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Multi-bounce Effect: an Overlooked Aspect in Analysis of Ambient Backscatter Networks

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Abstract
The scope of the Internet of Things has driven significant attention towards ambient backscatter communication (AmBC) systems as a possible solution. However, the fundamental performance limits of the AmBC-enabled wireless systems are not yet well-understood. This paper evaluates the performance limits of an AmBC system with binary phase-shift keying input and multi-bounce effect between AmBC nodes which has been overlooked in literature. For this purpose, the study applied a multiplicative channel model modified from a reverberant one. The obtained results indicate that the multi-bounce effect between the AmBC nodes is non-ignorable on the performance of the legacy and the AmBC systems, and improves the AmBC achievable rate.

Categories and Subject Descriptors
C.2.1 [Network Architecture and Design]: Wireless communication

General Terms
Backscatter communication

Keywords
Ambient backscatter, multi-bounce channel, multiplicative channel, reverberant channel, BPSK

1 Introduction
The Internet of Things (IoT) is now arguably one of the most heavily discussed and researched topics in the technology industry, and it has the potential of completely revolutionizing how we work and how we live. Future success and sustainability of IoT depend greatly on the ability of devices to communicate using very little power, as this is one of the most limiting factors of being able to connect devices without incurring additional costs or worsening our energy footprint. The scope of the IoT is a wealth of new services and is far beyond such as a smart home, reading a smart meter, assistive technologies for elderly and disables people, medical applications, emergency responses, and vehicular safety [23, 1, 18]. This issue has driven significant attention towards ambient backscatter communication (AmBC) systems as a possible solution for ultra-low power connections [16, 20, 2, 18, 9, 11].

Modern wireless networks have been witnessed an unprecedented evolution from classical architectures to heterogeneous ones. AmBC is to leverage green IoT applications and to enhance the future wireless networks. In contrast to traditional systems, AmBC devices do not need a power-hungry transceiver and can achieve up to 1000 times lower power consumption and 10 to 100 times lower device cost than those in the contemporary active-transceiver-based solutions. Although the circuit power consumption could still be a serious problem in practice [31], it is nevertheless much smaller than in case of active transmitters [2]. This significantly simplifies the energy harvesting problem. In AmBC, the backscatterers can be powered by the RF emitted by, e.g. TV signals, cellular transmissions, Bluetooth signals and WiFi signals [19, 20, 33, 10] among others. Particularly, one of the recent work [10] achieves a significant advance to create WiFi and ZigBee-compatible signals using backscatter communications to achieve 2-11 Mbps WiFi standards-compliant signals by backscattering Bluetooth transmission. To increase the communication range, the ambient frequency modulation radio signals have been considered in [29, 32, 27], and a LoRa backscatter has been designed in [24].

The ultra-low power AmBC backscatterers do not amplify the signal, but modulate it instead. The fundamental performance limits of the AmBC enabled wireless systems are not yet well-understood. Initial steps towards understanding of the performance limits of a backscatter-enabled wireless system have been conducted in [4] where loose capacity bounds for single antenna system have been obtained. Considering AmBC, the symbol detection and bit error rate for the single-input-single-output (SISO) scenarios have been deduced in [30, 22]. However, to the best of our knowledge, the previous models did not consider joint decoding of the legacy and backscatter systems. Multiple-antenna techniques can be applied to AmBC systems to increase the capacity, increase the communication range, and improve the reliability [13]. The unmodulated continuous carrier multiple input and multiple...
output (MIMO) backscatter systems have been studied, e.g. [3, 7, 8]. Considering a modulated bi-static MIMO AmBC system, authors in [5] showed that the MIMO system with cooperation of the scatters achieves higher rate than what the MIMO system could achieve alone; the excess rate can be achieved by the primary system alone or it can be shared by the two systems; in a rich scattering environment and perfect channel state information (CSI) the limiting sum rate of the AmBC approaches the sum of the limiting rates of a MIMO channel and a multiple-keyhole MIMO channel; and a joint pilot signal should be designed properly to estimate the channels. In order to serve the AmBC devices, a minimum mean square error receiver with successive interference cancellation could be applied.

The previous research investigated the backscatter communication mainly by considering single backscatter node, developing testbeds, or conducting coding design and theoretical analysis for RFID-based backscatter systems. Therefore, the possible signal interaction between the AmBC nodes has been overlooked in literature. The multi-bounce phenomenon is likely to appear in a dense backscatter network. This paper evaluates the performance limits of an AmBC system with binary phase-shift keying (BPSK) input and multi-bounce effect between AmBC nodes. The information of the legacy MIMO system (referred to the legacy transmitter and receiver pair) and the AmBC system will be jointly decoded. In addition, we consider that the multi-antenna receiver tries to sequentially decode both the original signal sent by the legacy transmitter and the signal sent by the AmBC nodes. The AmBC nodes will act as passive relays to each other increasing the path diversity. For this purpose, the study applied a multiplicative channel mode modified from a reverberant one. The results indicate that the multi-bounce effect between the AmBC nodes is non-ignorable on the performance of the legacy and the AmBC systems.

The rest of this paper is organized as follows. Section 2 introduces the system and the channel models. In Section 3, we consider sequential decoding and a linear minimum-mean-squared-error (MMSE) receiver with successive interference cancellation (SCI) technique. Section 4 presents the simulation results. Finally, Section 5 concludes this paper.

Notations: Throughout the paper, vectors and matrices are represented by lower-case and upper-case bold-face letters, respectively. The superscript \(^\dagger\) denotes the matrix conjugate transpose operation and \((\cdot)^T\) is matrix transpose. We use \(\mathbb{C}A(0, A)\) to denote the zero-mean complex Gaussian vector covariance matrix \(A\) and \(I_n\) is an \(n \times n\) identity matrix, and the subscript \(n\) may be omitted sometimes for simplicity. The notation \(\mathbb{E}[\cdot]\) denotes the expectation, and \(\otimes\) denotes the (block) Kronecker product operator. Furthermore, we use \(|A|_2\) and \(|A|_F\) to denote the spectral norm and Frobenius norm of the matrix \(A\), respectively.

2 System Model

We consider an AmBC MIMO system shown in Fig. 1 that consists of a legacy system and 2 single-antenna AmBC nodes. The legacy transmitter \((L_{tx})\) and receiver \((L_{rx})\) are equipped with \(n_t\) and \(n_r\) antenna elements, respectively. The AmBC nodes adopt the BPSK modulation technique, and are synchronized to the legacy system. Information transmitted from the \(L_{tx}\) to the \(L_{rx}\) propagates through the direct links and the links passing through the AmBC nodes. The multi-bounce phenomenon of the signals occurs between the two AmBC nodes. The signals passing through the AmBC are modulated accordingly. We consider fixed channels for analysis.

In this paper, we have adopted the following commonly used assumptions for the signal model, e.g. [14] among others:

(A1) The CSI is perfectly available at the receiver, \(L_{rx}\), but not at the \(L_{tx}\). For instance, the CSI can be measured by using pilots [5];

(A2) A narrow-band system is considered. The channels are frequency flat and follow a block fading process, i.e. the entities of channel vectors remain constant over each coding block and are independent and identically distributed across from one block to another; In addition, the coherence time of the channel is much longer than the frame duration;

(A3) At the transmitter, \(L_{tx}\), the transmit signal \(x_0\) is Gaussian distributed with transmit power equally allocated to each antenna and with covariance matrix \(\mathbb{E}[x_0 x_0^H] = I_n\), i.e., \(x_0 \sim \mathbb{C}A(0, I_n)\). The transmit signal to noise ratio (SNR) per antenna is \(\text{snr}\).

2.1 Reverberant Channel Model

We follow the propagation graph model [21, 25] to model the reverberant channel caused by the interaction of the two AmBC nodes. We denote the propagation time of a link as \(\tau_{ij}\). Let \(H_d = \left[h_{0j,0i}\right] \in \mathbb{C}^{n_t \times n_t}\) denote the channel matrix of the direct link, and \(h_{0j,0i}\) be the complex channel coefficient between antenna \(i\) at the \(L_{rx}\) and antenna \(j\) at the \(L_{tx}\), with propagation time \(\tau_{0j,0i}\). We denote the channel matrix between the AmBC nodes and the \(L_{tx}\) as \(H_{m} = \left[h_{mj,0i}\right] \in \mathbb{C}^{n_t \times n_t}\), where \(h_{mj,0i}\) denotes the complex channel coefficient with \(\tau_{mj,0i}\) between antenna \(i\) of the \(L_{tx}\) and the AmBC node \(m \in \{1, 2\}\). Similarly, \(H_{m} = \left[h_{mj,0i}\right] \in \mathbb{C}^{n_t \times n_t}\) defines the channel matrix between the nodes and the \(L_{rx}\) antennas. Moreover, \(G = \left[g_{mn}\right] \in \mathbb{C}^{2 \times 2}\) and \(m, n \in \{1, 2\}\) denotes the (single

![Figure 1. Example of an AmBC MIMO system with an \(n_t\)- and \(n_r\)-antenna legacy transmitter and receiver, and 2 single-antenna AmBC nodes.](image-url)
bounce) channel matrix between AmBC nodes, where $g_{m,n}$ is the complex channel coefficient between AmBC nodes $n$ and $m$ with the associated propagation time $\tau_{m,n}$. Assume that the AmBC nodes are far away (i.e. not forming an array), and the self-coupling of the signal from an antenna is small, i.e., $|g_{m,m}| \rightarrow 0$, $\forall m = 1, 2$. Due to channel reciprocity, we have $g_{m,n} = g_{n,m}$. An AmBC node $m$ modulates the signal by $x_m = \alpha_m \theta_m$, $m = 1, 2$ with a scattering factor (amplitude) $0 \leq \alpha \leq 1$ and a phase shift $\theta_m$.

Assuming that the channel coherence time is long, the signal re-scattered from AmBC node $m$ at time instance $t$ reads

$$
\upsilon_m(t) = x_m(t) \left( \sum_{n=1}^{2} g_{m,n} \upsilon_n(t - \tau_{m,n}) + \sqrt{\text{snr}} \sum_{i=1}^{n_t} h_{m,0} \upsilon_0(t - \tau_{m,0}) \right).
$$

The signal $\upsilon_m(t)$ consists of the signals from the legacy transmitter $L_{tx}$, the AmBC nodes, and the self-coupled signal. The signal received by the antenna $j$ of the $L_{rx}$ can be written as

$$
y_j(t) = \sqrt{\text{snr}} \sum_{i=1}^{n_t} h_{0,j,0} \upsilon_0(t - \tau_{0,j,0})
+ \sum_{m=1}^{2} h_{0,j,m} \upsilon_m(t - \tau_{0,j,m}) + z_j(t),
$$

where $z_j(t)$ denotes the circular complex Gaussian noise at the receiver antenna $j$ at time $t$. As the symbol duration is long, we can drop the time indexes and write

$$
\upsilon_m = x_m \left( \sum_{n=1}^{2} g_{m,n} \upsilon_n + \sqrt{\text{snr}} \sum_{i=1}^{n_t} h_{m,0} \upsilon_0 \right), \quad (1a)
\upsilon_j = \sqrt{\text{snr}} \sum_{i=1}^{n_t} h_{0,j,0} \upsilon_0 + \sum_{m=1}^{2} h_{0,j,m} \upsilon_m + z_j. \quad (1b)
$$

Let the vector $x = [x_m] \in \mathbb{C}^2$ denote the phase shift induced by all AmBC nodes, and its diagonal matrix version is $X = \text{diag} \{x\}$. We denote $z = [z_j] \in \mathbb{C}^n$ as the noise vector at the receiver, i.e. $z \sim CN(0, I_n)$. Thus, the received signal vector at the receiver $y = [y_j] \in \mathbb{C}^n$ and the reflected signal from all the AmBC nodes $\upsilon = [\upsilon_m] \in \mathbb{C}^2$ in Eq. (1) read

$$
y = H_x \psi + \sqrt{\text{snr}} H_{d} x_0 + z, \quad \text{and} \quad \psi = X G \upsilon + \sqrt{\text{snr}} X \psi X_0.\quad (2)
$$

Provided that the spectral radius of $G$ is less than unity $[21, 25]$ and $\|x\|_2 \leq 1$, the iteration

$$
\psi[m + 1] = X G \upsilon[m] + \sqrt{\text{snr}} X \psi x_0 \quad (3)
$$

converges to

$$
\psi = \sqrt{\text{snr}} (I - X G)^{-1} X \psi x_0 \quad (4)
$$

starting from arbitrary initial value $\psi[0], \|\psi[0]\|_2 < \infty$. We define the AmBC channel matrix from Eq. (2) as $H_{d} = H_x \psi X_0$, and hence the overall channel matrix reads $H \triangleq H_{d} + H_{r}$, i.e.,

$$
y = \sqrt{\text{snr}} \left[ H_{d} + H_{r} (I - X G)^{-1} X H \right] x_0 + z. \quad (5)
$$

### 2.2 Multiplicative Signal Model

The reverberant channel model produced in the previous section is challenging from the receiver design perspective as the AmBC signals $X$ appear inside the product chain of the channel matrices. We propose an applicable and simple linear model if the AmBC nodes use BPSK modulation scheme. For BPSK, we have $x_m \in \{-\alpha, \alpha\}$ and $x_m^2 = \alpha^2, \forall m = 1, 2$. A multi-bounce path $L_{tx} \rightarrow m \rightarrow m \rightarrow L_{rx}$ would be modulated by $x_m^2 \upsilon_0 = \alpha^2 \upsilon_0$, which, however, is indistinguishable from the path $L_{tx} \rightarrow n \rightarrow L_{rx}$ which is also modulated by $\upsilon_0$. In addition, some longer paths such as $L_{tx} \rightarrow m_1 \rightarrow m_2 \rightarrow m_1 \rightarrow m_2 \rightarrow n \rightarrow L_{rx}$ would effectively be modulated only by $\upsilon_0$. Moreover, there are multi-bounce paths that contribute to the direct $L_{tx} \rightarrow L_{rx}$ path such as $L_{tx} \rightarrow m \rightarrow n \rightarrow L_{rx}$ which is modulated by $x_m^2 \upsilon_0 = \alpha^4$. In two-node scenario, the longest distinguishable multi-hop path would have 2 bounces and be modulated by $x_1 x_2$. We formulate the multiple-bounce signal model by assuming that channels between AmBC nodes are reciprocal, i.e. $g_{m,n} = g_{n,m} = g$, and there is no self-coupling of the signal from an antenna. It follows that $G = \begin{bmatrix} 0 & g \end{bmatrix}^T$ and $X = \begin{bmatrix} 1 & 0 \end{bmatrix}$. Therefore

$$
(I - X G)^{-1} X = 
\begin{bmatrix}
\frac{1}{1 - |g|^2} x_1 & g x_1 x_2 \\
\frac{1}{1 - |g|^2} x_2 & g x_1 x_2 + \frac{|g|^2 g}{x_2}
\end{bmatrix}
$$

$$
= \frac{1}{1 - |g|^2} \begin{bmatrix} x_1 + |g|^2 x_2 & g x_1 x_2 + |g|^2 x_1 \\
\frac{|g|^2}{x_2} x_1 x_2 + \frac{|g|^4}{x_2} x_2 & x_1 + |g|^2 x_2 + \frac{|g|^4}{x_2} x_2
\end{bmatrix}
$$

$$
= F_0 + F_{11} x_1 + F_{12} x_2 + F_{21} x_1 x_2,
$$

where $F_0 = \alpha^4 \begin{bmatrix} 0 & x_1 x_2 \\
0 & 0 \end{bmatrix}$, $F_{11} = \frac{|g|^2 x_2}{\beta}$, $F_{12} = \frac{|g|^2 x_2}{\beta}$, $\beta = 1 - \alpha^4 |g|^4$. Since AmBC symbol products appear only once, the received signal in (5) yields

$$
y = \sqrt{\text{snr}} \left[ H_{0} x_0 + H_{11} x_1 x_1 + H_{12} x_0 x_2 + H_{20} x_0 x_1 x_2 + z \right]. \quad (6)
$$

where $H_0 = H_d + H_{d} F_0 H_x$, $H_{11} = H_x F_{11} H_x$, $H_{12} = H_x F_{12} H_x$, and $H_2 = H_x F_{21} H_x$. In addition, we denote that $H_1 = [H_{11}, H_{20}]$. Such a channel model shows that certain recurrent paths become independent of the phase of AmBC nodes and thus contribute to $H_0$. Those multi-bounce paths from AmBC contributing to the direct paths cannot be distinguished from them. Moreover, $H_1$ and $H_2$ correspond to the (effective) 1- and 2-bounce paths, respectively. In consequence, for the scenario consisting of 2-node AmBC with BPSK input and a legacy MIMO system, the multiplicative channel model in (6) can be written as

$$
y = \sqrt{\text{snr}} \left[ \begin{bmatrix} H_0 \quad H_1 \quad H_2 \end{bmatrix} \otimes x_0 \right] \psi + z
$$

$$
= \sqrt{\text{snr}} \left[ \begin{bmatrix} H_0 \quad H_1 \quad H_2 \end{bmatrix} \psi \right] x_0 + z. \quad (7)
$$

We denote the block Kronecker product operation by $[A_1; A_2; A_3] \otimes b = [A_1 b; A_2 b; A_3 b]$, and the block product operation by $[A_1; A_2; A_3] b = A_1 b_1 + A_2 b_2 + A_3 b_3$.2

2
where the \( \left( \sum_{b=1}^{2} \left( \begin{array}{c} 2 \\ b \end{array} \right) \right) \times 1 \) vector \( \psi \) is given by
\[
\psi = [1, \psi_1^T, \psi_2^T]^T,
\]
and the sub-vector \( \psi_b^T \) combines all unique \( b \)-length products of the modulation coefficients of the AmBC nodes with \( \psi_1^T = [x_1, x_2]^T \) and \( \psi_2^T = [x_1, x_2]^T \). We denote that \( \mathbf{H} \triangleq [\mathbf{H}_0, \hat{\mathbf{H}}_1, \hat{\mathbf{H}}_2] \).

Without considering the multi-bounce effect, the overall channel model can be expressed as:
\[
\hat{\mathbf{y}} = ([\mathbf{H}_d, \hat{\mathbf{H}}_1, \hat{\mathbf{H}}_2] \otimes x_0) \psi + z,
\]
where \( \hat{\mathbf{H}}_1 = h_{11}h_{11}^\dagger, \hat{\mathbf{H}}_2 = h_{22}h_{22}^\dagger, \) and \( \psi = [1, x_1, x_2]^T \) with \( h_{ij} \) and \( h_{ti} \) denoting the \( i \)-th column of \( \mathbf{H} \) and the \( i \)-th row of \( \mathbf{H} \), respectively. We denote that \( \hat{\mathbf{H}} \triangleq [\mathbf{H}_d, \hat{\mathbf{H}}_1, \hat{\mathbf{H}}_2] \).

Remark: Our proposed method using multiplicative channel model can be readily applied into the scenario that the AmBC nodes adopt the on-off keying (OOK) modulation technique. In addition, an multiplicative signal model can be found for any M-ary Phase Shift Keying (PSK). However, the dimension of the channel input grows fast.

3 Sequential Decoding and SINR

We consider sequential decoding that the receiver would be able to decode \( x_0 \) first. One approach to obtain \( x_0 \) first is to adopt a linear minimum-mean-squared-error (MMSE) receiver with successive interference cancellation (SIC) acting upon the matrix. The MMSE-SIC receiver successively decodes the strongest stream of the legacy system first, and then after removing the stream it decodes the remaining strongest stream. When the receiver decodes the signal of AmBC node 1 by treating the signal of another node as interference. Each of the two users has equal probability to be decoded first. Conditioned on the channel matrices, the SINR and the MMSE of a flow satisfy the following relation [26, 15]
\[
\text{SINR} = \frac{1}{\text{MMSE}} - 1.
\]

Without loss of generality, we assume that the strength of the flows of the legacy system are sorted in a decreasing order. Conditioned on the channel matrices \( \mathbf{H}_0 \) \( (x_1 \text{ and } x_2 \text{ are unknown, and so are } \mathbf{H}_1 \psi_1 \text{ and } \mathbf{H}_2 \psi_2) \), the SINR for the currently decoded flow, i.e. the \( i \)-th flow, of the legacy system can be expressed as
\[
\text{SINR}_{0,i} = \left( \left( \mathbf{I} + \text{snr} \mathbf{H}_{0,i}^\dagger \mathbf{H}_{0,i} \right) \right)^{-1} - 1, \quad \forall i = 1, \cdots, n,
\]
where \( \mathbf{H}_{0,i} \) is the matrix whose columns associated to the decoded streams of the legacy user have been removed. Hence, the achievable rate of the legacy system is
\[
\tilde{r}_0 = \sum_{i=1}^{n} \log_2 (1 + \text{SINR}_{0,i}).
\]

Similarly, substituting \( \mathbf{H} \) by \( \hat{\mathbf{H}} \), we obtain the achievable rate of the legacy system for the scenario that there are no multi-bounce paths.

Once \( x_0 \) has been decoded, we can treat it as a known part and the term \( \mathbf{H}_0 x_0 \) in (7) can be removed after \( x_0 \) is decoded at the receiver. The remained signal reads
\[
\tilde{\mathbf{y}}_1 = \sqrt{\text{snr}} \mathbf{H}_1 x_0 + z,
\]
where \( \tilde{x} = [x_1, x_2, x_1 x_2]^T, \tilde{\mathbf{H}} = [\hat{\mathbf{H}}_1, \hat{\mathbf{H}}_2] \otimes x_0 \) denotes the associated channel matrix which is assumed to be known at the receiver, and \( x_0 \) can be treated as fast fading channel.

\[
\text{SINR}_{1,i} = \left( \left( \mathbf{I} + \text{snr} \tilde{\mathbf{H}}_{1,i}^\dagger \tilde{\mathbf{H}}_{1,i} \right) \right)^{-1} - 1, \quad \forall i = 1, 2.
\]

There are three streams that the first two are associated to nodes 1 and 2, respectively. The third one does not contain any information of the two nodes, though affects the SINR of other streams. For BPSK signaling, the achievable rate with soft decision decoding of the AmBC nodes can be expressed as [6, 12, 28]:
\[
r_{\text{BPSK},i} = 1 - \int_{-\infty}^{\infty} \frac{e^{-x^2}}{\sqrt{\pi}} \log_2 \left( 1 + e^{-4 \sqrt{\text{SINR}_{1,i}(x + \sqrt{\text{SINR}_{1,i}})}} \right) \, dx,
\]
\[
\forall i = 1, 2.
\]

Therefore, substituting (12) into (13), we obtain the achievable rate of the AmBC nodes while considering the multi-bounce effect.

As shown in (8), without the multi-bounce, that the backscattered paths do not directly contribute to the channel matrix of the direct link. Substituting \( \mathbf{H} \) in (9) by \( \hat{\mathbf{H}} \), we obtain the SINR of the legacy system as
\[
\text{SINR}_{0,i} = \left( \left( \mathbf{I} + \text{snr} \hat{\mathbf{H}}_{0,i}^\dagger \hat{\mathbf{H}}_{0,i} \right) \right)^{-1} - 1, \quad \forall i = 1, \cdots, n.
\]

Hence, the corresponding achievable rate of the legacy system reads
\[
\tilde{r}_0 = \sum_{i=1}^{n} \log_2 (1 + \text{SINR}_{0,i}).
\]

Similarly, after decoding \( x_0 \) the received signal, we obtain the SINR for the AmBC nodes by substituting \( \mathbf{H} \) in (12) by \( \hat{\mathbf{H}} = [\hat{\mathbf{H}}_1, \hat{\mathbf{H}}_2] \otimes x_0 \). Then the achievable rate of the AmBC nodes without considering the multi-bounce phenomenon between AmBC nodes can be obtained by substituting \( \text{SINR}_{1,i} \) in (13).

4 Simulation Results

In the simulation, we adopt the following parameters: 2 transmit antennas, 2 AmBC nodes, and 4 receive antennas (for a large number of antennas \( n_t = 100 \) as a comparison). The AmBC nodes apply BPSK modulation technique. All results are averaged over \( 10^5 \) realizations. A channel matrix \( \mathbf{A}^{n_t \times n_t} \) is normalized so that \( \mathbb{E}[|A|_F^2] = a \times b \) [14, 17]. Note that the scattering factor of the nodes is denoted by \( \alpha \). \( \alpha = 1 \)
means that there is no attenuation, and $\alpha = 0$ denotes that there is no signal scattered from the node.

Fig. 2 shows the achievable rate of the legacy system as a function of the total transmit SNR at the legacy transmitter. Considering the transmission of the AmBC nodes as interference, we illustrate three scenarios: legacy alone (marker ‘o’), with multi-bounce effect (marker ‘*’), and without multi-bounce effect (marker ‘$\diamond$’). The solid curves represent the case that $\alpha = 1$ and $n_r = 4$; the dashed ones represent the scenario that $\alpha = 1$ and $n_r = 100$; the dotted ones depict that $n_r = 4$ and $\alpha = 0.5$. First, the results show that larger value of the scattering factor causes more loss to the achievable rate of the legacy user with a small amount of receiver antenna, e.g., $n_r = 4$. This loss is ignorable and vanishing as $n_r$ grows larger. Second, it is shown in the high SNR regime with a small number of receiver antennas, e.g., $n_r = 4$ that the multi-bounce effect between the AmBC results in, given $\alpha$, more rate loss than the case without multi-bounce effect. However, in the low SNR regime, the multi-bounce and the scattering factor $\alpha$ has negligible effect.

In Fig. 3, we plot the achievable rate of the legacy system as a function of the total transmit SNR at the legacy transmitter. The solid curves represent the case that $\alpha = 1$ and $n_r = 4$; the dashed ones represent $n_r = 100$. The marker ‘$\diamond$’ denotes that the legacy system is alone; the marker ‘$\diamond$’ represents that there are no multi-bounce between the two backscatters; the marker ‘$*$’ represent that the multi-bounce exists. The results confirm that higher value of the scattering factor $\alpha$ causes more loss to the legacy system. However, the effect could be compensated by adopting more receiver antennas. In addition, in the low SNR regime, the multi-bounce effect is ignorable.

Fig. 4 shows the achievable rate of AmBC nodes after decoding the message of the legacy user as a function of the total transmit SNR of the primary system. The multi-bounce effect and the scattering factor $\alpha$ play an important role on the achievable rate. For small values of $\alpha$, the multi-bounce paths has higher contributions to increasing the achievable rate than the scenario with larger values of $\alpha$. That is if $\alpha$ is large, the multi-bounce effect is not significant. We show the achievable rate of the AmBC nodes as a function of $\alpha$ in Fig. 5. Given the total SNR, with consideration of the multi-bounce effect the achievable rate of the AmBC nodes is not sensitive to the scattering factor. However, without considering the multi-bounce paths the scattering factor affects significantly the rate of the AmBC nodes, particularly in the low SNR scenario.
Figures 2-5 indicate that from the perspective of the legacy system, the multi-bounce phenomenon between the backscatterers should be avoided if there is no cooperation from the backscatterers. One possible solution is that the backscatterers should be far away enough. However, the backscatterers advocate the multiple bounces to achieve better data rate. Therefore, we should take the multi-bounce effect in a proper way to optimize the backscatter communication networks. For instance, if a backscatter has a simple receiver, we could use some control information to schedule the transmissions of multiple backscatter devices.

5 Conclusions and Future Work

The considered model consists of the modulated backscatter system together with the legacy system is practical in modeling a real ambient backscatter system. Particularly, we proposed a multiple-bounce channel model for investigating the considered system. We analyzed the performance for a two-node AmBC system applying BPSK modulation technique. For such a system, we derived the achievable rates. The obtained results indicate that the backscatterers could improve the achievable rate through the reverberated channels between the backscatterers.

This invokes a system design issue that how the AmBC system can benefit the primary link. One possible solution was suggested in [5] by using time duplex access technique such that the primary link and the AmBC system can share the excess rate. In addition, other different modulation techniques used by the backscatterers need to be studied, for instance on-off keying, quadrature amplitude modulation, and so on. Moreover, proper multiple access protocols and scheduling schemes are of importance in dense backscatter networks.

6 References


