Outage probability computation in multi-backscatter systems with multi-modes of operation

Dinh-Thuan Do, Anh-Tu Le
Faculty of Electronics Technology, Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam

ABSTRACT
In this article, we study the outage performance of an ambient multi-backscatter system supported by non-orthogonal multiple access (NOMA) downlink transmission, where legacy users receive information either directly from the base station (BS) or from multiple backscatter devices (BDs) as well. Specifically, we characterize the network connections between the BS and network users into three modes of operation. In the first mode, the BS communicates with the users via the BDs by exploiting NOMA. In the second mode, the BS communicates directly with the users by employing selection combining (SC) beamforming. In the third mode, the users receive signals from both the BS and BDs simultaneously, by using maximal ratio combining (MRC) to combine the BS and BDs links at the users. Consequently, we derive the exact outage expressions of each mode and utilize Monte Carlo simulations to validate the individual exact expressions.

1. INTRODUCTION
The rapid deployment of internet-of-things (IoTs) in diverse systems such as energy systems (Smart Grid), healthcare systems, industrial systems, and transportation systems, has seen a tremendous push into researching ways of powering these billions of devices in a sustainable and environmentally friendly way [1], [2]. Ambient backscatter communication (AmBC) has been proposed by the research community as a solution to address this unique challenge [3]. AmBCs can free up IoT devices from needing batteries as backscatter devices (BDs) harvest energy from traditional radio frequency (RF) transmitters such as television and radio transmitters to transmit information to nearby IoT devices [2]–[13]. Yang et al. in [4], the authors note that the harvested energy from ambient RF transmitters is adequate to provide power to high-rate battery-less sensors. Therefore, AmBC can be used in IoT environments where it’s not convenient to replace or maintain sensor batteries, e.g., in wide-body area networks (WBANs) [14], [15]. However, due to the broadcast nature of ambient RF transmitters, AmBC tend to suffer from direct-link interference from the RF transmitter [2]–[6]. Several methods such as the design of maximum-likelihood (ML) detectors, and interference cancellation techniques, have been proposed to eliminate the direct-link interference, see [4], [6] and references therein for more details.

In this study, we propose utilizing non-orthogonal multiple access (NOMA) technology to address this problem, owing to its ability to simultaneously serve multiple wireless users over the same radio resource via linear superposition coding at the transmitter and successive interference cancellation (SIC) at the user’s receiver [2], [16]–[18]. Therefore, integrating NOMA with AmBC networks shows great promise for future
Apart from NOMA, there have been several recent studies on deploying reconfigurable intelligent surfaces (RIS) to improve backscatter communication performance [19]–[21]. However, in this article, we focus on the contribution of NOMA to AmBCs performance. Our main contributions are: Firstly, we derive exact outage expressions for three practical AmBC link cases. In the first case, the base station (BS) communicates with the users via the BDs. In the second case, the BS communicates directly with the users. In the third case, the users receive signals from both the BS and BDs simultaneously; Secondly, from these expressions, we analyze the role of channel vectors, power allocation coefficients and backscatter reflection coefficient on outage probability.

All expressions are confirmed using Monte Carlo simulations. The paper is organized is being as. In section 2, we describe the proposed system model and signal characteristics at the users. Thereafter, in section 3, we derive exact outage probability (OP) expressions depending on the mode of operation. In section 4, we explain results, followed by the summary in section 5.

2. RECEIVED SIGNALS AT TWO USERS

In this paper, we study a downlink wireless system to allow the base station (BS) serving two multiple antennas users (user \( U_1 \) and user \( U_2 \)) under assistance of multiple backscatter devices (BDs), shown in Figure 1. In some practical case, the second user \( U_2 \) might connect with the BS directly.

![Figure 1. System model of multi-backscatter NOMA](image)

The criteria to choose best multi-backscatter is given by:

\[
 n^* = \arg \max_{n=1,2,\ldots,N} |h_{0,n}|^2. 
\]

(1)

BS broadcasts the information \( x^{BS} \) to multi-backscatter (\( BD_n \)), \( n = 1, 2, \ldots, N \), which is given by:

\[
x^{BS} = \sqrt{a_1 P_S} x_1 + \sqrt{a_2 P_S} x_2, \]

(2)

where \( x_1 \) and \( x_2 \) are the messages with unit power transmitted to \( U_1 \) and \( U_2 \), respectively. Further, \( P_S \) is the total transmit power of the BS with power allocation parameters \( a_1 \) and \( a_2 \), respectively, with \( a_1 > a_2 \) and \( a_2 + a_1 = 1 \).

The maximal-ratio combining (MRC) is used with beamforming vector to achieve optimal transmission scheme as in [22], [23] with \( \|w_i\| = 1 \):

\[
w_i = \frac{h_i^T}{\|h_i\|}, \quad i \in \{1, 2\},
\]

(3)

where \( \|\cdot\| \) denotes the Euclidean norm of a matrix.

The BD the BS signal to \( U_1 \) and \( U_2 \) with its own message \( s \), where \( \mathbb{E}\{s^2\} = 1 \). Thus, \( U_1 \) and \( U_2 \) receive one type of signal: the backscatter link signal from the BD. The received signals at \( U_1 \) and \( U_2 \) can thus be written as:
Thus, RVs \( y_{U_1} = \beta h_{0,n^*} \| h_{1} w_1 \| x^{BS} s + n_{U_1}, \) \( y_{U_2} = \beta h_{0,n^*} \| h_{2} w_1 \| x^{BS} s + n_{U_2}, \) respectively as:

\[
y_{U_1} = \beta h_{0,n^*} \| h_{1} w_1 \| x^{BS} s + n_{U_1},
\]
\[
y_{U_2} = \beta h_{0,n^*} \| h_{2} w_1 \| x^{BS} s + n_{U_2},
\]

where \( \beta \) is a complex reflection coefficient used to normalize, \( h_1 \) and \( h_2 \) are the \( 1 \times M \) channel vector of \( BD-U_1 \) link and \( 1 \times K \) channel vector of \( BD-U_2 \) link, \( n_{U_1} \) and \( n_{U_2} \) are the additive white Gaussian noise (AWGN) with zero mean and variance matrix \( \sigma^2_{h_1} I_M \) and \( \sigma^2_{h_2} I_K \), respectively. Hence, the signal \( x_1 \) is detected successfully and \( x_2 \) as interference. Then, the signal-interference to ratio at \( U_1 \) is given by:

\[
\gamma_{1,1} = \frac{\rho a_1 \beta^2 \| h_1 \|_2^2 \| h_{0,n^*} \| ^2}{\rho a_2 \beta^2 \| h_1 \|_2^2 \| h_{0,n^*} \| ^2 + 1},
\]

where \( \rho = \frac{P_0}{\sigma^2_{h_i}} \), \( i \in \{ 1, 2 \} \) is the transmit signal-to-noise ratio (SNR).

Thus, the instantaneous SINR at \( U_2 \) to detect \( x_1 \) and the instantaneous SNR at \( U_2 \) to detect \( x_2 \) is given respectively as:

\[
\gamma_{2,1} = \frac{\rho a_1 \beta^2 \| h_2 \|_2^2 \| h_{0,n^*} \| ^2}{\rho a_2 \beta^2 \| h_2 \|_2^2 \| h_{0,n^*} \| ^2 + 1}, \quad \gamma_{2,2} = \frac{\rho a_2 \beta^2 \| h_2 \|_2^2 \| h_{0,n^*} \| ^2}{\rho a_2 \beta^2 \| h_2 \|_2^2 \| h_{0,n^*} \| ^2 + 1}.
\]

3. OUTAGE PROBABILITY COMPUTATION OF DIFFERENT MODES

3.1. Scheme 1: outage probability for backscatter-non-orthogonal multiple access system without direct link

In this study, we assume independent Rayleigh-distributed random variables (RVs) for all the channels. Thus, RVs \( \| h_{0,n^*} \| ^2, \| h_1 \| ^2 \) have exponential distributions, with \( f_{\| h_{0,n^*} \| ^2} (x) = \sum_{n=1}^{N} \binom{N}{n} \frac{(n-1)^{n-1}}{n!} e^{- \frac{x}{n}}, \)

\[
f_{\| h_1 \| ^2} (x) = \frac{x^{N-1} e^{- \frac{x}{\Omega_{h_1}}}}{\Gamma(N) \Omega_{h_1}^N} \quad \text{and} \quad F_{\| h_1 \| ^2} (x) = 1 - e^{- \frac{x}{\Omega_{h_1}}} \sum_{p=0}^{P-1} \frac{x^p}{\Gamma(p+1) \Omega_{h_1}^p} \quad \text{with} \quad \Gamma (x) = (x-1)! \quad \text{is the gamma function.}
\]

The OP of \( U_1 \) is:

\[
\text{OP}_{U_1}^T = \Pr (\gamma_{1,1} < \gamma_1),
\]

where \( \gamma_1 = 2^{R_1} - 1 \) with \( R_1 \) being the target rate at \( U_1 \) to detect \( x_1 \).

Theorem 1. The exact OP expression of \( U_1 \) is calculated as:

\[
\text{OP}_{U_1}^T = 1 - 2 \sum_{m=0}^{M-1} \sum_{n=1}^{N} \binom{N}{n} \frac{(-1)^{n-1} \theta_1^m n}{\Gamma(m+1) \Omega_{h_1}^m \Omega_{h_0}^n} \times \left( \frac{\theta_1 \Omega_{h_0}}{\Omega_{h_1} n} \right)^{K_{-m}} (2 \sqrt{\frac{\theta_1 \Omega_{h_0}}{\Omega_{h_1} n}})
\]

where \( \theta_1 = \frac{\gamma_1}{(a_1 - \gamma_{a_2} \rho)}. \) Note \( \theta_1 \) is based on the condition of \( a_1 > \gamma_{a_2} \).

Proof:

\[
\text{OP}_{U_1}^T = 1 - \Pr \left( \| h_1 \| ^2 > \frac{\theta_1}{\beta^2 \| h_{0,n^*} \| ^2} \right)
\]

\[
= 1 - \int_0^\infty F_{\| h_1 \| ^2} \left( \frac{\theta_1}{\beta^2 t} \right) f_{\| h_{0,n^*} \| ^2} (t) \, dt
\]

\[
= 1 - \sum_{m=0}^{M-1} \sum_{n=1}^{N} \binom{N}{n} \frac{(-1)^{n-1} \theta_1^m n}{\Gamma(m+1) \Omega_{h_1}^m \Omega_{h_0}^n} \Phi (t),
\]

Outage probability computation in multi-backscatter systems with multi-modes of operation (Dinh-Thuan Do)
where \( F_{\|h_n\|^2} (x) = 1 - F_{\|h_n\|^2} (x) \) and \( \Phi (t) = \int_0^\infty e^{-\frac{x^2}{\gamma}} \frac{m^m}{\gamma^m} t^{-m} dt \).

Based on [24], (3.471.9). We can rewrite (10) as:

\[
\mathcal{O} \mathcal{P}^T_{U_1} = 1 - 2 \sum_{m=0}^{M-1} \sum_{n=0}^{N} \left( \begin{array}{c} N \\ n \end{array} \right) \frac{(-1)^{n-1} \theta^m n}{\Gamma (m+1) \Omega_{h_1}^m \beta^2 \Omega_{h_0}} \times \left( \frac{\theta_1 \Omega_{h_0}}{\beta^2 \Omega_{h_1} n} \right) \frac{1}{\gamma} K_{1-m} \left( 2 \sqrt{\frac{\theta_1 n}{\Omega_{h_2} \beta^2 \Omega_{h_0}}} \right).
\]  

(11)

Next, the OP of \( U_2 \) is given by:

\[
\mathcal{O} \mathcal{P}^T_{U_2} = \Pr (\gamma_{2,2} < \gamma_2) = 1 - \Pr \left( \|h_2\|^2 | h_{0,n}^2/\|h_{0,n}^2\|^2 > \theta_2 \right),
\]  

(12)

where \( \gamma_2 = 2^{R_2} - 1 \) with \( R_2 \) being the target rate at \( U_2 \) to detect \( x_2, \theta_2 = \frac{x_2}{\rho x_2} \). Similarly with solving \( \mathcal{O} \mathcal{P}^T_{U_1} \), can be achieved \( \mathcal{O} \mathcal{P}^T_{U_2} \) as:

\[
\mathcal{O} \mathcal{P}^T_{U_2} = 1 - 2 \sum_{k=0}^{K-1} \sum_{n=1}^{N} \left( \begin{array}{c} N \\ n \end{array} \right) \frac{(-1)^{n-1} \theta_2^m n}{\Gamma (k+1) \Omega_{h_2}^k \beta^2 \Omega_{h_0}} \times \left( \frac{\theta_2 \Omega_{h_0}}{\beta^2 \Omega_{h_2} n} \right) \frac{1}{\gamma} K_{1-k} \left( 2 \sqrt{\frac{\theta_2 n}{\Omega_{h_2} \beta^2 \Omega_{h_0}}} \right).
\]  

(13)

3.2. Scheme 2: outage probability of directed link by selection combining mode

In the MRT scheme, to maximize the signal-to-interference noise (SINR) at \( U_1 \) and \( U_2 \), \( BS \) uses a beamforming transmit vector \( w_r = \frac{h_r}{\|h_r\|}, r \in \{SU_1, SU_2\} \) to signal \( x^{BS} \) before sending \( w_r \) to users, \( h_{SU_1} \) and \( h_{SU_2} \) are the \( 1 \times M \) and \( 1 \times K \) channel vector of \( BS \) to \( U_1 \) link and \( BS \) to \( U_2 \) link, respectively. The \( BS \) transmits signals directly to two users as:

\[
y_r = \|h_r w_r\|^2 x^{BS} + n_r, r \in \{SU_1, SU_2\}.
\]  

(14)

We have SINR at \( U_1 \) as:

\[
\gamma_{SU_1} = \frac{\|h_{SU_1}\|^2 a_1 \rho}{\|h_{SU_2}\|^2 a_2 \rho + 1}.
\]

(15)

and SINR and the successive interference cancellation (SIC) at \( U_2 \) as \( \gamma_{SU_2,1} = \frac{\|h_{SU_2}\|^2 a_1 \rho}{\|h_{SU_2}\|^2 a_2 \rho + 1} \) and \( U_2 \) as \( \gamma_{SU_2} = \frac{\|h_{SU_2}\|^2 a_1 \rho}{\|h_{SU_2}\|^2 a_2 \rho + 1} \) respectively.

Finally, the instantaneous SINRs at \( U_1 \) and \( U_2 \) based on selection combining, can be written as:

\[
\gamma_{i}^{SC} = \Pr (\max (\gamma_{SU_1, i} , \gamma_{SU_2, i}) < \gamma_i), \quad i \in \{1, 2\}
\]

(16)

The OP of \( U_1 \) is given by:

\[
F_{\gamma_{1,1}} (x) = \Pr \left( \|h_1\|^2 < \frac{x}{\Delta (x)} \|h_{0,n}^*\|^2 \right) = 1 - \int_0^\infty F_{\|h_1\|^2} \left( \frac{x}{\Delta (x)} \|h_{0,n}^*\|^2 \right) (t) dt = 1 - \sum_{m=0}^{M-1} \sum_{n=1}^{N} \left( \begin{array}{c} N \\ n \end{array} \right) \frac{a^n x^n (-1)^{n-1}}{\Gamma (m+1) \Omega_{h_1}^m \Omega_{h_0} \Delta (x)^m} \delta (t | x),
\]

(17)

where \( \delta (t | x) = \int_0^\infty e^{-\frac{t}{\Omega_{h_1} \Delta (x)}} \frac{m^m}{\Omega_{h_0}^m} t^{-m} dt \) and \( \Delta (x) = (a_1 - a_2 x \rho^2 ) \). Using [24], (3.471.9) and after some transform. \( F_{\gamma_{1,1}} (x) \) and \( F_{\gamma_{SU_2}} (x) \) can be express respectively as:

\[
F_{\gamma_{1,1}} (x) = 1 - 2 \sum_{m=0}^{M-1} \sum_{n=1}^{N} \left( \begin{array}{c} N \\ n \end{array} \right) \frac{a^n x^n (-1)^{n-1}}{\Gamma (m+1) \Omega_{h_1}^m \Omega_{h_0} \Delta (x)^m} \times \left( \frac{x \Omega_{h_0}}{\Omega_{h_1} \Delta (x)} \right)^{1-m} K_{1-m} \left( 2 \sqrt{\frac{x \Omega_{h_0}}{\Omega_{h_1} \Omega_{h_0} \Delta (x)}} \right),
\]

(18)
and,
\[ F_{\gamma_{SU_1}}(x) = 1 - \sum_{m=0}^{M-1} \frac{x^m e^{-\frac{\gamma_{SU_1} - \gamma_2}{m+1}}} {\Gamma(m+1) \Omega_{SU_1}^m (\alpha_1 - x \alpha_2)^m \rho^m}. \] (19)

Substituting (18) and (19) into (16), the close-form of OP of \( OP_{U_1}^{\text{III}} \) is obtained as:
\[ OP_{U_1}^{\text{III}} = \left[ 1 - \sum_{m=0}^{M-1} \frac{e^{-\frac{\gamma_{SU_1} - \gamma_2}{m+1}} (\alpha_1 - x \alpha_2)^m \rho^m} {\Gamma(m+1) \Omega_{SU_1}^m} \right] \times \left[ 1 - \sum_{m=0}^{M-1} \frac{e^{-\frac{\gamma_{SU_1} - \gamma_2}{m+1}} (\alpha_1 - x \alpha_2)^m \rho^m} {\Gamma(m+1) \Omega_{SU_1}^m} \right]. \] (20)

Next, the OP of \( U_2 \) is:
\[ OP_{U_2}^{\text{III}} = \Pr \left( \frac{\gamma_{SU_2}}{\gamma_2} < 1 \right) = \Pr \left( \gamma_{SU_2} < \gamma_2 \right) \Pr \left( \gamma_{2,2} < \gamma_2 \right). \] (21)

Similarly, \( OP_{U_2}^{\text{III}} \) can be achieved as:
\[ OP_{U_2}^{\text{III}} = \left[ 1 - \sum_{m=0}^{M-1} \frac{e^{-\frac{\gamma_{SU_2} - \gamma_2}{m+1}} (\alpha_1 - x \alpha_2)^m \rho^m} {\Gamma(m+1) \Omega_{SU_2}^m} \right] \times \left[ 1 - \sum_{m=0}^{M-1} \frac{e^{-\frac{\gamma_{SU_2} - \gamma_2}{m+1}} (\alpha_1 - x \alpha_2)^m \rho^m} {\Gamma(m+1) \Omega_{SU_2}^m} \right]. \] (22)

3.3. Scheme 3: outage probability of directed link by maximal ratio combining mode

In this scheme, the backscattering link signals and direct link signals are combined by maximal ratio combining (MRC) at the two users. Hence, after using MRC the received SINR two users are given by:
\[ \gamma_{U_i}^{\text{MRC}} = \gamma_{SU_i} + \gamma_{i,i} \quad i \in \{1, 2\} \] (23)

Then, the OP at \( U_1 \) can be calculated as:
\[ OP_{U_1}^{\text{III}} = \Pr \left( \gamma_{SU_1} < \gamma_1 - \gamma_{1,1} \right) \]
\[ = \int_0^1 f_{\gamma_{SU_1}}(x) f_{\gamma_{SU_1}}(y) dy dx. \] (24)

It is very difficult to obtain the close-form solution of the integral of (24). Therefore, we use the approach in [25] by making an I-step staircase approximation to the actual triangular integral region in [24] with sufficiently large I to obtain:
\[ OP_{U_1}^{\text{III}} \approx \frac{I-1}{I} \sum_{i=0}^{I-1} \left( F_{\gamma_{SU_1}} \left( \frac{i+1}{I} \gamma_1 \right) - F_{\gamma_{SU_1}} \left( \frac{i}{I} \gamma_1 \right) \right) \times \left( F_{\gamma_{i,i}} \left( \frac{I-i}{I} \gamma_1 \right) \right). \] (25)

Thus, the OP at \( U_2 \) is given by:
\[ OP_{U_2}^{\text{III}} = \Pr \left( \frac{\gamma_{U_2}^{\text{MRC}}}{\gamma_2} < 1 \right) \]
\[ = \int_0^1 f_{\|[b_{SU_2}]^2 \gamma_{SU_2}}(x) f_{[\|b_2^2 \gamma_{SU_2}]^2 \Omega_{SU_2}} \left( \frac{\theta_2}{\|B_2\|^2} - \frac{x}{\|B_2\|^2} \right) dx \] (26)
\[ = \frac{1}{\Gamma(K) \Omega_{SU_2}^K} [Y_1 - Y_2], \]
where $\theta_2 = \frac{\gamma_0}{\rho_2}$. $\Upsilon_1$ can be calculated as:

$$
\Upsilon_1 = \int_0^{x_\text{K}} x^{-1} e^{-\frac{x}{\Omega_{\text{SU}2}}^n} \, dx = \Omega_{\text{SU}2}^n \gamma \left( K, \frac{\theta_2}{\Omega_{\text{SU}2}}^n \right),
$$

(27)

where $\gamma (x, y)$ is the lower incomplete Gamma function [24]. (3.351.1). And $\Upsilon_2$ is written as:

$$
\Upsilon_2 = 2 \sum_{n=1}^{N} \sum_{k=0}^{K-1} \left( \sum_{l=1}^L \sum_{n} \left( \begin{array}{c} N \\ n \end{array} \right) \right) \frac{n^{(k+1)/2}(-1)^{-n-1} \theta_2^K \Omega_{\text{SU}2}^{n-1} \Omega_{\text{SU}2}^{1+1/2} \pi \sqrt{1 - \xi_0^2} \xi_0^2 (\xi_0 + 1)^{K-1} \Lambda (x) (\xi_0 + 1)^{(k+1)/2}}{\Gamma (K) \Omega_{\text{SU}2}^{K-1} \Gamma (k+1) L} \times K_{1-k} \left( \frac{2}{\sqrt{n \Omega_{\text{SU}2}^{K-1}}} \right).
$$

(28)

Putting $t = 2x/\theta_2 - 1 \Rightarrow \theta_2 (t+1)/2 = x \Rightarrow \theta_2/2 \, dt = dx$. But it is very difficult to obtain the close-form solution of $\Upsilon_2$, to do so, we use Gaussian-Chebyshev quadrature [20], (25.4.38), to get:

$$
\Upsilon_2 \approx \sum_{n=1}^{N} \sum_{k=0}^{K-1} \sum_{l=1}^L \sum_{n} \left( \begin{array}{c} N \\ n \end{array} \right) \frac{n^{(k+1)/2}(-1)^{-n-1} \theta_2^K \Omega_{\text{SU}2}^{n-1} \Omega_{\text{SU}2}^{1+1/2} \pi \sqrt{1 - \xi_0^2} \xi_0^2 (\xi_0 + 1)^{K-1} \Lambda (x) (\xi_0 + 1)^{(k+1)/2}}{\Gamma (K) \Omega_{\text{SU}2}^{K-1} \Gamma (k+1) L} \times K_{1-k} \left( \frac{2}{\sqrt{n \Omega_{\text{SU}2}^{K-1}}} \right).
$$

(29)

Substituting (26) and (28) into (25), $OP_{U_2}^{\text{TTT}}$ is given by:

$$
OP_{U_2}^{\text{TTT}} \approx \frac{\gamma (K, \theta_2 / \Omega_{\text{SU}2})}{\Gamma (K)} - \sum_{n=1}^{N} \sum_{k=0}^{K-1} \sum_{l=1}^L \sum_{n} \left( \begin{array}{c} N \\ n \end{array} \right) \frac{n^{(k+1)/2}(-1)^{-n-1} \theta_2^K \Omega_{\text{SU}2}^{n-1} \Omega_{\text{SU}2}^{1+1/2} \pi \sqrt{1 - \xi_0^2} \xi_0^2 (\xi_0 + 1)^{K-1} \Lambda (x) (\xi_0 + 1)^{(k+1)/2}}{\Gamma (K) \Omega_{\text{SU}2}^{K-1} \Gamma (k+1) L} \times K_{1-k} \left( \frac{2}{\sqrt{n \Omega_{\text{SU}2}^{K-1}}} \right) - \frac{\theta_2 (x+1)}{2 \pi r^2}.
$$

(30)

where $\xi_0 = \cos \left( \frac{2x+1}{2x} \right)$ and $\Lambda (x) = \left( \frac{\theta_2}{\beta^2} - \frac{x + 1}{2 \pi r^2} \right)$.

4. NUMERICAL RESULTS

In this section, we set $d_0 = d_1 = d_{\text{SU}1} = d_{\text{SU}2} = 1$, $d_2 = 2$, $\Omega_n = d_{\text{SU}}^{-\tau}$, $\Omega_n = d_{\text{SU}}^{-\tau}$, $\Omega_{\text{SU}1} = d_{\text{SU}1}^{-\tau}$ and $\Omega_{\text{SU}2} = d_{\text{SU}2}^{-\tau}$ and $\tau$ is the path-loss exponent setting to be $\tau = 2$. In particular, main parameters can be seen in Table 1. In addition, the Gauss-Chebyshev parameter is selected as $L = 100$ to yield a close approximation.

| System Parameters                        | Values            |
|------------------------------------------|-------------------|
| Monte Carlo simulations repeated          | 1000 iterations   |
| The power allocation coefficients $\{a_1, a_2\}$ | $\{0.8, 0.2\}$  |
| The target rate at $U_1$                  | $R_1 = 2$ bps/Hz  |
| The target rate at $U_2$                  | $R_2 = 2$ bps/Hz  |
| The complex reflection coefficient $\beta$| $\beta = 0.5$    |

Figure 2 plots OP and base station transmit SNR relationship, with with varying $N = K = M = 3$. In (8), (12), (19), (20), (23), and (29) are used to plot the analytical lines. From Figure 2, we notice that the network users experience different outage performances depending on the $N = K = M$ values. The best performances are achieved by scheme 3, with the worst performance obtained by scheme 1. We can see the analytical curves fit with Monte Carlo simulations.
Figure 3 plots the OP relationship between outage and base station transmit SNR, with varying $\beta = 0.3$ and $\beta = 0.7$. As in Figure 2, from Figure 3, we also observe that the users experience different outage performances depending on the complex reflection coefficient $\beta$. The best performances are achieved by scheme 3, with the worst performance obtained by user 2 in scheme 1.

Figure 4 plots the relationship between OP and $\gamma_1 = \gamma_1$ (dB), varying $\beta = 0.3$, and $\beta = 0.7$. From Figure 4, we observe that some network users performance curves approach an outage probability ceiling. Generally, the outage performance reduces with increase in $\gamma_1 = \gamma_1$ (dB). The best performances are achieved by scheme 3, with the worst performance obtained by scheme 1.
5. CONCLUSION

In this paper, we provided the outage probability (OP) analysis of an ambient multi-backscatter system with multi-modes of operation. We derived exact solutions of OP for different users depending on the mode of operation. We observe from the simulation results, that the direct link between the base station and users affects the OP. In future work, we will consider ergodic capacity of the system.

REFERENCES

[1] H. Jayakumar, K. Lee, W.S. Lee, A. Raha, Y. Kim, and V. Raghunathan, “Powering the internet of things,” in Proceedings of the 2014 international symposium on Low power electronics and design, pp. 375–380, 2014, doi: 10.1145/2627369.2631644.

[2] F. Jameel, S. Zeb, W. U. Khan, S. A. Hassan, Z. Chang, and J. Liu, "NOMA-Enabled Backscatter Communications: Toward Battery-Free IoT Networks," in IEEE Internet of Things Magazine, vol. 3, no. 4, pp. 95–101, 2020, doi: 10.1109/IOTM.0001.2000055.

[3] N. Van Hayth, D. T. Hoang, X. Lu, D. Niyato, P. Wang, and D. I. Kim, "Ambient Backscatter Communications: A Contemporary Survey," in IEEE Commun. Surv. & Tutor., vol. 20, no. 4, pp. 2889-2922, 2018, doi: 10.1109/COMST.2018.2841964.

[4] G. Yang, Y.-C. Liang, R. Zhang, and Y. Pei, "Modulation in the Air: Backscatter Communication Over Ambient OFDM Carrier," in IEEE Transactions on Communications, vol. 66, no. 3, pp. 1219-1233, March 2018, doi: 10.1109/TCOMM.2017.2772261.

[5] W. Zhao, G. Wang, R. Fan, L. Fan, and S. Atapattu, "Ambient Backscatter Communication Systems: capacity and Outage Performance Analysis," in IEEE Access, vol. 6, pp. 22695-22704, 2018, doi: 10.1109/ACCESS.2018.2828021.

[6] G. Yang, Q. Zhang, and Y. Liang, "Cooperative Ambient Backscatter Communications for Green Internet-of-Things," in IEEE Internet of Things Journal, vol. 5, no. 2, pp. 1116-1130, April 2018, doi: 10.1109/JIOT.2018.2799848.

[7] Q. Zhang, L. Zhang, Y. Liang, and P. Kam, "Backscatter-NOMA: A Symbiotic System of Cellular and Internet-of-Things Networks," in IEEE Access, vol. 7, pp. 20000-20013, 2019, doi: 10.1109/ACCESS.2019.2897822.

[8] B. Lyu, Z. Yang, G. Gu, and Y. Feng, "Wireless Powered Communication Networks Assisted by Backscatter Communication," in IEEE Access, vol. 5, pp. 7254-7262, 2017, doi: 10.1109/ACCESS.2017.2677521.
Outage probability computation in multi-backscatter systems with multi-modes of operation (Dinh-Thuan Do)

**Dinh-Thuan Do** (Senior Member, IEEE) received the B.S., M.Eng., and Ph.D. degrees in communications engineering from Vietnam National University (VNU-HCM), in 2003, 2007, and 2013, respectively. His research interests include signal processing in wireless communications networks, cooperative communications, nonorthogonal multiple access, full-duplex transmission, and energy harvesting. He was a recipient of the Golden Globe Award from the Vietnam Ministry of Science and Technology, in 2015 (Top ten excellent young scientists nationwide). He has served as a guest editor for eight prominent SCIE journals. He is currently serving as an associate editor for five journals, including EURASIP Journal on Wireless Communications and Networking, Computer Communications (Elsevier), ICT Express, Electronics and KSII Transactions on Internet and Information Systems. He can be contacted at email: dodinhthuan@iuh.edu.vn.

**Anh-Tu Le** (Member, IEEE) was born in Lam Dong, Vietnam, in 1997. He is pursuing the Ph.D. degree in communication and information system the field of wireless communication. He is currently a Research Assistant with the WICOM Laboratory, which was led by Dr. Thuan. He has authored or co-authored over 25 technical articles published in peer-reviewed international journals (SCIE). His research interests include the wireless channel modeling, NOMA, cognitive radio, and MIMO. He can be contacted at email: leanhtu@iuh.edu.vn.