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Outage Analysis for Tag Selection in Reciprocal Backscatter Communication Systems

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Abstract—**Applying tag selection to backscatter networks can greatly improve the system outage performance. In this letter, the analytical expressions on outage probability for both ideal and outdated tag selection in reciprocal backscatter networks are derived with a truncated series expansion. Furthermore, the asymptotic analysis with large transmission power is conducted to give an insight into the effects of system parameters. From the asymptotic analysis, it is found that the diversity order of outage probability for ideal tag selection is equal to half of the number of tags. However, when applying outdated tag selection, the diversity order is equal to one, and thereby no diversity gain can be harvested, regardless of the temporal correlation and the number of tags.**

Index Terms—**Backscatter communications networks; tag selection; outdated tag selection; outage probability; performance analysis.**

I. Introduction

Due to low power consumption and low cost, backscatter communication has attracted considerable attention from both academia and industry. Considering the application of backscatter in cellular networks, the authors in [1] proposed a novel optimization technique and derived the expressions on outage probability. Simulation results showed that a significant performance gain can be achieved compared with the traditional single-mode communications. Using the non-coherent power detection algorithm, the authors in [2] proposed a novel waveform design for high-order backscatter communication systems, and provided an exact expressions on detection error probability. Acting as an intermediate node, the tag was used to help the data transmission in a two-state communication protocol in [3]. Besides, the authors derived the channel fading distribution function, outage probability as well as the error bound. In order to reduce the complexity of the receiver design, a non-coherent demodulation algorithm was adopted in [4], and the closed-form performance expressions were derived. Moreover, focusing on monostatic cascaded channels, the maximum eigenvalue based detection strategy was proposed in [5] for the readers equipped with multiple antennas.

It is well known that transmitting or receiving diversity is an effective technique to combat wireless fading. Similarly, tag selection, which can improve the end-to-end communication reliability by effectively exploiting multiple tags and the spatial diversity, has been studied in depth for various application scenarios [6]. According to this opportunistic communication protocol, in each time slot, only the best tag is activated. In the long run, due to the random and independent nature of wireless channel fading, each tag has a certain probability to be selected and reflect its own information to the reader.

In practice, due to the time difference between the training phase and the transmission phase, the CSI used in the transmission phase is in fact an outdated version of that in the training phase [7]. However, the effect of outdated tag selection on outage performance in reciprocal backscatter networks is still unknown and worth investigating. To bridge this gap, we study the tag selection in reciprocal backscatter networks relying on outdated CSI and quantify the impacts of outdated tag selection on system performance. Particularly, the analytical expressions on the outage probability for both ideal and outdated tag selection in backscatter communication networks are derived and compared. To give an insight into the impacts of system parameters on outage performance, the asymptotic analysis with large transmission power is also conducted in this letter.

II. System Model

We consider a wireless network with L backscatter tags and a single reader. It is assumed that both the reader and the tags are equipped with a single antenna. Following the real-world application scenarios, we can also assume that the distance between two arbitrary tags is much smaller than that between the reader to an arbitrary tag. To simplify the following analysis, the distance from the reader to each tag is considered to be equal, referring to a homogeneous scenario. The reader transmits wireless signals to the backscatter tags, and the tags reflect the received signals with response information. In order to improve the quality of wireless links, at each transmission

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round, a tag with the strongest signal power is activated to direct the message transmission.

With the help of the nth tag, the received signal at the reader is given by

$$y_n = \beta h_n x b + w_n = \beta f_n g_n x b + w_n, \tag{1}$$

where x is the original signal transmitted from the reader with fixed average power, i.e., $\mathbb{E}(|x|^2) = P$, where $\mathbb{E}(\cdot)$ denotes the statistical expectation operation; b is the reflected information bit from the tag with unit power, i.e., $\mathbb{E}(|b|^2) = 1$; β denotes the average channel fading power, which can be treated as the combination of the fading and the path loss. Thus, system parameters can be set as in practical scenarios by adjusting β and P. f_n and g_n denote the instantaneous channel gains of the forward links and the backward links, respectively; h_n is the cascaded channel gain incorporating f_n and g_n, i.e., $h_n = f_n g_n$; and $w_n \sim \mathcal{CN}(0, \sigma^2)$ is the additive white Gaussian noise with average power σ^2. Moreover, it is assumed that both f_n and g_n are standard complex Gaussian random variables, denoted as $f_n \sim \mathcal{CN}(0,1)$ and $g_n \sim \mathcal{CN}(0,1)$. [1]

Considering different network topologies, there are two types of backscatter communication channel models: the monostatic model [10] and the bi-static model [11]. Specifically, for the monostatic model, a single antenna is used at the reader to transmit signals to the tags, as well as to receive the reflected signals from the tags. Due to the reciprocity between the cascaded channels, the forward and the reward links are fully correlated. On the other hand, in the bi-static model, two separated antennas are employed at the reader for transmission and reception. As a consequence, the forward and the backward links are uncorrelated. In order to reduce the complexity of the networks, the monostatic model is widely adopted in existing literature. For this reason, the reciprocal channel model is used in this study, which closely fits the practical scenarios and can provides more insightful analysis. Due to the reciprocity between the forward links and the backward links, f_n and g_n are fully correlated, i.e., $f_n = g_n$. Then, the cascaded channel can be written as

$$h_n = f_n g_n = f_n^2. \tag{2}$$

Thus, the instantaneous SNR of the nth branch can be written as

$$\gamma_n = \gamma_0 |f_n g_n|^2 = \gamma_0 |h_n|^2, \tag{3}$$

where γ_0 is the average SNR of the nth branch, which can be expanded to be

$$\gamma_0 = \frac{P\beta^2}{\sigma^2}. \tag{4}$$

In practical wireless systems, it takes two steps to complete the entire information transmission procedure, which are called the *training phase* and the *transmission phase*. In the training phase, the reader can estimate the signal power of each tag and select the best tag with the largest channel gain. In the transmission phase, the optimally selected tag in the training phase is activated and responses to the reader, and the reader can recover the original message directed by the tag. Because of the time delay between the training phase and the transmission phase, the CSI utilized in the transmission phase is in fact an outdated version of the CSI estimated in the training phase. The outdated channel model can be constructed as

$$h_{n,o} = \sqrt{\rho} h_n + \sqrt{1-\rho}\,\epsilon_n, \tag{5}$$

where $h_{n,o}$ and h_n denote the authentic channel fading gains of the nth tag at the time instance in the transmission phase and the training phase, respectively; $\rho \in [0,1]$ is the temporal correlation coefficient; and $\epsilon_n \sim \mathcal{CN}(0,1)$ is a standard complex Gaussian random variable characterizing the random channel variation between the training and transmission phases. Specifically, $\rho = 0$ implies that $h_{n,o}$ and h_n are statistically independent with each other, while $\rho = 1$ indicates a fully correlated case resulting in $h_{n,o} = h_n$.

Denoting $z_{n,o} = |h_{n,o}|^2$ and $z_n = |h_n|^2$, the conditional probability function is given by [12]

$$f_{z_{n,o}|z_n}(z_o|z) = \frac{1}{(1-\rho)} e^{-\frac{z_o+\rho z}{(1-\rho)}} \mathrm{I}_0\left(\frac{2\sqrt{\rho z_o z}}{(1-\rho)}\right), \quad \text{for } 0 \le \rho < 1, \tag{6}$$

where $\mathrm{I}_0(\cdot)$ is the zero-order first kind modified Bessel function as defined in eq. (8.406) in [13].

By applying Taylor series expansion given by eq. (8.455) in [13] on $\mathrm{I}_0(\cdot)$ and reserving the low-order components, we have

$$\mathrm{I}_0(z) = \sum_{j=0}^{\infty} \frac{1}{(j!)^2}\left(\frac{z}{2}\right)^{2j} \simeq \sum_{j=0}^{T} \frac{1}{(j!)^2}\left(\frac{z}{2}\right)^{2j}, \tag{7}$$

where T is the truncation length, which is a trade-off parameter between computational accuracy and complexity [14]. Thus, a larger T is beneficial to improve the accuracy at the cost of increasing computational complexity and vice versa. Specifically, the computation complexity is linear with respect to the truncation length. The approximation can release the complexity of the theoretical analysis, while some approximate errors will be introduced.

According to the given selection criterion, the best tag which experiences the strongest channel gain will be activated. Thus, the index of the selected tag can be yielded by the relation infra:

$$n^* = \arg \max_{n \in [1,L]} |h_n|^2. \tag{8}$$

Given a minimum capacity threshold C, the outage probability can be defined and calculated as

$$P_O = \Pr[\gamma_{n_*,o} < \gamma_{th}] = \Pr\left[z_{n_*,o} < \frac{\gamma_{th}}{\gamma_0}\right], \tag{9}$$

where $\gamma_{th} = 2^C - 1$ denotes the SNR threshold, and $\Pr[\cdot]$ denotes the probability of the random event enclosed.

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[1] Note that the Rician or Nakagami-m fading models are more generalized channel models, especially for the communication scenarios with the access to perfect CSI [8] , while the complex Gaussian channel model is widely adopted in backscatter communications [9]. In order to reduce the complexity of the underlying analysis for outdated tag selection, we also follow this assumption in our study, but in the meantime admit that employing generalized channel models for analysis is worth investigating as the future work.

III. OUTAGE PERFORMANCE ANALYSIS

In this section, we derive the analytical expressions on the outage probability for the backscatter communication systems adopting ideal and outdated tag selections.

A. *Ideal Tag Selection*

Since f_n follows the standard complex Gaussian distribution, with definition that $x_n = |h_n| = |f_n|^2$, we have the following cumulative distribution function (CDF)

$$F_{x_n}(x) = 1 - e^{-x}, x \geq 0. \tag{10}$$

Due to the statistical independence between different wireless channels, the CDF of x_{n^*} can be calculated as

$$F_{x_{n^*}}(x) = (1 - e^{-x})^L, x \geq 0. \tag{11}$$

Since $z_n = |x_n|^2$, we can derive the CDF of the channel fading power corresponding to the optimally selected tag as follows:

$$F_{z_{n^*}}(z) = F_{x_{n^*}}(\sqrt{z}) = (1 - e^{-\sqrt{z}})^L, z \geq 0. \tag{12}$$

In the case of perfect tag selection, i.e., $\rho = 1$ and $z_{n_*,o} = z_{n_*}$, we can derive the outage probability as follows:

$$P_I = \Pr\left[z_{n_*} < \frac{\gamma_{th}}{\gamma_0}\right] = \left(1 - e^{-\sqrt{\frac{\gamma_{th}}{\gamma_0}}}\right)^L. \tag{13}$$

B. *Outdated Tag Selection*

In this subsection, we focus on the outdated tag selection, i.e., $0 \leq \rho < 1$. Firstly, the probability density function (PDF) can be obtained by taking the derivative of (12) as

$$\begin{aligned} f_{z_{n^*}}(x) &= L(1 - e^{-\sqrt{x}})^{L-1} \frac{e^{-\sqrt{x}}}{2\sqrt{x}} \\ &= \frac{L}{2\sqrt{x}} \sum_{k=0}^{L-1} \binom{L-1}{k} (-1)^k e^{-(k+1)\sqrt{x}}, x \geq 0. \end{aligned} \tag{14}$$

According to the conditional probability formula, the PDF of the outdated channel gain $z_{n^*,o}$ can be obtained as follows

$$f_{z_{n^*,o}}(z_o) = \int_0^\infty f_{z_{n^*,o}|z_{n^*}}(z_o|z) f_{z_{n^*}}(z) \mathrm{d}z. \tag{15}$$

By substituting (6) and (14) into (15), we obtain

$$\begin{aligned} f_{z_{n^*,o}}(z_o) = &\int_0^\infty \frac{1}{(1-\rho)} e^{-\frac{z_o + \rho z}{(1-\rho)}} \mathrm{I}_0\left(\frac{2\sqrt{\rho z_o z}}{(1-\rho)}\right) \frac{L}{2\sqrt{z}} \\ &\times \sum_{k=0}^{L-1} \binom{L-1}{k} (-1)^k e^{-(k+1)\sqrt{z}} \mathrm{d}z. \end{aligned} \tag{16}$$

By variable substitution and mathematical simplification, we derive the following expression

$$\begin{aligned} f_{z_{n^*,o}}(z_o) = &\int_0^\infty \frac{L}{(1-\rho)} e^{-\frac{z_o + \rho z^2}{(1-\rho)}} \mathrm{I}_0\left(\frac{2\sqrt{\rho z_o}}{(1-\rho)} z\right) \\ &\times \sum_{k=0}^{L-1} \binom{L-1}{k} (-1)^k e^{-(k+1)z} \mathrm{d}z. \\ = &\frac{L}{(1-\rho)} \sum_{k=0}^{L-1} \binom{L-1}{k} (-1)^k e^{-\frac{z_o}{(1-\rho)}} \\ &\times \int_0^\infty e^{\left(-\frac{\rho}{(1-\rho)} z^2 - (k+1)z\right)} \mathrm{I}_0\left(\frac{2\sqrt{\rho z_o}}{(1-\rho)} z\right) \mathrm{d}z. \end{aligned} \tag{17}$$

Here, we propose the following lemma to assist the derivation of outage probability:

Lemma 3.1: Given a defined function

$$G(a,b,c) = \int_0^\infty e^{(-ax^2 - bx)} \mathrm{I}_0(cx) \mathrm{d}x, a > 0, c > 0, \tag{18}$$

we have the following tight approximation

$$\begin{aligned} G(a,b,c) \simeq &\sum_{j=0}^{T} \frac{1}{(j!)^2} \left(\frac{c}{2}\right)^{2j} (2a)^{-(2j+1)/2} \Gamma(2j+1) \\ &\times e^{\frac{b^2}{8a}} D_{-(2j+1)}\left(\frac{b}{\sqrt{2a}}\right), \end{aligned} \tag{19}$$

where $D_p(\cdot)$ is the parabolic cylinder functions defined as eq. (9.240) in [13], and $\Gamma(\cdot)$ is the gamma function..

Proof 3.1: Substituting (7) into (18), we have

$$\begin{aligned} G(a,b,c) &\simeq \int_0^\infty e^{(-ax^2 - bx)} \sum_{j=0}^{T} \frac{1}{(j!)^2} \left(\frac{cx}{2}\right)^{2j} \mathrm{d}x \\ &= \sum_{j=0}^{T} \frac{1}{(j!)^2} \left(\frac{c}{2}\right)^{2j} \int_0^\infty e^{(-ax^2 - bx)} x^{2j} \mathrm{d}x. \end{aligned} \tag{20}$$

Considering the formula eq. (3.462) given in [13] that

$$\begin{aligned} &\int_0^\infty e^{(-ax^2 - bx)} x^{v-1} \mathrm{d}x \\ &= (2a)^{-v/2} \Gamma(v) e^{\frac{b^2}{8a}} D_{-v}\left(\frac{b}{\sqrt{2a}}\right), a > 0, v > 0, \end{aligned} \tag{21}$$

we can derive (19) by substituting (21) into (20). This completes the proof of *Lemma* 3.1.

By applying *Lemma* 3.1 to (17), the analytical expression on PDF of $z_{n^*,o}$ can be obtained as follows:

$$f_{z_{n^*,o}}(z_o) = e^{-\frac{z_o}{1-\rho}} \frac{L}{(1-\rho)} \sum_{k=0}^{L-1} d_k \sum_{j=0}^{T} d_j D_{-(2j+1)}\left(\frac{k+1}{\sqrt{2c_1}}\right) z_o^j, \tag{22}$$

where

$$\begin{cases} c_1 &= \frac{\rho}{1-\rho}, \\ d_k &= \binom{L-1}{k} (-1)^k e^{\frac{(k+1)^2}{8c_1}}, \\ d_j &= \frac{\Gamma(2j+1)\rho^j}{(j!)^2 (1-\rho)^{2j} (2c_1)^{(j+1/2)}}. \end{cases} \tag{23}$$

Thus, the CDF of $z_{n^*,o}$ can be obtained by integrating the PDF given in (22) from 0 to x:

$$\begin{aligned} F_{z_{n^*,o}}(x) = &\int_0^x f_{z_{n^*,o}}(y) \mathrm{d}y \\ = &\frac{L}{(1-\rho)} \sum_{k=0}^{L-1} d_k \sum_{j=0}^{T} d_j D_{-(2j+1)}\left(\frac{k+1}{\sqrt{2c_1}}\right) \int_0^x e^{\left(-\frac{y}{1-\rho}\right)} y^j \mathrm{d}y. \end{aligned} \tag{24}$$

By using the incomplete exponential integral formula eq. (3.351) derived in [13]

$$\int_0^u x^n e^{-\mu x} \mathrm{d}x = \mu^{-n-1} \gamma(n+1, u\mu), \tag{25}$$

we can derive the CDF in closed form as

$$F_{z_{n^*,o}}(x) = \sum_{k=0}^{L-1} s_k \sum_{j=0}^{T} p_j D_{-(2j+1)}\left(\frac{k+1}{\sqrt{2c_1}}\right) \gamma\left(j+1, \frac{x}{1-\rho}\right), \tag{26}$$

where

$$\begin{cases} s_k &= \frac{L}{\sqrt{2c_1}}\binom{L-1}{k}(-1)^k e^{\frac{(k+1)^2}{8c_1}}, \\ p_j &= \frac{\Gamma(2j+1)}{(j!)^2 2^j}. \end{cases} \tag{27}$$

Substituting the CDF of $z_{n^*,o}$ derived in (26) into (9), the outage probability of the outdated tag selection algorithm can be determined as

$$\begin{aligned} P_O &= F_{z_{n^*,o}}\left(\frac{\gamma_{th}}{\gamma_0}\right) \\ &= \sum_{k=0}^{L-1} s_k \sum_{j=0}^{T} p_j D_{-(2j+1)}\left(\frac{k+1}{\sqrt{2c_1}}\right)\gamma\left(j+1, \frac{\gamma_{th}}{\gamma_0(1-\rho)}\right). \end{aligned} \tag{28}$$

IV. Asymptotic Performance Analysis

To give an insight into the impact of outdated tag selection on system outage probability, we conduct the asymptotic performance analysis when the transmission power is large, i.e., $\gamma_0 \to \infty$. Both the ideal selection and the outdated tag selection algorithms are considered, and the diversity orders with respect to the average SNR γ_0 are derived in this section.

A. Ideal Tag Selection

Considering the outage probability formula for ideal tag selection algorithm in (13). Since $\gamma_0 \to \infty$, using the approximation relation $1 - e^{-x} \simeq x$ for small x, we have the following asymptotic expression when $\rho = 1$:

$$P_I \simeq \left(\frac{\gamma_{th}}{\gamma_0}\right)^{L/2}. \tag{29}$$

Remark 1: From the asymptotic analysis for the ideal tag selection algorithm, it is obvious that the diversity order of the outage probability with respect to the average SNR γ_0 is $L/2$.

B. Outdated Tag Selection

In this subsection, we consider the outdated tag selection algorithm with $0 \le \rho < 1$. As for the incomplete exponential integral formula, we have the following series expansion by employing eq. (8.354) in [13]

$$\gamma(s, x) = x^s \sum_{k=0}^{\infty} \frac{(-x)^k}{k!(s+k)}. \tag{30}$$

If $x \to 0$, omitting the high-order terms yields

$$\gamma(s, x) \simeq \frac{x^s}{s}. \tag{31}$$

By substituting (31) into (28) gives

$$P_O \simeq \sum_{k=0}^{L-1} s_k \sum_{j=0}^{T} p_j \frac{\left(\frac{\gamma_{th}}{\gamma_0(1-\rho)}\right)^{j+1}}{(j+1)} D_{-(2j+1)}\left(\frac{k+1}{\sqrt{2c_1}}\right). \tag{32}$$

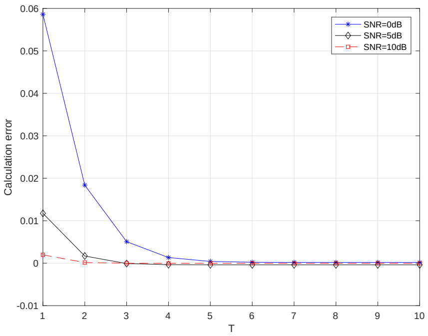

Fig. 1. Impacts of truncation length T on the calculation error of outage probability.

When $\gamma_0 \to \infty$, only low-order terms with $j = 0$ are reserved, and therefore we can asymptotically obtain

$$\begin{aligned} P_O &\simeq \sum_{k=0}^{L-1} s_k p_0 \frac{\gamma_{th}}{\gamma_0(1-\rho)} D_{-1}\left(\frac{k+1}{\sqrt{2c_1}}\right) \\ &= \frac{\gamma_{th}}{\gamma_0(1-\rho)} \sum_{k=0}^{L-1} s_k D_{-1}\left(\frac{k+1}{\sqrt{2c_1}}\right). \end{aligned} \tag{33}$$

Remark 2: From the asymptotic analysis for the outdated tag selection algorithm, it is found that regardless of the correlation coefficient and the number of tags, the diversity order of outage probability with respect to the average SNR remains to be one. The reason is that there is a fixed interference component in the outdated version as in (5). Although the number of tags grows larger, the proportion of the interference source remains, which imposes a great negative impact on the performance of tag selection. Thus, the diversity order of the outdated tag selection cannot benefit from an increasing number of tags when such an interference source is involved.

V. Simulation Results

In this section, numerical simulation results are presented to verify the effectiveness and accuracy of the derived outcomes in the previous sections. Moreover, the impacts of system parameters on outage performance are discussed under different system setups. All of the simulation parameters are similar with those given in [15]. Specifically, the small scale fading model can be set as $\beta = d^{-\alpha}$, where $\alpha = 2$ denotes the path loss exponent, and $d = 2$ m denotes the distance between the reader and the tags.

Firstly, the impacts of truncation length T on the calculation error of outage probability is depicted in Fig. 1. The system setup parameters are listed as follows: the correlation coefficient is set as $\rho = 0.5$; the tags number is set as $L = 3$; the capacity threshold is set as $C = 1$ bps/Hz; the average SNRs are $\gamma = 0, 5, 10$ dB, respectively; and the truncation length T grows from 1 to 10. The calculation errors between the analytical results given by (28) and the simulation results with respect to different truncation length T are presented. From this figure, we can see that larger T can reduce the calculation error significantly. Specifically,

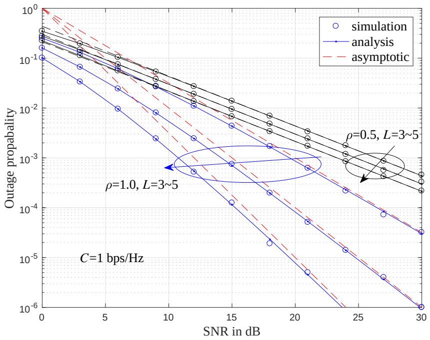

Fig. 2. Effect of the number of tags L on system outage probability.

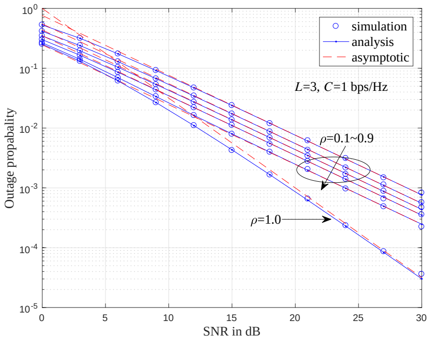

Fig. 3. Effect of correlation coefficients ρ on system outage probability.

when $T \geq 7$, the calculation error becomes convergent. That is, with acceptable computation complexity, the proposed analytical expression on the outage probability of outdated selection shows sufficiently high accuracy. Also, it verifies the effectiveness of the theoretical analysis. As a result, $T = 10$ is adopted in the following discussion.

The effect of the number of tags L on system outage probability for ideal and outdated tag selection is shown in Fig. 2. The system setup parameters are listed as follows: the correlation coefficient is set as $\rho = 1$ for ideal tag selection and $\rho = 0.5$ for outdated tag selection; the capacity threshold is set as $C = 1\,\mathrm{bps/Hz}$, and the number of tags L changes from 3 to 5. The simulation results, the theoretical results derived in (13) as well as the asymptotic results given in (29) are all plotted to verify the proposed analysis for both ideal and outdated tag selection. It can be observed that the theoretical analysis match well with that of simulation curves with different L. Furthermore, in the high SNR region, the theoretical curves converge to the asymptotic curves. Specifically, the diversity order is equal to $L/2$, which is consistent with *Remark* 1. Moreover, for the outdated tag selection with $\rho = 0.5$, the slopes of all curves at high SNR remain one regardless of the number of tags. That is, the diversity order of system outage probability with outdated tag selection remains one, which is in line with *Remark* 2.

The effect of correlation coefficients ρ on system outage probability is presented in Fig. 3, where the number of tags is set as $L = 3$; the capacity threshold is set as $C = 1\,\mathrm{bps/Hz}$; and the correlation coefficient ρ grows from 0.1 to 0.9 in 0.2 increments. We can observe from this figure that, with outdated tag selection, i.e., $0 \leq \rho < 1$, the slopes of curves representing system outage probability at high SNR are always equal to one, while the slope of the curve corresponding to ideal tag selection with $\rho = 1$ is equal to $L/2$. Again, the simulation results are aligned with *Remark* 1 and *Remark* 2. Moreover, a larger correlation coefficient ρ leads to better outage performance. This is simply because with a larger correlation coefficient, lower interference power is received in the transmission phase. As a direct result of lower interference power, a lower system outage probability is achievable.

VI. CONCLUSION

In this letter, the analytical expressions on outage probability for both ideal and outdated tag selection in reciprocal backscatter networks were derived. Furthermore, to give an insight into the impacts of key parameters on outage performance, the asymptotic analysis with large transmission power was also conducted. Based on the theoretical analysis, it can be concluded that the diversity order of outage probability for ideal tag selection is equal to half of the number of tags, while applying outdated tag selection, the diversity order is always equal to one, regardless of the correlation coefficient and the number of tags.

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