

Multi-Antenna Receiver for Ambient Backscatter Communication Systems

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Abstract—Consider an ambient modulated backscatter communication (AmBC) system adopting binary phase shift keying modulation that the receiver is to decode the backscatter device induced message without knowledge of the channel state information, the statistical channel covariance matrices, and the noise variance at the receiver antennas. In this paper, we apply the fact that the ambient orthogonal frequency-division multiplexing (OFDM) signals with a large number of subcarriers contain repetitive elements inducing time correlation. We propose a simple sample covariance matrix distance based rule that does not need to invert the estimated covariance matrices. The results show that the developed method enables the receiver to detect the backscatter symbol over one ambient OFDM symbol period applying the time correlation induced by the wideband ambient OFDM transmission which contains repetitive elements.

Index Terms—Ambient backscatter, binary phase-shift keying, OFDM, sample covariance matrix, time-varying channel.

I. INTRODUCTION

One of the limiting factors of connecting things to the Internet using wireless technologies is the availability of energy. One solution is provided by the modulated backscattering systems, e.g., radio-frequency identification, where the tags modulate their information onto a carrier generated by a reader, and the reader decodes the modulated information [1], [2]. Although circuit power consumption can still be a serious problem in practice [3], [4], it is nevertheless much smaller than in case of active transmitters [5]. A new technology, referred to as ambient modulated backscatter communication (AmBC) introduced in [6], has been emerging and captured much attention. In AmBC, the tags can backscatter ambient modulated signals with added information, e.g., [5], [7]–[11] among others. Particularly, [12], [13] have analyzed that with proper design the AmBC can benefit the legacy system.

Various detectors have been studied for AmBC systems, such as, energy detector (ED), covariance-based detector, maximum a posteriori (MAP), and maximum likelihood (ML) detector. See Table I for a brief summary of some works. The bit error rate (BER) has been considered as one performance metric. The work in [14] considered an ED to detect the on-off keying (OOK) signals of an AmBC system consisting of a multi-antenna receiver and a single-antenna backscatter tag. To improve the BER at low signal to noise ratio (SNR), [15] proposed a covariance matrix (CM) based signal detection

algorithm for signal-antenna AmBC systems. The ratio of the two CMs, representing that the backscatter signal is absent or present, was used to detect the presence of the reflected signal. The authors of [16] focused on the signal detection with an ED and analyzed the BER of an AmBC system adopting OOK modulation and differential encoding method.

An ML detector based analysis has been conducted for the noncoherent [7] and the semi-coherent [17] ambient backscatter systems, where the backscatter applies OOK modulation and differential encoding scheme to the original symbols of the tag. The semi-coherent detection in [17] discriminates the received signal strengths of transmitting '0' and '1' by the tag using short training sequence instead of the channel state information (CSI). The work in [18] proposed a signal detection scheme for IEEE 802.11n ambient backscatter systems consisting of a 2-antenna tag being allocated different transmit power by detecting the strongest signal first. Authors of [8] proposed a method to determine the signal detection thresholds for Wi-Fi backscatter systems with a multi-antenna receiver based on the maximum distance of the received power (pilot sequences) at each antenna. Applying coding and detection schemes, [19] considered a three-state tag, i.e., positive phase, negative phase, and non-backscattering. However, the ambient RF signal was assumed to be OOK modulated, and the receiver knows the CSI of all channels for an MAP detector.

Considering the ambient orthogonal frequency-division multiplexing (OFDM) modulated signals, authors in [13] considered that the legacy system transmits OFDM signals and the backscatter device adopts OOK with a differential encoder and the readers has no CSI of all the channels. Then the ML rule was applied to obtain the ML decision regions to minimize the BER. In addition, the work in [11] jointly designed the waveforms for the short-range ambient backscatter devices and the receiver detector. In this design, '1' and '0' indicate that there is a state transition or not within in a backscatter symbol period. The backscatter modulates the ambient OFDM signals using the unknown and time-varying spreading codes. The receiver is able to cancel out the direct ambient signal interference exploiting the repeating structure of the ambient OFDM signals with cyclic prefix.

The previous works require either a large number of samples or some knowledge of the strength of the backscatter channels

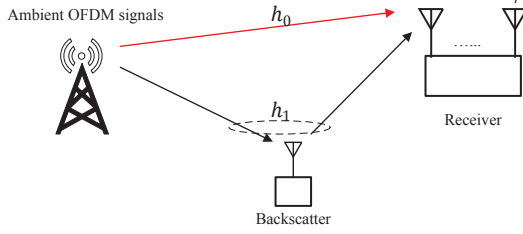


Fig. 1. An illustration of the considered system.

or the noise variance. We highlight our work as follows. Firstly, we consider an AmBC system adopting binary phase shift keying (BPSK) modulation. Secondly, the receiver has no knowledge of the CSI, the statistical channel covariance matrices, and the noise variance at the receiver antennas, and makes the decision over one ambient OFDM symbol. Thirdly, the ambient signal is wideband OFDM signal having repetitive elements such as control and synchronization information that causes it to have correlation even if the sample rate is slow. The considered system is extremely challenging to acquire accurate statistical covariance matrices for time-variant channels with large variances. In this work, we propose a simple sample covariance matrix (SCM) distance based rule with no need to invert the estimated covariance matrices. We show that the developed method enables the receiver to detect the backscatter symbol over one ambient OFDM symbol period applying the time correlation induced by the wideband ambient OFDM transmission which contains repetitive elements.

The remainder of this paper is organized as follows. In Section II, we outline the system and signal models, and discuss the receiver design and the spreading method for the backscatter symbols. The asymptotic analysis is conducted in Section III. We present the simulation results in Section IV. Section V concludes this paper and discusses the future work.

II. SYSTEM MODEL

Consider an AmBC system shown in Fig. 1 that consists of a single-antenna ambient backscatter, a n_r -antenna receiver, and a legacy OFDM communication system generating waveform $s_N[t] = \sum_{k=0}^{N-1} s_{N,k} e^{-i\omega_k t}$, $0 \leq t \leq T_c$, where N is the number of subcarriers, $s_{N,k} \in \mathbb{C}$ is the complex information symbol sent on sub-carrier k , $\mathbb{E}\{|s_{N,k}|^2\} = 1/N$, and $\omega_k = \omega_0 + 2\pi k/NT_c$ is the sub-carrier frequency. When the signal passes through a channel with frequency response (FR) $G(\omega)$, the received signal becomes

$$v_N[t; G] \approx \sum_{k=0}^{N-1} s_{N,k} G(\omega_k) e^{-i\omega_k t}. \quad (1)$$

It is shown in [20] that as the number of carriers $N \rightarrow \infty$, the complex envelop of the transmitted OFDM signal weakly converges, i.e. converges in distribution, to a complex Gaussian random process: $s_N[t] \xrightarrow{d} s[t] \sim \mathcal{CN}(0, 1)$ and $v_N[t; G] \xrightarrow{d} v[t] \sim \mathcal{CN}(0, p[G])$, where \xrightarrow{d} denotes the convergence in distribution, and $p[G] = \int_{-\infty}^{\infty} |G(\omega)|^2 d\omega$ denotes the signal

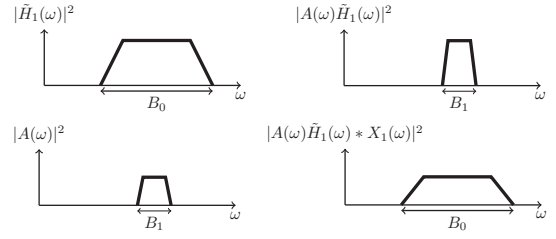


Fig. 2. An illustration of an AmBC modulated signal.

power. The legacy system OFDM signals $s_N[t]$ have repetitive elements such as control and sync info that results in time correlation even if the sample rate is slow. The OFDM signal is thus approximated with a band-limited Gaussian random process having auto correlation function $\mathbf{R}_{ss}(\tau) = \text{sinc}(\tau/T_c)$.

Consider an AmBC device modulating the ambient OFDM signals impinging at its antenna. Let $x_1[t] \in \{-1, 1\}$ denote the ambient backscatter symbol. The AmBC device has limited bandwidth B_1 affecting only a certain subset of the OFDM carriers as shown in Fig. 2. A practical work in [21] has proved this design. Let $A(\omega)$ is the AmBC device FR, and thus $A(\omega)x_1[t]$ denotes the FR of the AmBC device at time instant t . The FR of the composite channel, consisting of the direct and scattered paths, reads

$$H(\omega) = \sqrt{\gamma_0}H_0(\omega) + \sqrt{\gamma_1}H_1(\omega), \quad (2)$$

where $H_0(\omega)$ is the channel FR of the direct path, $H_1(\omega)$ is the FR of the scattered path, and the parameters γ_0 and γ_1 are the total received SNR of the direct and the backscatter links, respectively. The scattered path can further be written as

$$H_1(\omega) = H_{12}(\omega) (A(\omega)H_{11}(\omega) * X_1(\omega)), \quad (3)$$

where $H_{11}(\omega)$ denotes the channel FR between the transmitter and the AmBC antenna, $X_1(\omega)$ is the spectrum of the AmBC signal, $H_{12}(\omega)$ is the channel FR of the link between the AmBC antenna and the receiver, and $*$ denotes convolution operation. Let $B_0 = N/T_c$, and $B_1 = M/T_c$ be the bandwidth of the AmBC filter $A(\omega)$. We assume that $M \ll N$ such that only a subset of the subcarriers are affected by the AmBC modulator. In addition, the AmBC symbol duration $T_1 = T_c/K$ is shorter than the OFDM symbol duration T_c . If $M + K \leq N$, the AmBC modulated signal stays within an original signal bandwidth B_0 as illustrated in Fig. 2.

To simplify the assumptions, we consider that there is line-of-sight path from AmBC antenna to the receiver and the channel is flat $H_{12}(\omega) \approx H_{12}$ for all ω . This happens, for instance, when an AmBC device is in the close proximity of the receiver. Then, we can define $H_1(\omega) = A(\omega)\tilde{H}_1(\omega) * X_1(\omega)$, where $\tilde{H}_1(\omega) = H_{12}H_{11}(\omega)$. Applying the Gaussian approximation described above, the received signal in time domain can be approximated as

$$y[t] \approx \sqrt{\gamma_0}h_0[t] + \sqrt{\gamma_1}h_1[t]x_1[t] + z[t], \quad (4)$$

where $v_N[t, H_0] \xrightarrow{d} h_0[t]$, $v_N[t, \tilde{H}_1 A] \xrightarrow{d} h_1[t]$ and $z[t]$ are circular complex Gaussian random variables with distribution

TABLE I
SOME SIGNAL DETECTION APPROACHES FOR AMBC.

Detector	Backscatter Modulation	System Model	Notes	Literature
ED	OOK	$1 \times M$	BER floor exists	Ma, <i>et al.</i> [14]
ED & ML	OOK and differential encoding	1×1	Large number of samples	Wang, <i>et al.</i> [16]
Covariance-based	OOK	1×1	Large number of samples	Zeng, <i>et al.</i> [15]
ED	OOK	$M \times 1$	packet-level detection	Kang, <i>et al.</i> [18]
ED	OOK	$1 \times M$	WiFi backscatter	Lee, <i>et al.</i> [8]
MAP	3-state tag	1×1	CSI at the receiver	Liu, <i>et al.</i> [19]
ML& Joint-ED	OOK and differential encoding	1×1	Large number of samples	Qian, <i>et al.</i> [7]
ML & ED	OOK and differential encoding	1×1	Large number of samples	Qian, <i>et al.</i> [17]
ML	BPSK	$1 \times M$	Knowledge of the backscatter channel strength	Yang, <i>et al.</i> [11]

* $n_b \times n_r$: numbers of the tag and the receive antennas, respectively.

$CN(0, 1)$. We can further extend this to the scenario that the receiver employs n_r antennas so that $h_0[t]$, and $h_1[t]$ are n_r dimensional Gaussian vectors. We use bold lower-case letters to denote the vectors. We consider that the AmBC device adopts BPSK modulation. Hence, $\mathbb{E}\{x_1[t]\} = 0$ and $\mathbb{E}\{x_1^2[t]\} = 1$. The statistical covariance matrix of $\mathbf{y}[t]$ reads

$$\mathbb{E}\{\mathbf{y}[t]\mathbf{y}^\dagger[t]\} = \mathbb{E}\{\gamma_0\mathbf{h}_0[t]\mathbf{h}_0^\dagger[t] + \gamma_1\mathbf{h}_1[t]\mathbf{h}_1^\dagger[t]\} + \mathbf{I} =: \mathbf{R}_0[t],$$

which does not depend on $x_1[t]$. However, the conditional covariance matrix given $x_1[t]$ has the following form:

$$\mathbb{E}\{\mathbf{y}[t]\mathbf{y}^\dagger[t]|x_1[t]\} = \mathbf{R}_0[t] + \mathbf{R}_1[t]x_1[t] =: \mathbf{R}[x_1[t]; t], \quad (5)$$

where $\mathbf{R}_1[t] = \sqrt{\gamma_0\gamma_1}\mathbb{E}\{\mathbf{h}_0[t]\mathbf{h}_1^\dagger[t] + \mathbf{h}_1[t]\mathbf{h}_0^\dagger[t]\}$. The time correlation structure of the ambient signal also causes the received signal samples to be correlated, i.e.,

$$\mathbb{E}\{\mathbf{y}[t_1]\mathbf{y}^\dagger[t_2]\} = q(t_1, t_2)\mathbf{R}[x[t_1]]^{1/2}\mathbf{R}[x[t_2]]^{1/2}, \quad (6)$$

where $q(t_1, t_2) \approx \text{sinc}((t_2 - t_1)/2)$.

Consider that the AmBC device is able to modulate the legacy OFDM signal multiple times within one OFDM symbol duration¹. To mitigate the impact of the strong unknown direct signal $\sqrt{\gamma_0}\mathbf{h}_0[t]$, the AmBC uses direct-sequence spread spectrum (DSSS) method to spread its symbols. We consider a single AmBC symbol is spread over L chips $\{c_0, c_1, \dots, c_{L-1}\}$, each of which has a duration of T . The received k -th sample at the receiver reads

$$\mathbf{y}[kT] = \sqrt{\gamma_0}\mathbf{h}_0[kT] + \sqrt{\gamma_1}\mathbf{h}_1[kT]c_kx_1 + \mathbf{z}[kT]. \quad (7)$$

The receiver is to decode the AmBC symbol x_1 from the measurements in (7). This is an especially challenging task from two reasons. Firstly, in practical conditions the AmBC signal is very weak compared to the direct path, i.e., $\gamma_1 \ll \gamma_0$. Secondly, the legacy signal is rapidly changing making the coherence time of the signal extremely short from the AmBC point of view even if the actual channel would be constant.

If the receiver would have access to $\mathbf{R}[1; t]$ and $\mathbf{R}[-1; t]$, we can apply maximum likelihood detection on the SCM $\mathbf{Y}[t] := \mathbf{y}[t]\mathbf{y}^\dagger[t]$, which is known to follow the complex

Wishart distribution [23]. Leading to the well-known maximum likelihood (ML) decision rule [24]

$$\mathbf{y}^\dagger[t] \left(\mathbf{R}[1; t]^{-1} - \mathbf{R}[-1; t]^{-1} \right) \mathbf{y}[t] \stackrel{x_1=-1}{\underset{x_1=1}{\gtrless}} \ln \frac{|\mathbf{R}[-1; t]|}{|\mathbf{R}[1; t]|}. \quad (8)$$

Unfortunately, the ML receiver requires a large number of samples and is very sensitive to the estimation errors in the covariance matrices. Hence, it is extremely challenging to acquire accurate statistical covariance matrices for timing-variant channels with large variances. Also, a large number of samples spanning multiple OFDM symbol periods results in a low data rate to the AmBC. Particularly, the receiver does not have the channel state information, the statistical channel covariance matrices, and the noise variance. In this paper, we propose a simple SCM distance based rule that does not need the estimated covariance matrices to be inverted.

Since the channel is time-varying, we need to estimate the SCM of the received signal frequently. For this purpose we propose that the transmission of pilots and data symbols by the AmBC device are interlaced and a spreading code is utilized to spread both the pilots and data symbols. Let \mathcal{K}_x denote the set of time indexes utilized to transmit the data symbol, \mathcal{K}_1 the set of time indexes utilized to transmit pilot symbol '1', and \mathcal{K}_{-1} denote the set of time indexes utilized to transmit pilot symbol '-1'. We use $\mathbf{Y}[\mathcal{K}_p] = [\mathbf{y}[kT], k \in \mathcal{K}_p]$ to denote an $n_r \times L$ matrix containing the received signal vectors for the time indexes defined by \mathcal{K}_p , where $p \in \{-1, x, 1\}$. To allow for both time and frequency domain processing of the samples, we introduce an $L \times L$ unitary matrix \mathbf{D} . In case of frequency domain processing \mathbf{D} is the DFT matrix. In time domain case it can be taken to be identity matrix. The received signal in the transformed domain can be written as $\tilde{\mathbf{Y}} = \mathbf{Y}\mathbf{D}$.

The receiver uses the known code-word $\mathbf{C} = \text{diag}\{c_1, c_2, \dots, c_L\}$ to de-spread the signal. The estimated CMs in the domain of interest can now be written as

$$\hat{\mathbf{R}}[\mathcal{K}_p] = \frac{1}{L} \tilde{\mathbf{Y}}[\mathcal{K}_p] \mathbf{C}^* \tilde{\mathbf{Y}}^\dagger[\mathcal{K}_p], \quad (9)$$

which can be equivalently written as

$$\hat{\mathbf{R}}[\mathcal{K}_p] = \frac{1}{L} \sum_{l=1}^L c_l \tilde{\mathbf{y}}_p[l] \tilde{\mathbf{y}}_p^\dagger[l], \quad (10)$$

¹This is a practically reasonable assumption that an off-the-shelf dialect component, used by an ambient backscatter device for switching the status, can complete the status switching as short as $4ns$, e.g., 1N4148 diode [22].

where $\bar{\mathbf{y}}_p[l]$ denotes the l^{th} column of $\bar{\mathbf{Y}}$.

The receiver uses simple distance metric. We quantify the difference between two SCMs using the Frobenius norms of the two SCMs, i.e. $\|\hat{\mathbf{R}}[\mathcal{K}_1] - \hat{\mathbf{R}}[\mathcal{K}_x]\|_F^2$ and $\|\hat{\mathbf{R}}[\mathcal{K}_{-1}] - \hat{\mathbf{R}}[\mathcal{K}_x]\|_F^2$. The receiver decides which symbol was transmitted according to the following decision rule

$$\hat{x}_1 = \text{sign trace} \left\{ \left(\hat{\mathbf{R}}[\mathcal{K}_1] - \hat{\mathbf{R}}[\mathcal{K}_{-1}] \right) \hat{\mathbf{R}}[\mathcal{K}_x] \right\}, \quad (11)$$

where $\text{sign}(\cdot)$ denotes the sign function.

III. ASYMPTOTIC PERFORMANCE ANALYSIS

Consider that the number of receiver antennas grows, i.e., $n_r \rightarrow \infty$, so that there are a large number of received signal samples in spatial domain. Considering a decision rule of the form $m = \text{trace} \{ \mathbf{M} \hat{\mathbf{Y}}[\mathcal{K}_p] \}$, we have

$$m = \frac{1}{L} \sum_{l=1}^L c_l \text{trace} \{ \mathbf{M} \bar{\mathbf{y}}[l] \bar{\mathbf{y}}^\dagger[l] \} = \frac{1}{L} \sum_{l=1}^L c[l] \bar{\mathbf{y}}^\dagger[l] \mathbf{M} \bar{\mathbf{y}}[l],$$

where \mathbf{M} is a certain Hermitian matrix. Assume that the spreading code is random with $\mathbb{P}\{c_l = -1\} = \mathbb{P}\{c_l = 1\} = 1/2$. As the number of receive antennas $n_r \rightarrow \infty$ and the spreading factor L grows, we have

$$m \rightarrow \mathbb{E} \{ c_l \bar{\mathbf{y}}_p^\dagger[l] \mathbf{M} \bar{\mathbf{y}}_p[l] \}.$$

We note that $\bar{\mathbf{y}}_p[l] = \sum_{k \in \mathcal{K}_p} \mathbf{y}[kT] d_{kl}$. Hence,

$$\begin{aligned} m \rightarrow & \sum_{k_1} \sum_{k_2} \left[\mathbb{E}\{c_l\} \mathbb{E}\{z[kT] \mathbf{M} z[k_2T]\} \right. \\ & + d_{k_1 l} d_{k_2 l}^* \left(\mathbb{E}\{ \mathbf{h}_0[k_1T] \mathbf{M} \mathbf{h}_0[k_2T] \} \mathbb{E}\{c_l\} \right. \\ & + \mathbb{E}\{ \mathbf{h}_1[k_1T] \mathbf{M} \mathbf{h}_1[k_1T] \} \mathbb{E}\{c_l c_{k_1} c_{k_2}\} x_1^2 \\ & + \mathbb{E}\{ \mathbf{h}_0[k_1T] \mathbf{M} \mathbf{h}_1^\dagger[k_2T] \} \mathbb{E}\{c_l c_{k_2}\} x_1 \\ & \left. \left. + \mathbb{E}\{ \mathbf{h}_1[k_1T] \mathbf{M} \mathbf{h}_0^\dagger[k_2T] \} \mathbb{E}\{c_l c_{k_1}\} x_1 \right) \right]. \end{aligned}$$

Since $\mathbb{E}\{c_l\} = 0$, $\mathbb{E}\{c_l c_{k_1} c_{k_2}\} = 0$, and $\mathbb{E}\{c_l c_k\} = 1$ if $k = l$; otherwise $\mathbb{E}\{c_l c_k\} = 0$, we have

$$m \rightarrow \sum_k d_{kl} d_{ll}^* \text{trace} \{ \mathbf{M} \mathbf{R}_2 \} x_1,$$

where $\mathbf{R}_2 = \sum_k \left(d_{kl} d_{ll}^* \mathbb{E}\{ \mathbf{h}_0[t] \mathbf{h}_1[t] \} + d_{ll} d_{kl}^* \mathbb{E}\{ \mathbf{h}_1[t] \mathbf{h}_0[t] \} \right)$. Hence, by selecting $\mathbf{M} = \mathbf{R}_2$, we have $m = \|\mathbf{R}_2\|_F^2 x_1$ and $\hat{x}_1 = \text{sign}\{m\}$.

IV. NUMERICAL RESULTS

We present the simulation results. The receiver is equipped with 4 antennas. The time-varying channel realizations are generated by a commonly used model $h[t+1] = \rho h[t] + \sqrt{1-\rho^2} \xi$, where ξ is identical and independent random process to h [25]. An un-spread backscatter symbol period is equal to an OFDM period which consists of 10 sub-symbols after spreading. Each sub-symbol includes 2 pilot chips for '+1', 2 pilot chips for '-1', and 2 chips for data, and therefore $L = 60$. We provide the BER based on 10^7 runs. We consider a receiver that cannot conduct the matrix inversion computation

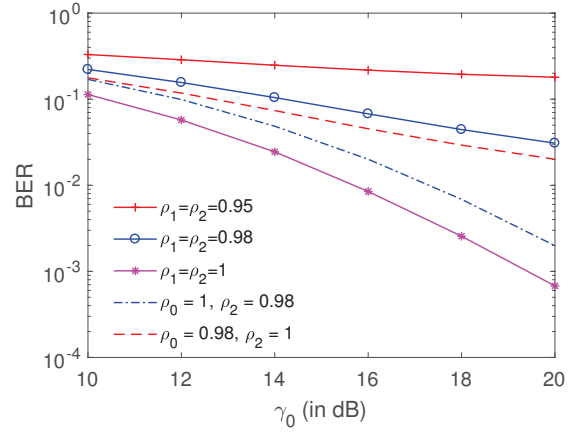


Fig. 3. BER as a function of γ_0 which is 25dB higher than γ_1 for different time-correlation scenarios.

of a large-dimension matrix. In addition, the ML receiver cannot work well in the considered scenario as there is no knowledge of the channel state information, the statistical channel covariance matrices, the noise variance at the receiver antennas.

Fig. 3 shows the BER as a function of the total received SNR of the direct link, where the receiver using sample covariance distance based detection for different time-correlation channels. In addition, Fig. 4 plots the BER as a function of $\Delta\gamma$ given $\gamma_0 = 15\text{dB}$. Due to the fact that the receiver makes decision within one OFDM symbol period, the backscatter can transmit at a higher data rate than that which the decision is made over multiple OFDM symbol periods. The time correlation highly affects the BER. In addition, the time correlation of the direct link leads to more degradation on the BER than that the backscatter link does. However, most of broadcasting systems, for instance, FM radio and digital TV systems, a channel has a high correlation within tens of micro seconds such that the proposed method allows an AmBC system to operate at a high data rate with an acceptable BER.

Fig. 5 shows the BER as a function of γ_0 for a large number of receiver antennas. The solid curves depict that a short pilot sequence of 4 chips was used to measure $\hat{\mathbf{R}}_1$, while the dashed ones for a long pilot sequence of 58 chips. The results indicate that a large number of antennas and a long pilot sequence are needed to achieve a low BER. In addition, with a larger number of antennas, for instance $n_r = 50$, the BER curve has a deeper slope as γ_0 grows. Moreover, the results show that the proposed sample covariance distance based method (using an interlaced transmission sequence of pilots and data with a length of 60 chips) with 4 receiver antennas works better than that which there is not a so large number of antennas, i.e. $n_r = 10$, even there is a long pilot sequence.

V. CONCLUSION AND DISCUSSIONS

This work studied an AmBC system adopting BPSK modulation aiming to propose a simple receiver. The receiver has no knowledge of the CSI of all channels, the statistical channel

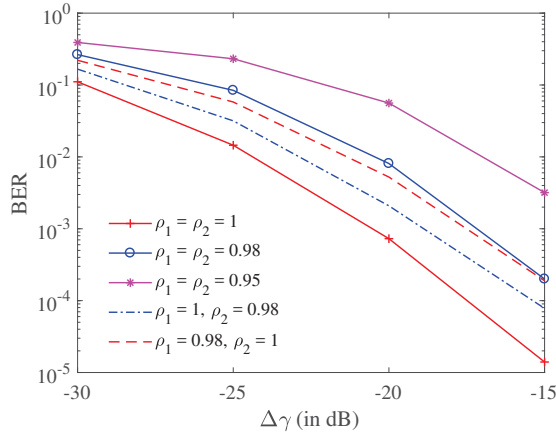


Fig. 4. BER as a function of $\Delta\gamma$, where $\gamma_0 = 15\text{dB}$ for different time-correlation scenarios.

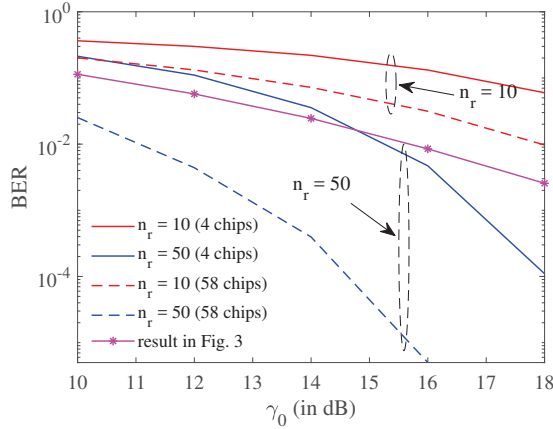


Fig. 5. BER as a function of $\Delta\gamma$ with a large number of antennas. Solid and dashed curves show short (4 chips) and long (58 chips) sequences for measuring $\hat{\mathbf{R}}_1$. Curve with marker * shows the result of $\rho_0 = \rho_0 = 1$ given in Fig. 3.

covariance matrices, or the noise variance at the receiver antennas. The developed simple sample covariance matrix distance based method enables the receiver to detect the backscatter symbol over one ambient OFDM symbol period applying the time correlation induced by the wideband ambient OFDM transmission which contains repetitive elements. There are also some limitations. If the backscatter modulates the ambient OFDM signals at a very high rate, then the backscattered path frequency response will shift to another band in the frequency domain. If the receiver has an analog bandpass filter, the AmBC signal will be filtered away. In addition, if there is a wideband receiver, it will cause severe adjacent band interference. We leave these to our future work.

REFERENCES

- [1] C. Boyer and S. Roy, "Backscatter communication and rfid: Coding, energy, and mimo analysis," *IEEE Transactions on Communications*, vol. 62, no. 3, pp. 770–785, March 2014.
- [2] C. He, Z. Wang, and V. Leung, "Unitary query for the $M \times L \times N$ MIMO backscatter RFID channel," *IEEE Trans. Wireless Commun.*, vol. 14, no. 5, pp. 2613–2625, May 2015.
- [3] J. Wu, J. Thompson, H. Zhang, R. V. Prasad, and S. Guo, "Green communications and computing networks [Series Editorial]," *IEEE Commun. Mag.*, vol. 54, pp. 106–107, May 2016.
- [4] Q. Wu, M. Tao, D. W. Kwan Ng, W. Chen, and R. Schober, "Energy-efficient resource allocation for wireless powered communication networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 3, pp. 2312–2327, Mar. 2016.
- [5] D. Bharadia, K. Johsi, M. Kotaru, and S. Katti, "BackFi: High throughput WiFi backscatter," in *ACM SIGCOMM*. New York, NY, USA: ACM, Aug. 2015, pp. 283–296.
- [6] V. Liu, A. Parks, V. Talla, S. Gollakota, D. Wetherall, and J. R. Smith, "Ambient backscatter: Wireless communication out of thin air," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 43, no. 4, pp. 39–50, Aug. 2013.
- [7] J. Qian, F. Gao, G. Wang, S. Jin, and H. Zhu, "Noncoherent detections for ambient backscatter system," *IEEE Trans. Wireless Commun.*, vol. 16, no. 3, pp. 1412–1422, Mar. 2017.
- [8] W. S. Lee, C. H. Kang, Y. K. Moon, and H. K. Song, "Determination scheme for detection thresholds using multiple antennas in Wi-Fi backscatter systems," *IEEE Access*, vol. 5, pp. 22 159–22 165, 2017.
- [9] W. Liu, X. Zhou, S. Durrani, and P. Popovski, "A novel receiver design with joint coherent and non-coherent processing," *IEEE Trans. Commun.*, vol. 65, no. 8, pp. 3479–3493, Aug. 2017.
- [10] C. Yang, J. Gummesson, and A. Sample, "Riding the airways: Ultra-wideband ambient backscatter via commercial broadcast systems," in *Proc. IEEE Infocom*, May 2017.
- [11] G. Yang, Y. C. Liang, R. Zhang, and Y. Pei, "Modulation in the air: Backscatter communication over ambient OFDM carrier," *IEEE Trans. Commun.*, vol. 66, no. 3, pp. 1219–1233, Mar. 2018.
- [12] R. Duan, R. Jäntti, H. Yigitler, and K. Ruttik, "On the achievable rate of bistatic modulated rescatter systems," *IEEE Trans. Veh. Technol.*, vol. 66, no. 10, pp. 9609–9613, Oct. 2017.
- [13] D. Darsena, G. Gelli, and F. Verde, "Modeling and performance analysis of wireless networks with ambient backscatter devices," *IEEE Trans. Commun.*, vol. 65, no. 4, pp. 1797–1814, Apr. 2017.
- [14] Z. Ma, T. Zeng, G. Wang, and F. Gao, "Signal detection for ambient backscatter system with multiple receiving antennas," in *IEEE 14th Canadian Workshop Inf. Theory*, Jul. 2015, pp. 50–53.
- [15] T. Zeng, G. Wang, Y. Wang, Z. Zhong, and C. Tellambura, "Statistical covariance based signal detection for ambient backscatter communication systems," in *IEEE 84th Vehicular Technology Conference (VTC-Fall)*, Sept. 2016, pp. 1–5.
- [16] G. Wang, F. Gao, R. Fan, and C. Tellambura, "Ambient backscatter communication systems: Detection and performance analysis," *IEEE Trans. Commun.*, vol. 64, no. 11, pp. 4836–4846, Nov. 2016.
- [17] J. Qian, F. Gao, G. Wang, S. Jin, and H. Zhu, "Semi-coherent detection and performance analysis for ambient backscatter system," *IEEE Trans. Commun.*, vol. 65, no. 12, pp. 5266–5279, Dec. 2017.
- [18] C. H. Kang, W. S. Lee, Y. H. You, and H. K. Song, "Signal detection scheme in ambient backscatter system with multiple antennas," *IEEE Access*, vol. 5, pp. 14 543–14 547, 2017.
- [19] Y. Liu, G. Wang, Z. Dou, and Z. Zhong, "Coding and detection schemes for ambient backscatter communication systems," *IEEE Access*, vol. 5, pp. 4947–4953, 2017.
- [20] S. Wei, D. L. Goeckel, and P. A. Kelly, "Convergence of the complex envelope of bandlimited ofdm signals," *IEEE Transactions on Information Theory*, vol. 56, no. 10, pp. 4893–4904, Oct. 2010.
- [21] T. Siddiqui, M. M. Islam, K. Rasilainen, and V. Viikari, "Transponder utilizing the modulated re-scattering communication principle," in *2017 XXXII General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS)*, Aug. 2017, pp. 1–4.
- [22] Nexperia, *Data sheet: 1N4148 High-speed diodes*, Jan. 2002. [Online]. Available: https://assets.nexperia.com/documents/data-sheet/1N4148_1N4448.pdf
- [23] A. M. Tulino and S. Verdú, *Random Matrix Theory and Wireless Communications*. Foundations and Trends in Communications and Information Theory, 2004, vol. 1, no. 1.
- [24] H. Van Trees, *Detection, Estimation, and Modulation Theory (Part IV): Optimum Array Processing*. New York: John Wiley & Sons, 2001.
- [25] G. L. Stüber, *Principles of mobile communication*, 2nd ed. Norwell, MA, USA: Kluwer Academic Publishers, 2001.