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Multi-Source Cognitive BackCom with Temporal Combining for Reliable IoT Communication

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Abstract—Backscatter communication has evolved over the years, but the research interest has predominantly focused on single carrier radio frequency source. In this paper, we seek to utilize the accessibility of multiple carrier sources to boost backscatter communication reliability. Under the framework of utilizing temporal combining, we show the bit error rate gain of our proposed bit-stream decoding scheme over the traditional approach through analysis and simulation.

Index Terms—Backscatter communication (BackCom), multi-carrier sources, temporal combining (TC), repetition coding.

I. INTRODUCTION

Internet-of-Things networks (IoTNs) have grown in popularity over recent years due to their potential to enable human-environment digital interactions [1]. Backscatter (BC) communication (BackCom) is a battery-less wireless communication technology for IoT devices, where the BC device reflects/absorbs a radio frequency (RF) signal emitted by a nearby source to convey its data on this signal.

This paper proposes a multi-source temporal combining (TC) solution for bit-stream decoding to enhance the reliability of BackCom in cognitive radio networks (CRNs), where primary transmitters (PTs) serve as carrier sources and BackCom devices are secondary transmitters (STs). Unlike previous research works on TC [2], [3], which primarily focused on a single RF source, our solution leverages multiple PTs to exploit increased transmission opportunities for TC. Our simulation results demonstrate the effectiveness of exploiting multiple sources in further enhancing BackCom reliability.

II. SYSTEM MODEL

In the CRN system model shown in Fig. 1, K single-antenna PTs ($\{T_k\}_{k=1}^K$) (i.e., RF multi-carrier sources) and an M -antenna BackCom tag (T_{g_1}) coexist and share spectrum. An N -antenna receiver (R_1) decodes both the PT data and the BackCom data within received signals. The following assumptions are made within this work concerning system operations: (i) All PTs are Wi-Fi devices with different transmission packet lengths and topological locations from R_1 , and there are direct links between the PTs and R_1 ; (ii) T_{g_1} uses the PTs RF signals for BackCom; (iii) The PTs transmit data orthogonally in the time domain using carrier sensing.

The T_k -to- T_{g_1} channels are denoted as \mathbf{h}_k , T_k -to- R_1 channel is given as \mathbf{f}_k and the T_{g_1} -to- R_1 channel is defined as \mathbf{g}_{R_1} ,

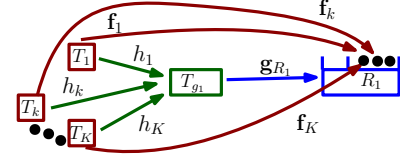


Fig. 1: BackCom with multiple carrier sources.

and the total PTs transmit time is denoted as $S = \sum_{k=1}^K \alpha_k$, where α_k is the airtime of T_k -to- R_1 transmission. P_k and $x_k(t_k)$ are T_k 's transmit power and instantaneous transmitted symbol at time t_k , respectively. T_{g_1} 's data symbol is defined as $x_{g_1}(t_k)$. During α_k , received T_k signal at T_{g_1} is given by

$$y_{k,g_1}(t_k) = \sqrt{P_k} \mathbf{h}_k x_k(t_k) + n_{g_1}(t_k), \quad (1)$$

where $\mathbb{E}[|x_k(t_k)|^2] \triangleq 1$ and $n_{g_1}(t_k) \sim \mathcal{CN}(0, \sigma_{g_1}^2)$ denotes additive white Gaussian noise (AWGN) with power $\sigma_{g_1}^2$ at T_{g_1} . The T_k signal received by R_1 is defined as

$$y_{k,R_1}(t_k) = \sqrt{P_k} \eta \mathbf{h}_k x_k(t_k) x_{g_1}(t_k) \mathbf{g}_{R_1} + \sqrt{P_k} x_k(t_k) \mathbf{f}_k + n_{R_1}(t_k), \quad (2)$$

where $\mathbb{E}[|x_{g_1}(t_k)|^2] \triangleq 1$, $n_{R_1}(t_k) \sim \mathcal{CN}(0, \sigma_{R_1}^2)$ is the AWGN at R_1 , and η is the reflection attenuation coefficient. For TC, T_{g_1} repeats the transmission of the same data packet over the duration S . Thus, the series $x_{g_1}(t)$ remains unchanged throughout S .

III. RECEIVER DESIGN AND TEMPORAL COMBINING

A. Linear Detectors under Frequency-Shift Technique

T_{g_1} utilizes the frequency-shift technique (FST), wherein R_1 captures two valid Wi-Fi signals, one on the carrier-signal channel and the other on the shifted channel, with a separation equal to the channel bandwidth. R_1 first decodes these received signals employing linear detection, as described below. The linear detectors under consideration are the maximal-ratio combining (MRC), the zero-forcing (ZF) and the minimum mean-squared-error (MMSE), which are defined as

$$\mathbf{w}_{k,R_1} = \begin{cases} \frac{\tilde{\mathbf{g}}_{k,R_1}}{\|\tilde{\mathbf{g}}_{k,R_1}\|^2}, & \text{for MRC} \\ \left((\tilde{\mathbf{g}}_{k,R_1})^H \tilde{\mathbf{g}}_{k,R_1} \right)^{-1} (\tilde{\mathbf{g}}_{k,R_1})^H, & \text{for ZF} \\ \left((\tilde{\mathbf{g}}_{k,R_1})^H \tilde{\mathbf{g}}_{k,R_1} + \frac{\sigma^2}{P_k} I \right)^{-1} (\tilde{\mathbf{g}}_{k,R_1})^H, & \text{for MMSE} \end{cases} \quad (3)$$

for detecting the T_k signal, where $\tilde{\mathbf{g}}_{k,R_1} = \sqrt{\eta} \mathbf{h}_k \mathbf{g}_{R_1}$ and I represents an identity matrix. By applying any of the above receiver designs, the bit-streams of the T_k and T_{g_1} signals can be extracted, respectively, as

$$\hat{x}_k(t_k) = \arg \max_{x_k(t_k) \in \mathbf{A}_{s,k}} |x_k(t_k) - y_{k,R_1}(t_k) \mathbf{w}_{k,R_1}^H|, \quad (4)$$

$$\hat{x}_{g_1}(t_k) = \arg \max_{x_{g_1}(t_k) \in \mathbf{A}_c} \left| x_{g_1}(t_k) - \frac{y_{k,R_1}(t_k) \mathbf{w}_{k,R_1}^H}{\hat{x}_k(t_k)} \right|, \quad (5)$$

where $\{\mathbf{A}_{s,k}, \mathbf{A}_c\}$ are $\{T_k, T_{g_1}\}$ symbol set, respectively [4]. Then, R_1 applies XOR operation on these two data bits, which finally leads to the extraction of K BackCom bit-streams.

B. Multi-Source Temporal Combining

Let $\mathcal{B} = \{B_1, \dots, B_K\}$ represent the set of acquired BackCom bit-streams. Note that the length of B_k is the same as L_k . Without loss of generality, we assume $L_1 < \dots < L_K$. The multi-source TC scheme is applied to \mathcal{B} in three steps: (i) The bit-streams are partitioned into smaller blocks based on their lengths. Each block includes an equal number of bits from each bit-stream, starting from the first bit up to L_1 in the first block, and continuing incrementally up to L_K . (ii) The scheme verifies if the number of received bit-streams in each block is odd, for majority voting. If not, the bit-stream with the minimum original length is excluded from the block. (iii) Within each block, bitwise majority voting is performed to determine the status of each bit as data-one or data-zero. Let $\mathcal{C} = \{\mathcal{C}_1, \dots, \mathcal{C}_K\}$ denote the set of blocks, where \mathcal{C}_k is the k th block containing corresponding segments of the bit-streams. Earlier blocks, comprising more bit sequences for TC, will result in fewer bit errors, while later blocks, with fewer bit sequences, may result in higher bit errors. Note that the voting process is not applied to the standalone block (last block). Finally, the voting results from individual blocks are concatenated in sequence, yielding the BackCom data.

The bit error rate (BER) after TC is obtained as follows. Assume that before TC, i.i.d. bit errors with probability p_b occur across bits in the bit-streams. Let the cardinality of \mathcal{C}_k be denoted by C_k , which is obtained as $\lceil (k+1)/2 \rceil \times 2 - 1$. Then, the BER after TC at the ℓ th bit, denoted by $p_{b,\ell}$, where $L_{k-1} < \ell \leq L_k$, is given by

$$p_{b,\ell} = \sum_{j=\lceil C_k/2 \rceil}^{C_k} \binom{C_k}{j} (1-p_b)^j p_b^{C_k-j}. \quad (6)$$

This demonstrates two important points. First, as C_k increases, $p_{b,\ell}$ decreases, indicating that exploiting more carrier sources for TC leads to increased reliability of BackCom. Second, since $C_1 \leq \dots \leq C_K$, we have $p_{b,1} \leq \dots \leq p_{b,L_K}$. Thus, the BackCom data after multi-source TC may experience higher BER at later bits, as fewer bit sequences remain to combine. This suggests the need for more reliable transmission schemes (e.g., coding) for later BackCom bits, which we leave for future work.

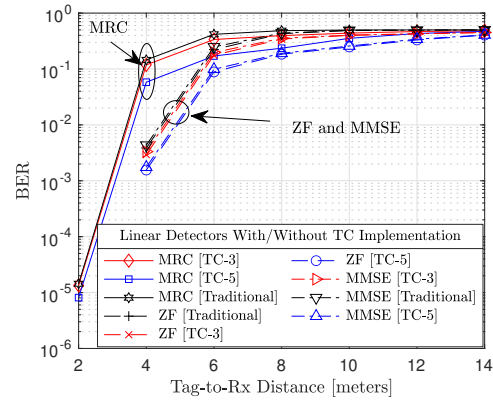


Fig. 2: BER performance of multi-source TC over distance.

IV. SIMULATION AND DISCUSSION

The simulation environment is implemented in MATLAB to emulate the PHY layer of the IEEE 802.11n configuration with a channel bandwidth of 20 MHz, a payload size of 500 bytes, and employing binary convolutional coding. The delay profile of Model-D is employed, while the remaining parameters follow the WLAN HT (high throughput) format for waveform generation. The simulation includes pathloss and AWGN, with $M = N = 2$, and considers a non-line-of-sight (NLOS) distance of 20m in Rayleigh fading channels. Two cases are examined: TC-3 and TC-5, corresponding to scenarios with 3 and 5 PTs, respectively.

We evaluate the BER performance of the proposed multi-source TC scheme with the three linear detectors, considering a fixed SNR of 13 dB. As shown in Fig. 2, the difference in BER between the traditional approach (without TC) and TC-3 remains marginal as the Tag-to-Rx distance increases, whereas a noticeable gap emerges for TC-5. On average, TC-3 demonstrates a 15.79% improvement in BER, while TC-5 achieves approximately 42.85% enhancement compared to the traditional method.

V. CONCLUSION

The utilization of multiple carrier sources within the TC framework has resulted in notable improvements in BER performance for BackCom. Specifically, our proposed scheme, evaluated with three linear detectors, demonstrated a substantial enhancement ranging from 15% to 42%.

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