the order of μW. Most traditional Backcom systems require a dedicated RF carrier source such as in commercial RFID [1]. In an RFID system, the reader acts as both carrier signal generator and receiver. One drawback is the high hardware complexity and high cost, preventing its application in the IoT domain.

To eliminate the dedicated carrier resource, the ambient Backcom concept was first introduced in [2]. The authors utilized an ambient digital TV signal as the carrier source to achieve tag-to-tag communication with an On-Off keying (OOK) modulation scheme. The communication distance achieved was less than 1 m. OOK modulation has been widely applied to a diverse of ambient carrier signals, such as ambient broadcasting frequency modulation (FM) [3], LoRa [4], Wi-Fi [5], and cellular (4G, 5G) [6] signals. When the waveforms of carrier signals are known, Backcom tag can employ codeword translation modulation to change the original carrier signals' phase, amplitude, and frequency into recognizable symbols according to the codeword book. Then the enclosed information can be demodulated by comparing the outputs from commodity devices in two adjacent channels. For example, FreeRider [7] realized an ambient Backcom link by employing ambient Wi-Fi, Zigbee, or Bluetooth signals. The ambient Backcom concept is promising but it is still challenging to realize it. OOK-based ambient Backcom suffers from short communication distance. This is because the energy detection [2], [3], [6] or phase jumping detection [4] demodulation methods are sensitive to channel noise, and the commodity-device-based system [7] is not flexible when ambient signals are inaccessible or there exist multiple ambient sources.

One possible solution is ambient Backcom frequency shift keying (FSK) modulation. Most previous literature is based on dedicated carriers [8], rather than ambient signals. FSK on ambient signals cannot operate for wideband signals whose bandwidth is greater than the selected frequency shift because it is difficult to distinguish the frequency shifting due to the spectrum overlap.

In this study, we propose an I/Q signal sample processing method for FSK-based ambient Backcom system. This approach works for various ambient carrier signals. Our proposed method is able to separate the ambient signal and backscattered waveform at the receiver end so that the system performance can be enhanced. The system is validated in both simulation and experiment, and the examples using an ambient FM carrier and a 40 kHz bandwidth quadrature phase shift keying (QPSK) carrier are presented.

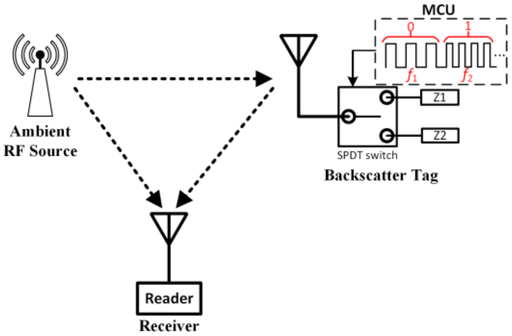


Fig. 1. Illustration of FSK-based Backcom system.

II. ENHANCED FSK-MODULATED AMBIENT BACKCOM THROUGH I/Q SAMPLE PROCESSING

Fig. 1 shows a general bistatic architecture of an FSK-modulated ambient Backcom system, including an ambient RF source, a backscatter tag, and a reader. In this section, the principle of an FSK backscatter tag is introduced. Then the mathematical modelling and our proposed I/Q sample processing method are presented. Finally, the simulated results of the proposed system are analyzed, utilizing captured ambient FM signals and a QPSK signal occupying 40 kHz bandwidth.

A. *FSK-modulated ambient Backcom*

The FSK-enabled backscatter tag is depicted at the top-right in Fig. 1. Here the backscatter modulation is based on the multiple-antenna-load system [3] that arranges two different loads connected to the antenna using a single-pole-double-throw (SPDT) RF switch to reflect the incoming ambient signals with two different phases. Ideally these two loads should be symmetric with respect to the matching load in the Smith chart. In the FSK modulated backscatter system, the binary data stream is modulated by changing the switching frequency f_{sw} (seen in Fig. 1) between two load states: taking 2FSK as an example, when transmitting a bit zero (or one) f_{sw} is selected to be f_1 (or f_2), for a symbol duration T. 2FSK modulation method has been employed in [8], [9] but with dedicated continues wave (CW) as the ambient signals. Whereas our proposed system is able to perform FSK modulation with unknown ambient carrier signal and the embedded information can be recovered by our proposed sample processing method. The system and processing methods are elaborated in the following subsections.

B. *Proposed I/Q sample processing*

In this subsection, the ambient backscatter system is mathematically expressed, and our proposed differentiation signal processing method is then introduced for frequency demodulation.

Using Fourier series an arbitrary ambient signal can be expressed in (1),

$$\boldsymbol{S}(t)=\sum_{i=1}^{\infty}P_i e^{j2\pi(f_c+f_i)t}\ , \tag{1}$$

where P_i is a complex coefficient and f_c is center frequency of the frequency band of interest. The backscatter tag acts as a frequency mixer that upconverts the binary data stream controlling the SPDT switch to the incoming RF frequency. The waveform generated by the tag is square-like, producing a number of positive and negative harmonics. Here only the first-order positive harmonic is considered. The backscattered waveform thus becomes

$$\boldsymbol{B}(t)=\sum_{i=1}^{\infty}P_i e^{j2\pi\left[f_c+f_i+f_{sw}(\tau)\right]t}\ . \tag{2}$$

At the receiver end, after frequency down-conversion and filtering, the received signals turn into

$$\boldsymbol{C}\left(t\right)=\sum_{i=1}^{\infty}P_i e^{j2\pi\left[f_i-f_{sw}(\tau)\right]t}+Q\sum_{i=1}^{\infty}P_i e^{j2\pi f_i t}\ . \tag{3}$$

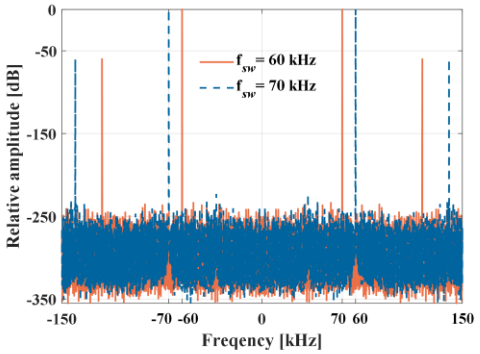


Fig. 2. The simulated spectrum of the first term in $\boldsymbol{R}(t)$ for f_{sw} = 60 kHz and 70 kHz.

Here the second term in (3) is the ambient signal coming directly from the ambient source with a weighting factor Q, whose absolute value is much greater than 1.

The traditional FSK-based Backcom system attempts to demodulate the message from $\boldsymbol{C}(t)$ in (3). However, since f_{sw} is not sufficiently high compared to the bandwidth of ambient signals, it become difficult to extract the backscatter signals because of spectrum overlapping. In order to separate the ambient signal and backscattered signals, we propose a differentiation based I/Q sample processing method by calculating the ratio between the differentiated samples and raw samples.

Applying differentiation to $\boldsymbol{C}(t)$, it becomes

$$\begin{aligned}\boldsymbol{C}^{'}\left(t\right)=&\ j\sum_{i=1}^{\infty}2\pi\left[f_i+f_{sw}\left(\tau\right)\right]P_i e^{j2\pi\left[f_i+f_{sw}(\tau)\right]t}\\&+jQ\sum_{i=1}^{\infty}2\pi f_i P_i e^{j2\pi f_i t}\ .\end{aligned} \tag{4}$$

Now the ratio of $\boldsymbol{C}'(t)/\boldsymbol{C}(t)$ can be obtained, which, after some derivations, is expressed in (5).

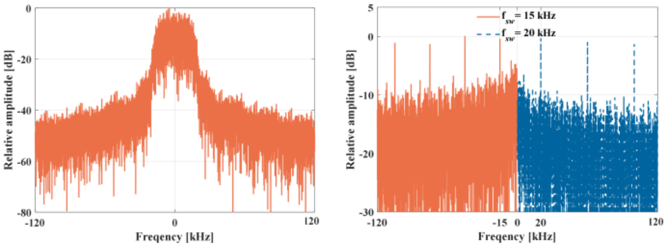
$$\begin{aligned}\boldsymbol{R}\left(t\right)=&\frac{\boldsymbol{C}^{'}\left(t\right)}{\boldsymbol{C}\left(t\right)}=\frac{j2\pi f_{sw}\left(\tau\right)}{1+Q\cdot e^{-j2\pi f_{sw}(\tau)t}}\\&+\frac{j\sum_{i=1}^{\infty}2\pi f_i P_i e^{j2\pi\left[f_i+f_{sw}(\tau)\right]t}+jQ\sum_{i=1}^{\infty}2\pi f_i P_i e^{j2\pi f_i t}}{\left(1+Q\cdot e^{-j2\pi f_{sw}(\tau)t}\right)\sum_{i=1}^{\infty}P_i e^{j2\pi\left[f_i+f_{sw}(\tau)\right]t}}\ ,\end{aligned} \tag{5}$$

The first term in $\boldsymbol{R}(t)$ produces a frequency spike at $f_{sw}(\tau)$ in FFT bins as depicted in Fig. 2, and this tone is independent of the ambient signals. In the plot, we show the spectrum in relative amplitude in dB, whose maximum is normalized to be 0 dB. Two switching frequencies f_{sw} = 60 and 70 kHz are used in the simulation, and the harmonics at the frequency of integer times of f_{sw} are also generated but with at least more than 60 dB attenuation. The second term in $\boldsymbol{R}(t)$ acts as interference to the first term and its strength varies with different ambient signals.

C. *Simulation results*

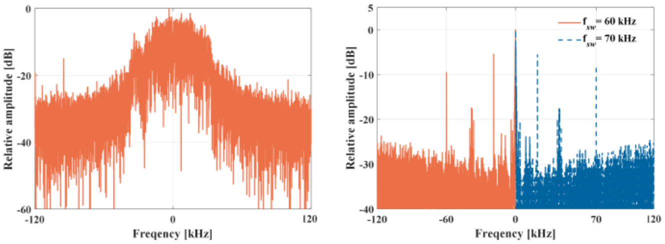
In the simulation, we consider two types of ambient signals: a signal of 40 kHz-bandwidth and an ambient FM signal. The former is generated by applying Root-Raised-

Cosine (RRC) digital filter to a QPSK signal stream, and ambient FM signals are real captured using a software-defined radio (SDR).



(a) (b)

Fig. 3. Simulated spectrum of received Backcom signal with the ambient QPSK signal of 40 kHz-bandwidth (a) raw signals when f_{sw} = 15 kHz, (b) after our proposed I/Q-sample processing.



(a) (b)

Fig. 4. Simulated spectrum of simulated received Backcom signal with the ambient signal of FM carrier (a) raw signals when f_{sw} = 60 kHz, (b) after our proposed I/Q-sample processing.

When combining the carrier signal and backscattered signal as in (3), only the amplitude difference between them is considered. In this simulation, another two factors are inspected. When signals propagate in different wireless channels, they may suffer distinct path losses and phase shifting. The former contributes to Q. Similarly, applying various phase shift will cause a phase difference between the carrier and backscattered signals, which is equivalent to the phase of Q. Here the phase difference is assumed as 90° in the simulation. Secondly, the time delay t_0 between BS signals and carrier signals is related to the path difference D, and it can be expressed as:

$$t_0 = \frac{D}{c} \tag{6}$$

where c is the speed of light. Here t_0 is assumed to be one sampling period of 0.5 μs, D =150 m which is much larger than the experiment setup, i.e. the worst case in simulation. The I/Q sample processing method is implemented by following a similar procedure described in the quadrature demodulation method [10].

Fig. 3 shows the spectra of the received signals when assuming an ambient signal of 40 kHz bandwidth before and after processing. The resulting spectrum of the processed received signals in the 2FSK-based Backcom system is symmetrical when down-converted to zero-IF domain. The harmonics shown in Fig. 3 are originated from the square wave of the switching control signals. Similarly, the simulation results with ambient FM signals are shown in Fig. 4. By comparing the plots with and without proposed I/Q sample method, the spectrum of the processed Backcom signals demonstrates a clear spike at f_{sw} no matter what the ambient signals are, such as an FM or a 40 kHz-bandwidth signals. The proposed processing method greatly simplifies the demodulation process by separating carrier and backscattered waveform, so that the FSK-based data can be demodulated by seeking the maximum spike/frequency response within the predefined window in the FFT bins.

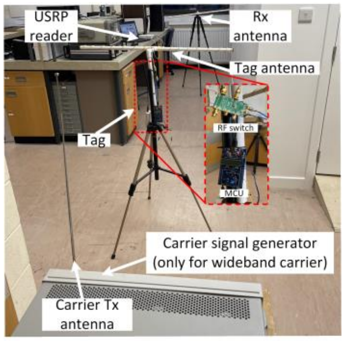
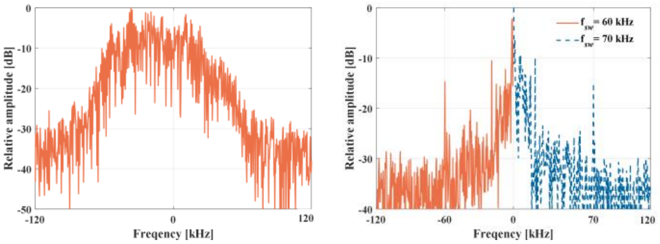
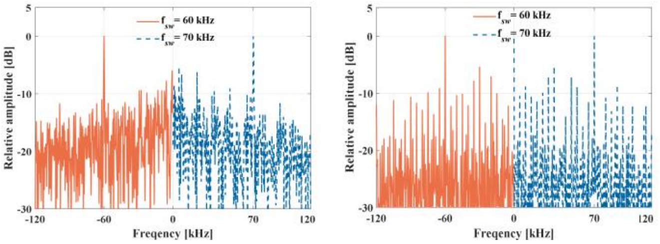


Fig. 5. Photo of experimental set-up.



(a) (b)

Fig. 6. Spectrum of received Backcom signal in the experiment when using ambient signal of FM carrier (a) raw signals when f_{sw} = 60 kHz, (b) after our proposed I/Q-sample processing.



(a) (b)

Fig. 7. Spectrum of received Backcom signal in the experiment when using ambient signal of 40 kHz-bandwidth (a) single tone, (b) multi subcarriers.

III. EXPERIMENTAL VALIDATION

In order to validate the proposed system and processing method, an indoor experiment was carried out as depicted in Fig. 5. Two dipole antennas are employed by the receiver and backscatter tag, separated by around 4 meters away. The tag is composed of an 8-bit STM8L microcontroller unit (MCU) and an ADG918 SPDT RF switch. The MCU is programmed to translates raw bits into 2FSK symbols, with f_{sw} = 60 or 70 kHz. The bit sequence consists of a 26-bit Barker coder preamble and a stream of 6495 bits extracted from a picture. Hamming coding and interleaving were applied. The symbol period is fixed at 5 ms, resulting in a bit rate of 200 bps. The reader is realized using an SDR with 2 MHz sampling rate. For the ambient FM carrier test, the reader is tuned to BBC Radio 2, 89.9 MHz, whose base station is located about 40 miles away from the building housing the experiment. The results in Fig. 6 show a clear spike at f_{sw} confirming the conclusion obtained in the simulations.

For the 40 kHz bandwidth QPSK carrier experiment, the single-tone and multi-subcarrier (5 subcarriers with 20 kHz spacing) RF signals are generated by MXG Vector Signal Generator with the employment of a commercial FM antenna at the transmitter, which is placed 1.5 m away from the tag as depicted in Fig. 5.

Fig. 7 presents the experimental results. In addition, one more test with an ambient multi-tone signal was conducted. A similar conclusion can be obtained that our proposed sample processing method can distinctively show a clear spike at f_{sw}. The bit error rate (BER) is validated by applying 2FSK demodulation and decoding to the processed signals. All the information is recovered in our test conditions with no bit errors. More details on experiment setup and results will be presented in the conference.

IV. CONCLUSION

In this work, we have introduced an I/Q sample processing method for FSK-enabled ambient Backcom system. The proposed method was able to separate the ambient carrier signal and the backscattered waveform in the spectrum and this was validated with both an ambient FM signal and a QPSK signal of 40 kHz-bandwidth. In our future work, more experiment results are expected to show the maximum communication distance and bit rate with the criteria of BER when utilizing in an environment of different ambient signals.

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