# Detection at Multi-Antenna Reader with Correlated RF Source in Ambient Backscatter Communication

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***Abstract*—This work considers a multi-antenna reader and a generalized correlated radio-frequency (RF) source signal in the ambient backscatter communication (AmBC) system. An optimal combining detector (OCD) at the multi-antenna reader is presented for the AmBC system, which detects the signal information embedded by the tag onto a generalized correlated RF source signal. The optimal combining detection statistic for the considered system framework maximizes the signal-to-interference-plus-noise ratio (SINR) at the reader. Further, the receiver operating characteristic (ROC) plots for the proposed optimal detector demonstrate superior performance over the allied detectors.**

***Index Terms*—Ambient backscatter communication (AmBC), correlated signal, optimal combiner.**

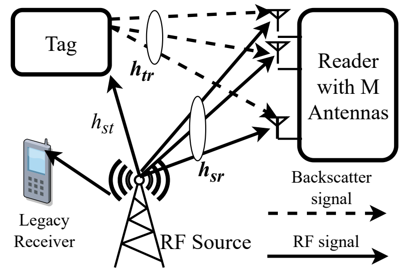



Fig. 1: Ambient backscatter communication (AmBC) system architecture with a single antenna RF source, a legacy receiver, a single antenna tag, and a reader with $M$ antennas.

## I. Introduction

Over the past few years, ambient backscatter communication (AmBC) systems have seen remarkable research progress. The tag in AmBC uses the ambient radio frequency (RF) signal to communicate with the reader, where the ambient RF signal is generated for communication between the legacy users, as illustrated in Fig. 1. Hence, AmBC has the potential to revolutionize the future of low-power devices-assisted communication applications, such as smart homes, IoT networks, healthcare monitoring, and supply chain management [1]. However, using ambient RF signals for communication introduces a challenge to detecting a weak backscattered signal in AmBC systems. The detection problem is challenging as the reader has to detect a signal received from the tag in the presence of an interfering RF source signal in the wireless fading and low signal-to-noise ratio (SNR) regimes [2].

The AmBC systems mainly use the energy detector (ED) because it's simple to implement in scenarios with a single antenna [3]–[5]. The authors in [6] have proposed a maximum posterior (MAP) based detector, which, upon simplification, reduced to the joint-energy detector [7]. Similarly, [8] also proposed the maximum likelihood (ML) based detection, which, upon simplification, converged to the ED.

The MAP-based optimal detector for the uncorrelated RF source signal in the AmBC systems with multiple antennas at the reader was presented in [9]. Under the multi-antenna AmBC setting, [10] used to average the power from the received signal to obtain the average power detector, [11] used the maximum eigenvalue of the received signal covariance matrix as a test derived from a maximum eigenvalue detector (M-EVD), and [12] have proposed an optimal beamforming-based ED. Further, for the multi-antenna setup in AmBC, authors in [13] proposed a MAP-based detection, whereas an ML-based detector in [14]. Further, [15] presented a $p$-norm based improved energy detector (IED). The above works [3]–[15] focus on a scenario with uncorrelated RF source signals, overlooking the potential correlation between the RF source signals. In wireless communication networks/ scenarios, such as cellular towers or Wi-Fi routers, the RF source signal exhibits correlation due to shared interference [16]–[18].

This work presents an optimal combining detector at the multi-antenna reader when considering a correlated RF source signal in the AmBC systems. Section II presents a framework with correlated RF source signal in the AmBC system with multiple receive antennas at the reader. Further, section III presents the formulation that maximizes the signal-to-interference-plus-noise ratio (SINR) to get a detection statistic for the optimal combining detector. Finally, Section IV presents the simulation results to validate the performance of the proposed optimal detector, and Section V presents the conclusions and future directions.

## II. System Model for AmBC

Consider an AmBC system setup shown in Fig. 1 with a single antenna Radio Frequency (RF) source to assist the communication of legacy receiver, accompanied by a single antenna tag/ backscatter transmitter and a reader/ backscatter receiver with $M$ antennas. The RF source broadcasts the signal $s_n$ designated to the licensed user. Let $\mathbb{C}$ be the set of complex numbers. The received symbol $x_n \in \mathbb{C}$ at the tag corresponding to the transmission of the RF source signal $s_n$ at the $n$th sample is expressed by

$$x_n = h_{st} s_n, \tag{1}$$

where $h_{st}$ is the flat faded Rayleigh channel coefficient between the RF source and tag. Tag listens to the RF signal to convey its information bits $d \in \{1, 0\}$ to the reader [3] corresponding to the change in the antenna impedance to reflect/ absorb the signal, respectively. Let $\zeta$ be the efficiency to backscatter the tag signal $d \in \{0, 1\}$. The tag transmission rate is considered $N$ times lower than the transmission rate of the RF source signal. The backscatter signal $x_{b_n} \in \mathbb{C}$ from the tag from (1) be expressed as

$$x_{b_n} = \zeta x_n d. \tag{2}$$

The channel coefficient $h_{sr_m}$ between RF source and $m$th antenna of reader, and the channel coefficient $h_{tr_m}$ between tag and $m$th antenna of reader are know flat faded, each following a complex Normal distribution with zero mean and unit variance. For $M$ antennas at the reader, as depicted in Fig. 1, these channel coefficient vectors can be denoted as $\mathbf{h}_{sr} = [h_{sr_1}, \ldots, h_{sr_m}, \ldots, h_{sr_M}]^T \in \mathbb{C}^{M\times 1}$ and $\mathbf{h}_{tr} = [h_{tr_1}, \ldots, h_{tr_m}, \ldots, h_{tr_M}]^T \in \mathbb{C}^{M\times 1}$, respectively. The received signal vector $\mathbf{y}_n \in \mathbb{C}^{M\times 1}$ at the reader corresponding to the backscatter signal $x_{b_n}$ in (2) and the RF source signal $s_n$ at the $n$th instant be expressed as

$$\begin{aligned} \mathbf{y}_n &= \mathbf{h}_{sr} s_n + \mathbf{h}_{tr} x_{b_n} + \mathbf{w}_n & (3)\\ &= \mathbf{h}_{sr} s_n + \mathbf{h}_{tr} \zeta h_{st} s_n d + \mathbf{w}_n, & (4) \end{aligned}$$

where the additive noise vector $\mathbf{w}_n \in \mathbb{C}^{M\times 1}$ follows a complex normal distribution $\mathbf{w}_n \sim \mathcal{CN}(\mathbf{0}, \sigma^2 \mathbf{I}_M)$. Use (2) in (3) to get (4). Let the composite received signal vector $\mathbf{y} = [\mathbf{y}_1^T, \ldots, \mathbf{y}_n^T, \ldots, \mathbf{y}_N^T]^T \in \mathbb{C}^{MN\times 1}$ at the reader corresponding to $M$ receive antennas be expressed as

$$\mathbf{y} = \mathbf{H}_{sr}\mathbf{s} + \mathbf{H}_{tr}\mathbf{s}d + \mathbf{w}, \tag{5}$$

where the channel coefficient matrices $\mathbf{H}_{sr} \in \mathbb{C}^{MN\times N}$ and $\mathbf{H}_{tr} \in \mathbb{C}^{MN\times N}$ are defined as $\mathbf{H}_{sr} = \mathbf{I}_N \otimes \mathbf{h}_{sr}$ and $\mathbf{H}_{tr} = \zeta h_{st} (\mathbf{I}_N \otimes \mathbf{h}_{tr})$ where $\mathbf{I}_N$ is a identity matrix of size $N \times N$ and $\otimes$ denotes the Kronecker product. The composite noise vector $\mathbf{w} = [\mathbf{w}_1^T, \ldots, \mathbf{w}_n^T, \ldots, \mathbf{w}_N^T]^T \in \mathbb{C}^{MN\times 1}$ follows a complex Normal distribution $\mathcal{CN}(\mathbf{0}, \sigma^2 \mathbf{I}_{MN})$. The RF source signal vector $\mathbf{s}$ be written as $\mathbf{s} = [s_1, \ldots, s_n, \ldots, s_N]^T \in \mathbb{C}^{N\times 1}$. The RF source signal vector $\mathbf{s}$ is assumed to follow a multivariate complex Normal distribution with zero mean and a covariance matrix $\mathbf{C_s} \in \mathbb{C}^{N\times N}$, i.e., $\mathbf{s} \sim \mathcal{CN}(\mathbf{0}, \mathbf{C_s})$ [19].

## III. Optimal Combining detector (OCD)

This section presents a framework to optimally combine the received signal at the reader that maximizes the SINR. For the combining vector $\mathbf{b} \in \mathbb{C}^{MN\times 1}$ that maximizes the SINR [20] for the received signal $\mathbf{y}$ at the reader in (5) be equivalently expressed as

$$\mathbf{b}^H\mathbf{y} = \underbrace{\mathbf{b}^H\mathbf{H}_{sr}\mathbf{s}}_{\text{Intereference Term}} + \underbrace{\mathbf{b}^H\mathbf{H}_{tr}\mathbf{s}d}_{\text{Signal Term}} + \underbrace{\mathbf{b}^H\mathbf{w}}_{\text{Noise Term}}. \tag{6}$$

The SINR expression $F_{\text{SINR}}(\mathbf{b})$ in (10) for the framework in (6) considering an optimal combining vector $\mathbf{b}$ [20] be expressed to

$$\begin{aligned} F_{\text{SINR}}(\mathbf{b}) &= \frac{\mathbb{E}\left\{|\mathbf{b}^H\mathbf{H}_{tr}\mathbf{s}d|^2\right\}}{\mathbb{E}\left\{|\mathbf{b}^H\mathbf{H}_{sr}\mathbf{s}|^2\right\} + \mathbb{E}\left\{|\mathbf{b}^H\mathbf{w}|^2\right\}} & (7)\\ &= \frac{\mathbb{E}\left\{d^2\right\}\mathbf{b}^H\mathbf{H}_{tr}\mathbb{E}\left\{\mathbf{s}\mathbf{s}^H\right\}\mathbf{H}_{tr}^H\mathbf{b}}{\mathbf{b}^H\mathbf{H}_{sr}\mathbb{E}\left\{\mathbf{s}\mathbf{s}^H\right\}\mathbf{H}_{sr}^H\mathbf{b} + \mathbf{b}^H\mathbb{E}\left\{\mathbf{w}\mathbf{w}^H\right\}\mathbf{b}} & (8)\\ &= \frac{0.5\mathbf{b}^H\mathbf{H}_{tr}\mathbf{C_s}\mathbf{H}_{tr}^H\mathbf{b}}{\mathbf{b}^H\mathbf{H}_{sr}\mathbf{C_s}\mathbf{H}_{sr}^H\mathbf{b} + \sigma^2\mathbf{b}^H\mathbf{b}} & (9)\\ &= \frac{\mathbf{b}^H\mathbf{Q}_{tr}\mathbf{b}}{\mathbf{b}^H\mathbf{Q}_{sr}\mathbf{b}}. & (10) \end{aligned}$$

In (7), $\mathbb{E}\{\cdot\}$ represent the expectation operator. Equation (8) is simplified using the independence between the terms $d$, $\mathbf{s}$, and $\mathbf{w}$. The factor of $\frac{1}{2}$ in (9) appears due to the equally likely tag bits $d \in \{0, 1\}$. Further in (10), $\mathbf{Q}_{sr} \in \mathbb{C}^{MN\times MN}$ and $\mathbf{Q}_{tr} \in \mathbb{C}^{MN\times MN}$ are defined as $\mathbf{Q}_{sr} = 2(\mathbf{H}_{sr}\mathbf{C_s}\mathbf{H}_{sr}^H + \sigma^2\mathbf{I}_{MN})$ and $\mathbf{Q}_{tr} = \mathbf{H}_{tr}\mathbf{C_s}\mathbf{H}_{tr}^H$, respectively. To derive the optimal combining vector $\mathbf{b}$ under limited power one needs to maximize the SINR, expressed as

$$\begin{aligned} &\max_{\mathbf{b}} \;\; F_{\text{SINR}}(\mathbf{b}),\\ &\text{s.t.} \;\; \|\mathbf{b}\| \le 1. \end{aligned} \tag{11}$$

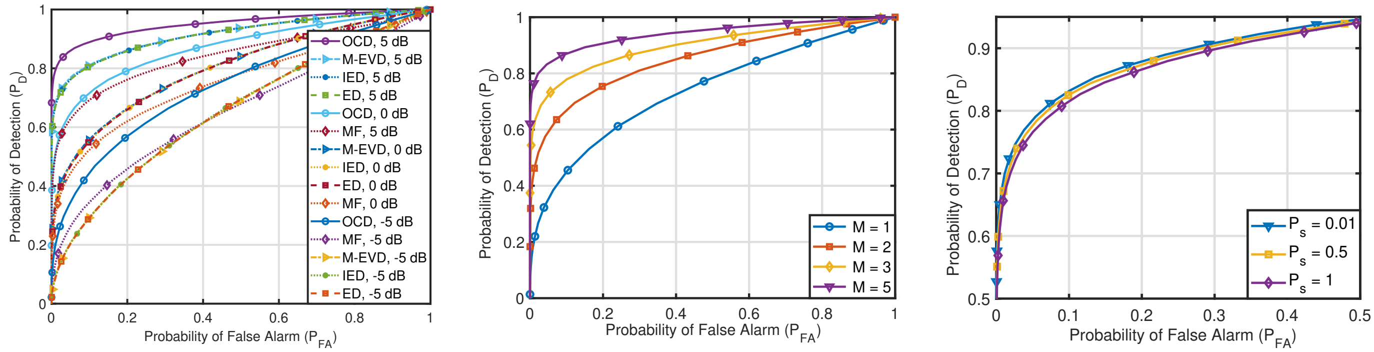
The optimal combining vector $\mathbf{b}$ from the optimization framework has a closed form solution and is obtained [21] by choosing the eigenvector corresponding to the maximum eigenvalue of the matrix $\mathbf{A} = \mathbf{Q}_{sr}^{-1}\mathbf{Q}_{tr}$. The cost function in (11) is maximized for the optimal combining vector $\mathbf{b}_{\text{opt}}$ that aligns with the eigenvector corresponding to the largest eigenvalue of $\mathbf{A}$. Hence, the optimal combining detector (OCD) for the multi-antenna reader when considering correlated RF source signal in AmBC system be derived as

$$T_{OCD}(\mathbf{y}) = \mathbf{b}_{\text{opt}}^H\mathbf{y} \underset{\hat{d}=0}{\overset{\hat{d}=1}{\gtrless}} \gamma. \tag{12}$$

Let $\hat{d}$ be the detected tag bit at the reader and $\gamma$ the detection threshold. Next section discusses the simulation results.

## IV. Simulation Result

Consider an AmBC system (5) having the elements of the channel coefficient matrices $\mathbf{H}_{sr}$ and $\mathbf{H}_{tr}$ are drawn from a standard complex Gaussian distribution. To generate the correlated RF source signal vector $\mathbf{s}$, for the applications discussed earlier [16]–[18], that follow a complex Normal distribution with zero mean and covariance matrix $\mathbf{C_s}$, i.e., $\mathbf{s} \sim \mathcal{CN}(0, \mathbf{C_s})$. The RF source signal vector covariance matrix $\mathbf{C_s}$ is given by $\mathbf{C_s} = \mathbf{U}\mathbf{\Sigma}\mathbf{U}^H$, where $\mathbf{U}$ is a unitary matrix and $\mathbf{\Sigma}$ is a diagonal matrix with the principal diagonal containing values evenly spaced, and normalized by the power $P_s$, between 1 and $N$. The transmission rate of the RF source is twice that of the tag signal, i.e., $N = 2$. The transmitted backscatter tag symbol $d \in \{0, 1\}$ takes binary values with equal probability with $\zeta$ set to unity and an additive white noise vector $\mathbf{w}$ following a complex Gaussian distribution with zero mean and covariance matrix $\sigma^2\mathbf{I}_{MN}$. The proposed OCD detection statistic $T_{OCD}(\mathbf{y})$ in (12) is compared with the allied detectors, where M-EVD has a similar implementation complexity.




(a) (b) (c)

Fig. 2: ROC Plots for the proposed optimal combining detector (OCD) in (12) (a) when compared with ED [4], M-EVD [11], IED [15], and MF at SINR $= \{-5, 0, 5\}$ dB, (b) for SINR $= 5$ dB for different reader antennas $M \in \{1, 2, 3, 5\}$, and (c) for various values of interference power $P_s \in \{0.01, 0.5, 1\}$.

Fig. 2a compares the receiver operating characteristics (ROC) performance of the proposed OCD with the ED [4], M-EVD [11], IED [15] and MF in AmBC systems with $M = 3$ at different SINR levels. Figure illustrates a superior ROC performance trend of the proposed OCD at different SINR levels. Fig. 2b illustrates the ROC performance of the OCD with a change in the receive antenna $M$ at the reader. An improvement in the detection performance is observed with an increase in $M$. In Fig. 2c, the ROC plot compares different interference power levels $P_s$ of the OCD and is observed an improved performance with the decrease in $P_s$.

## V. Conclusions and Future Work

This work presented an OCD at multiple antenna reader considering a generalized correlated RF source signal in an AmBC system. The proposed OCD outperformed the state-of-the-art ED, M-EVD, IED, and MF detectors when considering correlated RF source signal samples. In future, the presented framework with correlated RF source signal can be used to analyse the system performance, present closed form expressions and implement over testbed for real-world validation.

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