Backscatter Communications with NOMA

(Invited Paper)

Jing Guo*, Xiangyun Zhou*, Salman Durrani*, and Halim Yanikomeroglu†
*Research School of Engineering, The Australian National University, Canberra, ACT 2601, Australia.
Emails: {jing.guo, xiangyun.zhou, salman.durrani}@anu.edu.au.
†Department of Systems and Computer Engineering, Carleton University, Ottawa, ON K1S 5B6, Canada.
Email: halim@sce.carleton.ca.

***Abstract*— In this paper, we study a multiple access monostatic backscatter communication (BackCom) system, where one reader talks to multiple backscatter nodes (BNs). We propose to use non-orthogonal multiple access (NOMA) to improve the efficiency of BackCom system. Specifically, the reader uses the feedback signal during the training phase to separate the multiple BNs into two groups. The reader then randomly pairs the BNs from these two groups to implement NOMA. We propose to set the reflection coefficients for these two groups differently to further distinguish the reflected signal power for the paired BNs. To characterize the network performance, we derive an analytical expression for the success rate which shows the percentage of bits that can be successfully decoded in one time slot. We also present the design guideline of the reflection coefficients for the two groups to maximize the system performance. Our numerical results show that increasing the readers transmit power has little impact on the system performance when the channel condition on the transmission link is less severe. Instead, the proper choice of the reflection coefficients for the two groups of BNs can greatly enhance the BackCom system.**

I. Introduction

Backscatter communication (BackCom) is regarded as a promising technique for the Internet-of-things [1]. For the BackCom system, the passive/semi-passive backscatter nodes (BNs) can not only reflect and modulate the signal via intentionally mismatching the load impedance, but also implement energy harvesting to support its operation [2]. The power consumption for a low power BN is generally matched with the harvestable wireless energy from an RF source [3]. Thus, BackCom can greatly save the energy for low power devices.

The architecture of BackCom can be categorized into three configurations [3]: (i) *monostatic backscatter configuration*, which generally consists of the reader and the BN. The reader has the radio frequency (RF) emitter and backscatter receiver (i.e., the component used to decode the data from the backscattered modulated signal) co-located, e.g., the reader transmits the continuous wave (CW) signal to the BN and the BN then backscatters the modulated signal back to the reader; (ii) *bistatic backscatter configuration*, which is composed by the RF emitter, backscatter receiver and BN. The RF emitter and backscatter are spatially separated in this configuration; (iii) *ambient backscatter configuration*, which is similar to the bistatic backscatter configuration except that the ambient RF source plays the role of RF emitter instead of the dedicated RF source. In this work, we focus on the monostatic backscatter configuration.

This work was supported by the Australian Research Council's Discovery Project Funding Scheme (Project number DP170100939).

The monostatic backscatter configuration originates from the RFID systems, which have been widely investigated in the past decade. The monostatic backscatter configuration was recently proposed for extended-range communication, which attracts researchers's attention again. For example, the collision, i.e., interference, problem was investigated in [4] when one reader serves multiple access BNs. In [5], the physical layer security for BackCom system was studied. The authors in [6] developed an energy beamforming scheme to maximize the harvested energy at BNs. A multiple access scheme based on time-hoping spread-spectrum was proposed in [7] to reduce the interference and enable the full-duplex communication. The decoding probability for BackCom system was studied in [8] for different collision resolution mechanisms.

According to [3], a major drawback of the monostatic backscatter configuration is the doubly near-far problem, i.e., the signal experiences a round-trip path-loss. We propose to turn this weakness into an advantage for the BackCom system by employing non-orthogonal multiple access (NOMA). NOMA is being considered for 5G systems and its key feature is serving multiple users with different power level at the same time/frequency/code [9]. Due to the doubly near-far problem in the monostatic BackCom system, the channel gain difference between the near BN and far BN increases, which can benefit from NOMA. Thus, in this work, we study a monostatic BackCom system enhanced by NOMA.

The main contributions of this work are: (i) We develop an analytical framework to evaluate the success rate (i.e., the percentage of successfully decoded bits in one time frame) for the NOMA-assisted BackCom system, where the BNs are divided into two groups depending on the backscattered power and the reader pairs the BNs randomly chosen from these groups; (ii) We provide a design guideline for setting the reflection coefficient for the two groups to maximize the system performance; (iii) Our results suggest that, when the channel condition is less severe, the system performance can be greatly improved using proper chosen reflection coefficients rather than adjusting the reader's transmit power.

II. System Model

We consider a multiple access monostatic BackCom system, where a reader serves M BNs. The reader is assumed to be located at the center of an annular region with inner and outer radii R_1 and R. The location of BNs is modelled as a Binomial point process, i.e., the probability density function (pdf) of the distance from a BN to the reader r is $f_r(r) = \frac{2r}{R^2 - R_1^2}$.

The wireless communication link is modelled as a path-loss plus Nakagami-m block fading channel. For example, the received signal power from the reader to a BN is $P_T h r^{-\alpha}$, where P_T is the reader's transmit power, h is the identically and independently distributed fading power gain and α is the path-loss exponent. Note that the forward link (i.e., from the reader to a BN) and the backward link (i.e., from the BN to the reader) are assumed to be reciprocal. Moreover, the additive white Gaussian noise with power $\mathcal{N}$ is included.

Each BN is composed of an antenna, an information decoder, a micro-controller, variable impedances and battery, as illustrated in Fig. 1. Under the control of the reader, each BN switches between two states: (i) *waiting state*, where the BN harvests the energy from the reader and stores the energy in battery; (i) *backscattering state*, where the BN reflects the modulated signal to the reader via varying the impedance. We adopt the binary phase shift keying modulation. Each impedance set contains two impedances and these two impedances can generate two reflection coefficients, each with the same magnitude but two different phase shifts (0^o and 180^o). In this work, for the purpose of pairing, we assume that each BN has two impedance sets, where one set can backscatter a fraction ξ_1 of the incident power and another set reflects a fraction ξ_2 of the incident power, respectively. $\xi_1 \geq \xi_2$ is assumed. For simplicity, we refer to this fraction as the backscatter coefficient. The detail of pairing will be presented in the later section.

In this work, we assume that the reader adopts the successive interference cancellation (SIC) technique to decode the paired BNs. For example, the reader firstly detects and decodes the stronger signal, and treats the backscattered weaker signal as interference. If the SINR (signal-to-interference-plus-noise ratio) is higher than a threshold γ, this stronger signal is successfully decoded and removed from the composite signal. The reader then proceeds to decode the weaker signal. If the SINR is lower than γ, the reader stops decoding.

III. NOMA-assisted BackCom system

To improve the spectrum utilization, the power-domain NOMA is incorporated into the BackCom system [10]. We consider the uplink communication and assume that each communication time frame for M BNs is divided into sub-frames according to the pairing scenarios. The power division pairing approach is adopted. Specifically, M BNs are divided into two groups, namely the higher power BNs and lower power BNs. The higher power BNs switch to the first impedance set (i.e., the reflection coefficient is ξ_1 for this group) and the lower power BNs switch to the second impedance set (i.e., the reflection coefficient is ξ_2 for this group). For a certain time frame, given n higher power BNs and $n \leq M/2$, the frame will be divided into $M - n$ sub-frames. Under the first n sub-frames, with each one lasing $2/M$, the reader selects

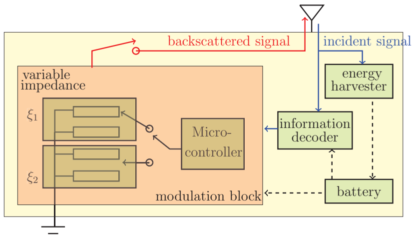

Fig. 1. Illustration of the structure of BN.

one BN from higher power group and one BN from the lower power group to implement NOMA on each sub-frame. Note that the selected BN is in backscattering status and can be selected once. Under the later $M - n$ sub-frames, with each one lasting $1/M$, the remaining (non selected) lower power BNs communicate with the reader one by one.

The following procedure can be used to classify BNs as higher or lower power BNs [10]. At the beginning of each communication frame, there is a training phase. The reader is assumed to have the knowledge of the number of BNs and their unique IDs. The reader also sets and broadcasts to all BNs a predefined power threshold β. Each BN decides which group it belongs to as follows. In the slotted training phase, the reader broadcasts a unique ID on each mini-slot. The corresponding BN takes action accordingly, that is, the BN compares its received power with β. If the power is greater than β, this BN knows that it belongs to the higher power BN group and backscatters the signal. It also selects the first impedance set in the following communication frame. Otherwise, the BN does not backscatter the training signal and it switches to the second impedance set. On the reader side, the reader can identify BNs into the corresponding groups depending on whether it receives the backscattered signal on the mini-slot or not.

IV. Performance Analysis

The metric used to characterize the BackCom system is named as the success rate, which is the percentage of bits decoded successfully in one time frame. It is defined as the ratio of the average number of bits successfully decoded by the reader in one time frame (namely, the average number of decoded bits $\bar{\mathcal{C}}_{\text{suc}}$) and the total number of bits transmitted by M BNs in one time frame (namely, the transmitted bits $\bar{\mathcal{C}}$). We assume that the data rate $\mathcal{R}$ for all BNs is unity. The formulation of this metric is presented below.

Proposition 1: Based on our system model, the success rate is given by

$$\epsilon = \bar{\mathcal{C}}_{\text{suc}}/\bar{\mathcal{C}}, \tag{1}$$

where the average number of decoded bits $\bar{\mathcal{C}}_{\text{suc}} = \sum_{n=0}^{M/2} \binom{n}{M} p_h^n (1 - p_h)^{M-n} \times \left(\frac{2n}{M}\bar{\mathcal{M}}_2 + \frac{M-2n}{M}\bar{\mathcal{M}}_{1h}\right) + \sum_{n=\frac{M}{2}+1}^{M} \binom{n}{M} p_h^n (1 - p_h)^{M-n} \left(\frac{2(M-n)}{M}\bar{\mathcal{M}}_2 + \frac{2n-M}{M}\bar{\mathcal{M}}_{1l}\right)$, the transmitted bits $\bar{\mathcal{C}} = 1 + 2p_h + \frac{4p_h^{\frac{M+2}{2}}(p_h-1)\left(\frac{M}{\frac{M+2}{2}}\right){}_2F_1\left[1, \frac{2-M}{2}, \frac{4+M}{2}, \frac{p_h}{p_h-1}\right]}{M(1-p_h)^{\frac{4-M}{2}}} - \frac{4p_h^{\frac{M+2}{2}} p_h \left(\frac{M}{\frac{M+4}{2}}\right){}_2F_1\left[2, \frac{4-M}{2}, \frac{6+M}{2}, \frac{p_h}{p_h-1}\right]}{M(1-p_h)^{\frac{4-M}{2}}}$, p_h is the average

$$p_2 = \begin{cases} 0, & \tilde{\beta} \le \frac{\mathcal{N}\gamma}{P_T \xi_2}; \\ \int_{\min\left\{\tilde{\beta}, \max\left\{\frac{\mathcal{N}\gamma}{P_T \xi_2}, \frac{\tilde{\beta}}{\gamma\kappa} - \frac{\mathcal{N}}{P_T \xi_2}\right\}\right\}}^{\tilde{\beta}} \left(1 - \frac{\Phi\left(\gamma\kappa x_2 + \frac{\mathcal{N}\gamma}{P_T \xi_1}\right) - \Phi\left(\tilde{\beta}\right)}{1 - \Phi\left(\tilde{\beta}\right)}\right) \frac{\phi(x_2)}{\Phi\left(\tilde{\beta}\right)} \mathrm{d}x_2 + \frac{\Phi\left(\min\left\{\tilde{\beta}, \max\left\{\frac{\mathcal{N}\gamma}{P_T \xi_2}, \frac{\tilde{\beta}}{\gamma\kappa} - \frac{\mathcal{N}}{P_T \xi_2}\right\}\right\}\right) - \Phi\left(\frac{\mathcal{N}\gamma}{P_T \xi_2}\right)}{\Phi\left(\tilde{\beta}\right)}, & \tilde{\beta} > \frac{\mathcal{N}\gamma}{P_T \xi_2}; \end{cases} \tag{7}$$

$$p_1 = \int_{\min\left\{\tilde{\beta}, \frac{\mathcal{N}\gamma}{P_T \xi_2}, \max\left\{0, \frac{\tilde{\beta}}{\gamma\kappa} - \frac{\mathcal{N}}{P_T \xi_2}\right\}\right\}}^{\min\left\{\tilde{\beta}, \frac{\mathcal{N}\gamma}{P_T \xi_2}\right\}} \left(1 - \frac{\Phi\left(\gamma\kappa x_2 + \frac{\mathcal{N}\gamma}{P_T \xi_1}\right) - \Phi\left(\tilde{\beta}\right)}{1 - \Phi\left(\tilde{\beta}\right)}\right) \frac{\phi\left(x_2\right)}{\Phi\left(\tilde{\beta}\right)} \mathrm{d}x_2 + \frac{\Phi\left(\min\left\{\tilde{\beta}, \frac{\mathcal{N}\gamma}{P_T \xi_2}, \max\left\{0, \frac{\tilde{\beta}}{\gamma\kappa} - \frac{\mathcal{N}}{P_T \xi_2}\right\}\right\}\right)}{\Phi\left(\tilde{\beta}\right)}. \tag{8}$$

---

probability that a BN belongs to the higher power BN group, $\bar{\mathcal{M}}_2$ is the average number of BNs whose bits are successfully decoded when two BNs are paired, and $\bar{\mathcal{M}}_{1h}$ ($\bar{\mathcal{M}}_{1l}$) is the average number of BN whose bits are successful when it accesses the reader alone and belongs to the higher (lower) power group.

Proof: Refer to Appendix A. ■

The decoding order in this work is based on the instantaneous received power instead of the distance from the BN to the reader. In the following, we present an important lemma, which helps the analysis of key elements determining the success rate.

Lemma 1: Define the random variable $x \triangleq g^2 r^{-2\alpha}$, where the pdfs of r and g are $f_r(r) = \frac{2r}{R^2 - R_1^2}$ and $f_g(g) = \frac{m^m g^{m-1} \exp(-mg)}{\Gamma[m]}$, respectively. The cumulative distribution function (cdf) and pdf for x is then given by

$$\Phi(x) = 1 + \frac{R_1^2 \Gamma[m, m R_1^\alpha \sqrt{x}] - R^2 \Gamma[m, m R^\alpha \sqrt{x}]}{(R^2 - R_1^2)\,\Gamma[m]} - \frac{(m\sqrt{x})^{-\frac{2}{\alpha}}\, \Gamma\left[m + \frac{2}{\alpha}, m R_1^\alpha \sqrt{x}, m R^\alpha \sqrt{x}\right]}{(R^2 - R_1^2)\,\Gamma[m]}, \tag{2}$$

$$\phi(x) = \frac{\Gamma\left[m + \frac{2}{\alpha}, m R_1^\alpha \sqrt{x}, m R^\alpha \sqrt{x}\right]}{m^{\frac{2}{\alpha}} x^{\frac{1}{\alpha}+1} \alpha\,(R^2 - R_1^2)\,\Gamma[m]}, \tag{3}$$

respectively.

Proof: Refer to [10].

With Lemma 1, we find that the received signal power at a BN is $P_T \sqrt{x}$ and the received signal power of the reader from a higher (or lower) power BN becomes $P_T \xi_1 x$ (or $P_T \xi_2 x$). Utilizing Lemma 1 and probability theory, we obtain the results for p_h, $\bar{\mathcal{M}}_2$, $\mathcal{M}_{1h}$ and $\mathcal{M}_{1l}$ as shown below.

Proposition 2: The probability that a BN belongs to the higher power BN group is

$$p_h = 1 - \Phi\left(\tilde{\beta}\right), \tag{4}$$

where $\tilde{\beta} \triangleq \beta^2 / P_T^2$.

Proof: The probability that a BN belongs to the higher power BN group is equivalent to the probability that the received power at the BN is higher than β. Mathematically, we have

$$p_h = \Pr\left(P_T g r^{-\alpha} \ge \beta\right) = \Pr\left(P_T \sqrt{x} \ge \beta\right) = \Pr\left(x \ge \beta^2 / P_T^2\right) = 1 - \Phi\left(\beta^2 / P_T^2\right). \tag{5}$$

Lemma 2: Given two BNs are paired, the average number of BNs whose data is successfully decoded is expressed as

$$\bar{\mathcal{M}}_2 = 2p_2 + p_1, \tag{6}$$

where p_2 is the average probability that both BNs' data are successfully decoded and p_1 is the average probability that only the stronger signal is successfully decoded. Their expressions are given by (7) and (8), which are shown at the top of this page.

Proof: Refer to Appendix B.

Lemma 3: Given that only the higher power BN accesses the reader alone, the average number of BN whose data is successfully decoded is

$$\bar{\mathcal{M}}_{1h} = 1 - \frac{\Phi\left(\frac{\mathcal{N}\gamma}{\xi_1 P_T}\right) - \Phi\left(\tilde{\beta}\right)}{1 - \Phi\left(\tilde{\beta}\right)} \mathbf{1}\left(\frac{\mathcal{N}\gamma}{\xi_1 P_T} > \tilde{\beta}\right), \tag{9}$$

and the average number of BN whose data is successfully decoded, given that this lower power BN accesses the reader alone, is

$$\bar{\mathcal{M}}_{1l} = \left(1 - \frac{\Phi\left(\frac{\mathcal{N}\gamma}{\xi_2 P_T}\right)}{\Phi\left(\tilde{\beta}\right)}\right) \mathbf{1}\left(\frac{\mathcal{N}\gamma}{\xi_2 P_T} < \tilde{\beta}\right). \tag{10}$$

Proof: Refer to Appendix C.

Remark 1 (**Discussion on the reflection coefficient**): As the BN is a passive/semi-passive device, the only practical method of tuning the reflected power is to modify either the reader's transmit power or the BN's reflection coefficient. In the following, we discuss how to set the reflection coefficient for the considered BackCom system to improve the performance.

We note that the final expression of the success rate involves a single integration, which makes it difficult to gain any design tuition. However, we can consider the selection of reflection of coefficient as follows. The best performance of ϵ is one, which indicates that all the transmitted data are successfully decoded. For the paired BNs, the ideal case is that both of the signals are successfully decoded. To achieve this ideal performance as much as possible, we first need to make sure that the stronger signal can always be successfully decoded. In other words, the stronger signal can be decoded successfully even for the worst case. Under the worst scenario (i.e., both $P_T \sqrt{x_1}$ and $P_T \sqrt{x_2}$ are equal to β), the SINR

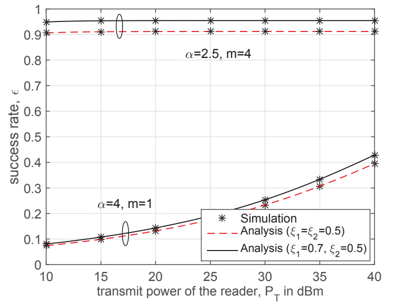

Fig. 2. Success rate ϵ versus the reader's transmit power P_T for $\gamma = 5$ dB.

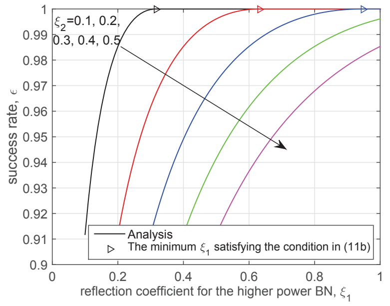

Fig. 3. Success rate ϵ versus the reflection coefficient of the higher power BN ξ_1 under $\alpha = 2.5$, $m = 4$, $P_T = 30$ dBm and $\gamma = 5$ dB.

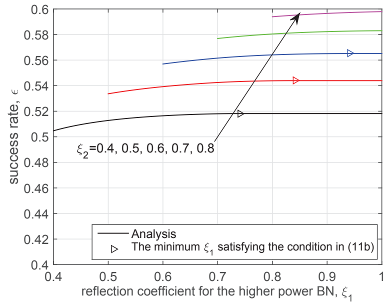

Fig. 4. Success rate ϵ versus the reflection coefficient of the higher power BN ξ_1 under $\alpha = 4$, $m = 1$, $P_T = 40$ dBm and $\gamma = 0$ dB.

for the strongest signal is $\mathsf{SINR}_1 = \frac{\xi_1\beta^2/P_T}{\xi_2\beta^2/P_T+\mathcal{N}}$. By setting $\mathsf{SINR}_1 \geq \gamma$ and rearranging this inequality, we obtain the condition $\xi \geq \gamma\left(\xi_2 + \frac{\mathcal{N}}{P_T\tilde{\beta}}\right)$ ensuring that the stronger signal is always successfully decoded. When it comes to decode the weaker signal, the weaker signal cannot be guaranteed to be always successfully decoded as the signal-to-noise-ratio at the weaker signal SNR_2 is ranging from 0 and $\frac{\xi_2\beta^2}{P_T\mathcal{N}}$. However, we note that a large value of ξ_2 can increase the probability of SNR_2 being greater than γ and we also need to ensure that the weaker signal can be decoded successfully under the best scenario (i.e., $\frac{\xi_2\beta^2}{P_T\mathcal{N}} \geq \gamma$).

In conclusion, in order to achieve a better BackCom performance, the reflection coefficients for the paired BNs need to satisfy the following conditions

$$\xi_2 \geq \gamma\frac{\mathcal{N}}{P_T\tilde{\beta}}, \tag{11a}$$

$$\xi_1 \geq \max\left\{\xi_2, \gamma\left(\xi_2 + \frac{\mathcal{N}}{P_T\tilde{\beta}}\right)\right\}. \tag{11b}$$

V. Results

In this section, we present numerical results for the considered BackCom system with NOMA. Unless specified otherwise, the following values of the system parameters are used: $R_1 = 1$ m, $R = 65$ m, $M = 60$, $\alpha = 2.5$ for Nakagami-m ($m = 4$) fading scenario *which is named as the good channel condition*, $\alpha = 4$ for Rayleigh fading *which is named as the severe channel condition*, and $\mathcal{N} = -100$ dBm. As for the power threshold β, we find a β value that makes $p_h = 0.5$, which makes sure that the average number of BNs in each group is the same. The detail discussion on the power threshold can be found in [10].

Analysis validation: Fig. 2 plots the success rate versus the transmit power of the reader. To validate our analysis, the simulation results are also plotted. From the figure, we can see that the analytical results match the analytical results perfectly, which validates our analysis.

Impact of the reader's transmit power: Fig. 2 shows that the sensitivity of success rate towards the reader's transmit power is different for different channel conditions. For example, when the channel condition are severe, the success rate increases as the reader's transmit power increases. This means that increasing P_T can enhance the BackCom system. This is because, under the severe channel condition, the backscattered signal power from the lower power BN is very small and this signal can hardly be decoded successfully, e.g., $\bar{\mathcal{M}}_{1l}$ tends to be zero and $\bar{\mathcal{M}}_2$ is far less than 2. Hence, increasing P_T (equivalently, increasing the backscattered signal power) can improve $\bar{\mathcal{M}}_2$, $\bar{\mathcal{M}}_{1h}$ and $\bar{\mathcal{M}}_{1l}$, which results in the better performance. When the channel condition is good, the curves for $\alpha = 2.5$ are almost flat as P_T increases. This means that, under the good channel condition, increasing the reader's transmit power does not further improve the performance of the BackCom system. Instead, as shown in the figure, the changing of the reflection coefficients can influence the system performance. This is discussed in detail in the following.

Impact of the reflection coefficient: Fig. 3 and Fig. 4 plot the success rate versus the reflection coefficient of the higher power BN for different channel conditions. The value of ξ_2 in these curves meets the first condition in (11a). We also mark the critical point of ξ_1 (i.e., the minimum ξ_1 meeting the second condition in (11b), where $\xi_1 \leq 1$). For some curves, this critical point does not exits as the value of critical point is greater than one, which is physically impossible. From both of these figures, we can find that, as ξ_1 increases, the success rate increases and it becomes constant after the critical point. This can be explained as follows. As ξ_1 increases, the backscattered signal power from the higher power BN increases. That is to say, for the paired BNs, the higher power BN is more likely to be decoded successfully. This causes the success rate to increase.

Regrading ξ_2, its impact varies for different channel conditions, as discussed below:

- *Good channel condition:* Fig. 3 shows that a smaller value of ξ_2 leads to a better system performance. This is due to the fact that, under the good channel condition, the signal from either the higher power BN or lower power BN can be almost always successfully decoded alone. When the BNs are paired, a larger value of ξ_2 implies the higher backscattered signal power from the lower power BN and increases the interference to the higher power BN thereby degrading the performance.
- *Severe channel condition:* In Fig. 4, we find that a larger value of ξ_2 can benefit the BackCom system. Since the

backscatter signal power from the lower power BN is very small under the severe channel condition, the signal from the lower power BN is not easy to be decoded successfully and its interference to the higher power BN is almost negligible when two BNs are paired. Increasing ξ_2 is equivalent to increasing the backscattered signal strength for the lower power BN, which increases the probability of its data being successfully decoded. Thus, the performance of the BackCom system is improved.

VI. Conclusions

In this paper, we have studied a NOMA-assisted monostatic BackCom system, where BNs with different power levels are randomly paired by the reader to implement power-domain NOMA. We derived the analytical result for the success rate which is the portion of successfully decoded bits in one time frame. We also proposed a criteria for setting the reflection coefficients for the paired BNs to improve the system performance, which was validated by results. Our results indicated that, under the good channel condition, the system performance can by greatly improved by properly setting the reflection coefficients.

Appendix

Appendix A: Proof of Theorem 1

Proof: For the paired BNs, the time allocated to each sub-frame is $2/M$. Then, the average bits decoded by the reader on one sub-frame will be $2\bar{\mathcal{M}}_2/M$. For the single access BN, the time for each sub-frame is $1/M$ and the average successfully decoded bits is $\mathcal{M}_{1h}/M$ or $\mathcal{M}_{1l}/M$ depending on whether this BN is higher power BN or not. Given the BackCom system has n higher power BNs, the bits decoded in one frame is $\frac{2n}{M}\bar{\mathcal{M}}_2 + \frac{M-2n}{M}\bar{\mathcal{M}}_{1h}$ if the number of lower power BNs exceeds the number of higher power BNs. Otherwise, it is equal to $\frac{2(M-n)}{M}\bar{\mathcal{M}}_2 + \frac{2n-M}{M}\bar{\mathcal{M}}_{1l}$. Note that n is following the Binomial distribution with parameters M and p_h. Averaging the bits decoded in one frame over n, we obtain the final expression of $\bar{\mathcal{C}}_{\text{suc}}$.

As for $\bar{\mathcal{C}}$, we set $\bar{\mathcal{M}}_2$ to 2 and both $\mathcal{M}_{1h}$ and $\mathcal{M}_{1l}$ to 1 in $\bar{\mathcal{C}}_{\text{suc}}$. With further simplifications, we arrive at the result of $\bar{\mathcal{C}}$. ■

Appendix B: Proof of Lemma 2

Proof: Let us consider the derivation of p_2 at first. We define $P_T\xi_1 x_1$ as the instantaneous received power from a higher power BN, which is the stronger signal strength. Clearly, $P_T\sqrt{x_1}$ is greater than β. Based on Lemma 1 and Bayes' theorem, we can have its cdf as

$$F_{x_1}(x_1) = \frac{\Phi(x_1) - \Phi\left(\tilde{\beta}\right)}{1 - \Phi\left(\tilde{\beta}\right)}, \tag{12}$$

where $x_1 \in [\tilde{\beta}, \infty)$.

Similarly, let $P_T\xi_1 x_1$ denote the instantaneous received power from a lower power BN. Its cdf is $F_{x_2}(x_2) = \frac{\Phi(x_2)}{\Phi(\tilde{\beta})}$, where $x_2 \in (0, \tilde{\beta})$.

Since the decoding order is always from the higher power BN group to the lower power BN group. The probability that both signals are successfully decoded can be written as

$$\begin{aligned} p_2 =& \mathbb{E}_{x_1,x_2}\left[\Pr\left(\frac{P_T\xi_1 x_1}{P_T\xi_2 x_2 + \mathcal{N}} \geq \gamma \& \& \frac{P_T\xi_2 x_2}{\mathcal{N}} \geq \gamma\right)\right] \\ =& \begin{cases} 0, & \tilde{\beta} \leq \frac{\mathcal{N}\gamma}{P_T\xi_2}; \\ \int_{\frac{\mathcal{N}\gamma}{P_T\xi_2}}^{\tilde{\beta}} p_{2|x_2} f_{x_2}(x_2)\,\mathrm{d}x_2, & \tilde{\beta} > \frac{\mathcal{N}\gamma}{P_T\xi_2}; \end{cases} \end{aligned} \tag{13}$$

where $p_{2|x_2}$ is the conditional probability of p_2, which is conditioned on x_2. We note that, under the case of $\tilde{\beta} > \frac{\mathcal{N}\gamma}{P_T\xi_2}$:

- when $\gamma\kappa x_2 + \frac{\mathcal{N}\gamma}{P_T\xi_1} < (x_1)_{\min} = \tilde{\beta}$, $p_{2|x_2} = 0$;
- Otherwise, $p_{2|x_2} = 1 - F_{x_1}\left(\gamma\kappa x_2 + \frac{\mathcal{N}\gamma}{P_T\xi_1}\right)$;

Based on the valid range of x_2 and the expression of $p_{2|x_2}$, we can obtain the simplified expression of p_2 following the similar derivation procedure [10]. With regards to p_1, we have $p_1 = \mathbb{E}_{x_1,x_2}\left[\Pr\left(\frac{P_T\xi_1 x_1}{P_T\xi_2 x_2 + \mathcal{N}} \geq \gamma \& \& \frac{P_T\xi_2 x_2}{\mathcal{N}} < \gamma\right)\right]$. Taking a similar approach mentioned above, we arrive at the result in (8). ■

Appendix C: Proof of Lemma 3

Proof: We consider $\bar{\mathcal{M}}_{1h}$ here and the derivation of $\bar{\mathcal{M}}_{1l}$ is omitted for the sake of brevity. $\bar{\mathcal{M}}_{1h}$ can be interpreted as the probability that the signal from a higher power BN can be successfully decoded. Hence, we have

$$\bar{\mathcal{M}}_{1h} = \Pr\left(\frac{P_T\xi_1 x_1}{\mathcal{N}} \geq \gamma\right) = 1 - F_{x_1}\left(\frac{\mathcal{N}\gamma}{P_T\xi_1}\right)\mathbf{1}\left(\tilde{\beta} < \frac{\mathcal{N}\gamma}{P_T\xi_1}\right). \tag{14}$$

By substituting the expression of $F_{x_1}(x_1)$ in (12), we arrive at the result in (9). ■

References

[1] W. Liu, K. Huang, X. Zhou, and S. Durrani, "Next generation backscatter communication: Theory and applications," 2017, submitted. [Online]. Available: https://arxiv.org/abs/1701.07588

[2] C. Boyer and S. Roy, "Backscatter communication and RFID: Coding, energy, and MIMO analysis," *IEEE Trans. Commun.*, vol. 62, no. 3, pp. 770–785, Mar. 2014.

[3] X. Lu, D. Niyato, H. Jiang, D. I. Kim, Y. Xiao, and Z. Han, "Ambient backscatter networking: A novel paradigm to assist wireless powered communications," *IEEE Wireless Commun.*, 2018.

[4] A. Bletsas, S. Siachalou, and J. N. Sahalos, "Anti-collision backscatter sensor networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 10, pp. 5018–5029, Oct. 2009.

[5] W. Saad, X. Zhou, Z. Han, and H. V. Poor, "On the physical layer security of backscatter wireless systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 6, pp. 3442–3451, Jun. 2014.

[6] G. Yang, C. K. Ho, and Y. L. Guan, "Multi-antenna wireless energy transfer for backscatter communication systems," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 12, pp. 2974–2987, Dec. 2015.

[7] W. Liu, K. Huang, X. Zhou, and S. Durrani, "Full-duplex backscatter interference networks based on time-hopping spread spectrum," *IEEE Trans. Wireless Commun.*, vol. 16, no. 7, pp. 4361–4377, Jul. 2017.

[8] C. Psomas and I. Krikidis, "Backscatter communications for wireless powered sensor networks with collision resolution," *IEEE Wireless Commun. Lett.*, vol. 6, no. 5, pp. 650–653, Oct. 2017.

[9] Z. Ding, Y. Liu, J. Choi, Q. Sun, M. Elkashlan, C. L. I, and H. V. Poor, "Application of non-orthogonal multiple access in LTE and 5G networks," *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 185–191, Feb. 2017.

[10] J. Guo, X. Zhou, S. Durrani, and H. Yanikomeroglu, "Design of non-orthogonal multiple access enhanced backscatter communication," Dec. 2017, submitted. [Online]. Available: https://arxiv.org/abs/1711.11193