Energy Efficiency Maximization in NOMA Enabled Backscatter Communications With QoS Guarantee

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***Abstract*—Energy efficiency (EE) is an important performance metric in communication systems. However, to the best of our knowledge, the energy-efficient resource allocation (RA) problem in non-orthogonal multiple access enabled backscatter communication networks (NOMA-BackComNet) comprehensively considering the user's quality of service (QoS) has not been investigated. In this letter, we present the first attempt to solve the EE-based RA problem for NOMA-BackComNet with QoS guarantee. The objective is to maximize the EE of users subject to the QoS requirements of users, the decoding order of successive interference cancellation and the reflection coefficient (RC) constraint, where the transmit power of the base station and the RC of the backscatter device are jointly optimized. To solve this non-convex problem, we develop a novel iteration algorithm by using Dinkelbach's method and the quadratic transformation approach. Simulation results verify the effectiveness of the proposed scheme in improving the EE by comparing it with the other schemes.**

***Index Terms*—Backscatter communications, energy efficiency, non-orthogonal multiple access.**

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I. Introduction

Backscatter communication (BackCom) can prolong the lifetime of wireless terminals (WTs) by directly reflecting radio frequency (RF) signals to the intended receivers without modulating or generating RF signals by itself in a low-power way [1]. Besides, non-orthogonal multiple access (NOMA) can provide more access opportunities for a massive number of WTs by allowing WTs to share the same spectrum [2]. As a result, the combination of BackCom and NOMA is very meaningful to further improve system capacity and spectral efficiency.

Resource allocation (RA) is very important for BackCom networks (BackComNets) to satisfy the required communication quality of users. For a bistatic wireless-powered NOMA enabled BackComNet (NOMA-BackComNet), the authors in [3] proposed a suboptimal RA scheme of joint backscatter time allocation (BTA) and reflection coefficient (RC) to maximize the minimum throughput among all backscatter devices (BDs) by exploiting the block coordinate decent (BCD) technique. For the same optimization objective, the authors in [4] extended the work into a full-duplex symbiotic NOMA-BackComNet by jointly optimizing subcarrier assignment, BTA and RCs. In [5], the authors proposed a hybrid channel access scheme for a wireless-powered NOMA-BackComNet to enhance the system throughput. In order to exploit the power-domain NOMA, the authors in [6] developed a RC selection criterion of BDs in a NOMA-BackComNet. However, [5], [6] have not considered the RA optimization problem. For a multicarrier NOMA-BackComNet [7], the sum data rates of multiple BDs were maximized by jointly optimizing the RCs, subcarrier allocation under the fixed transmit power. The approximate solutions were obtained by using the successive convex approximation (SCA) approach. In [8], for a full-duplex wireless-powered ambient BackComNet, a max-min throughput based RA problem was studied by jointly optimizing BTA and RCs. The suboptimal solution was obtained by using the BCD and the SCA techniques. In [9], a weighted sum-rate maximization problem was investigated by jointly optimizing BTA, power allocation, and energy beamforming in a single-user wireless-powered BackComNet with the harvest-then-transmit protocol. Notably, none of the aforementioned works considered the energy efficiency (EE) problem. To improve the system EE, Ye *et al.* in [10] proposed an efficient Dinkelbach-based iterative algorithm to obtain the optimal EE for a single-user wireless-powered BackComNet by jointly optimizing BTA, RC, and transmit power. Under the multiuser scenario, the authors in [11] studied the max-min EE RA problem. The throughput-based RA problem was studied in a two-hop BackCom relaying system in [12]. To the best of our knowledge, there is no open work to address the EE-based RA problem in NOMA-BackComNets.

In this letter, we study an EE-based RA problem with quality of service (QoS) guarantee in a NOMA-BackComNet. Unlike [5] and [6], which only focused on channel access and RC selection, our target is to maximize the EE of users under the minimum signal-to-interference-plus-noise ratio (SINR) requirement of each NOMA user, the maximum transmit power constraint and the user's successful decoding order constraint. We use Dinkelbach's method to convert the original problem into the parametric form and find the optimal solutions by applying the quadratic transformation approach and Karush-Kuhn-Tucker (KKT) conditions. Simulation results verify the superiority of the proposed scheme.

II. System Model and Problem Formulation

A. System Model

We consider a downlink NOMA-BackComNet, as shown in Fig. 1. By considering the hardware complexity of successive interference cancellation (SIC), we take the two-user case as an example.[1] A single-antenna BS transmits the superposition signal to NOMA user 1 and NOMA user 2 by allocating them with different transmit power in a power-domain NOMA [2]. Note that the BD only includes the passive components, so that the energy part of the received signal from the BS to the BD is absorbed by the BD for supporting its circuit operation. The remaining energy of the received signal is modified by the BD with its own signal and backscattered to the NOMA receivers. Considering the backscattering signal of the BD, the transmitted signal from the BD to the users is composed of the RF signal from the BS and the backscattering signal of the BD [13]. Motivated by the recent works [3]–[12] in this field, we assume that the information processing delay of the BD and the impact of the circuit power consumption of the BD on reflecting signals can be ignored. Besides, perfect channel state information and signal synchronization are available. Thus, the NOMA users can receive the signals from the BS and the BD. The composite signal received at the NOMA user is decoded by signal detection and SIC [3]–[7]. As a result, when $h_1 > h_2$ holds, user 2 decodes its own message by treating user 1's message as the interference [2], [5]. The forward and backscatter links are considered to be Rayleigh fading channels[2] [3]–[8].

Thus, the transmitted signal from the BS is

$$x(l) = \sqrt{p_1}x_1(l) + \sqrt{p_2}x_2(l), \tag{1}$$

where $x_1(l)$ and $x_2(l)$ are the transmitted signals from the BS to user 1 and user 2 at time slot l, respectively, and $\mathbb{E}[|x_1(l)|^2] = 1$, $\mathbb{E}[|x_2(l)|^2] = 1$. p_1 and p_2 are the allocated power by the BS to user 1 and user 2, respectively.

[1]Some works with a single-user scenario have been considered in the existing literatures due to the hardware complexity of SIC [9], [10].

[2]Rayleigh channel model is used for simplicity but other channel models such as Rice or Nakagami can also be considered. Our work focuses on the RA problem so that the channel model does not affect the results of processing procedure of our RA algorithm.

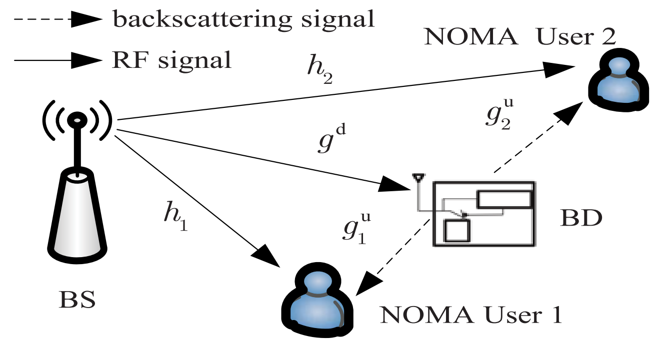

Fig. 1. A downlink NOMA-BackComNet.

Note that the noise at the BD can be neglected [9], [13], since the integrated circuit at the BD only has passive components which do not include any active RF components. Moreover, user 1 can receive two types of signals including the direct signal from the BS and the backscattering signal from the BD as shown in Fig. 1. As a result, the received signal at the user 1 can be expressed as

$$y_1(l) = \sqrt{h_1}x(l) + \sqrt{\rho g^{\mathrm{d}} g_1^{\mathrm{u}}}x(l)c(l) + n_1(l), \tag{2}$$

where h_1 and g^{d} denote the channel gains from the BS to the NOMA user 1 and the BD, respectively. g_1^{u} is the channel gain from the BD to user 1. $\rho \in [0, 1]$ is the RC of the BD, which is dynamically adjusted by the capacitor circuit [1]. $c(l)$ denotes the BD's message, and $\mathbb{E}[|c(l)|^2] = 1$. $n_1(l) \sim \mathcal{CN}(0, \sigma^2)$ denotes the complex Gaussian noise with zero mean and variance σ^2 at the user 1.

Based on the NOMA principle [2], user 1 can decode the user 2's signal (i.e., $x_2(l)$). The available SINR of user 1 to detect the message of user 2 is

$$\gamma_{1\to 2} = \frac{p_2(h_1 + \rho g^{\mathrm{d}} g_1^{\mathrm{u}})}{p_1(h_1 + \rho g^{\mathrm{d}} g_1^{\mathrm{u}}) + \sigma^2}, \tag{3}$$

If the decoding succeeds, user 1 invokes the classic SIC and decodes its own message. The available SINR of user 1 is

$$\gamma_{1\to 1} = \frac{p_1(h_1 + \rho g^{\mathrm{d}} g_1^{\mathrm{u}})}{\sigma^2}. \tag{4}$$

Similarly, the received signal at the user 2 is

$$y_2(l) = \sqrt{h_2}x(l) + \sqrt{\rho g^d g_2^{\mathrm{u}}}x(l)c(l) + n_2(l), \tag{5}$$

where h_2 and g_2^{u} denote the channel gains from the BS to user 2 and from the BD to user 2, respectively. $n_2(t) \sim \mathcal{CN}(0, \sigma^2)$ denotes the complex Gaussian noise with zero mean and variance σ^2 at the user 2. Thus, the available SINR at the user 2 is

$$\gamma_{2\to 2} = \frac{p_2(h_2 + \rho g^{\mathrm{d}} g_2^{\mathrm{u}})}{p_1(h_2 + \rho g^{\mathrm{d}} g_2^{\mathrm{u}}) + \sigma^2}. \tag{6}$$

B. Problem Formulation

To ensure the given decoding order, we have the following SINR constraint

$$\gamma_{1\to 2} \geq \gamma_{2\to 2}. \tag{7}$$

Thus, the optimization problem of the EE maximization is given by

$$\begin{aligned}
\max_{p_i,\rho}\ & \frac{\sum_{i=1}^{2}\log_2(1+\gamma_{i\to i})}{\sum_{i=1}^{2}p_i+P_\mathrm{c}}\\
s.t.\ & C_1: 0\le\rho\le 1,\\
& C_2: \sum_{i=1}^{2}p_i\le P,\ C_3: p_i\ge 0, i=1,2,\\
& C_4: \gamma_{i\to i}\ge\gamma_i^{\min},\ C_5: \gamma_{1\to 2}\ge\gamma_{2\to 2},
\end{aligned}\tag{8}$$

where P_c is the total circuit power consumption. P is the maximum transmit power of the BS. $\gamma_i^{\min}$ is the minimum SINR threshold of each user. C_1 is the RC constraint. C_2 is the sum power constraint. C_4 ensures the QoS of each user.

III. Optimal RA Algorithm

Since problem (8) is a non-convex optimization problem due to the coupled variables p_i and ρ, it is difficult to get the optimal solution directly. To solve problem (8), there are four steps as follows: i) apply Dinkelbach's method [14] to transform the objective function into a subtractive form; ii) compute the optimal RC via the monotonicity of the objective function and the feasible region in problem (8); iii) transform problem (8) into a convex one; iv) derive the closed-form solution by using Lagrange dual theory and subgradient methods [15].

A. Optimal RC

Define $\bar{g}_1=g^\mathrm{d}g_1^\mathrm{u}$ and $\bar{g}_2=g^\mathrm{d}g_2^\mathrm{u}$, based on Dinkelbach's method, problem (8) becomes

$$\begin{aligned}
\max_{p_1,p_2,\rho}\ & \log_2\left\{1+\frac{p_1(h_1+\rho\bar{g}_1)}{\sigma^2}\right\}-\eta\left(\sum\nolimits_{i=1}^{2}p_i+P_\mathrm{c}\right)\\
& +\log_2\left\{1+\frac{p_2(h_2+\rho\bar{g}_2)}{p_1(h_2+\rho\bar{g}_2)+\sigma^2}\right\}\\
s.t.\ & C_1-C_3,\ \bar{C}_5: h_1-h_2\ge\rho g^\mathrm{d}(g_2^\mathrm{u}-g_1^\mathrm{u}),\\
& C_6: \frac{p_1(h_1+\rho\bar{g}_1)}{\sigma^2}\ge\gamma_1^{\min},\\
& C_7: \frac{p_2(h_2+\rho\bar{g}_2)}{p_1(h_2+\rho\bar{g}_2)+\sigma^2}\ge\gamma_2^{\min},
\end{aligned}\tag{9}$$

where η is the maximum EE. $\bar{C}_5$ is obtained by substituting (3), (6) into C_5. C_6 and C_7 are obtained by substituting (4), (6) into C_4. Problem (9) is still difficult to solve. To deal with it, we give the following proposition.

Proposition: For any given system settings and variables, the optimal RC in problem (9) is

$$\rho^*=\min\left\{1,\max\left(0,\frac{h_1-h_2}{g^\mathrm{d}(g_2^\mathrm{u}-g_1^\mathrm{u})}\right)\right\}.\tag{10}$$

Proof: Please see the Appendix. ■

B. Optimal Power Allocation

For a fixed ρ^*, problem (9) becomes a pure power allocation problem, i.e.,

$$\begin{aligned}
\max_{p_1,p_2}\ & \log_2\left\{1+\frac{p_1(h_1+\rho^*\bar{g}_1)}{\sigma^2}\right\}-\eta\left(\sum_{i=1}^{2}p_i+P_\mathrm{c}\right)\\
& +\log_2\left\{1+\frac{p_2(h_2+\rho^*\bar{g}_2)}{p_1(h_2+\rho^*\bar{g}_2)+\sigma^2}\right\}\\
s.t.\ & C_2, C_3, \tilde{C}_6: \frac{p_1(h_1+\rho^*\bar{g}_1)}{\sigma^2}\ge\gamma_1^{\min},\\
& \tilde{C}_7: \frac{p_2(h_2+\rho^*\bar{g}_2)}{p_1(h_2+\rho^*\bar{g}_2)+\sigma^2}\ge\gamma_2^{\min},
\end{aligned}\tag{11}$$

Based on the quadratic transformation approach [16], problem (11) becomes

$$\begin{aligned}
\max_{p_1,p_2,y}\ & \log_2\left(1+\frac{p_1\bar{h}_1}{\sigma^2}\right)-\eta\left(\sum_{i=1}^{2}p_i+P_\mathrm{c}\right)\\
& +\log_2\left\{1+2y\sqrt{p_2\bar{h}_2}-y^2(p_1\bar{h}_2+\sigma^2)\right\}\\
s.t.\ & C_2, C_3, C_8: p_1\bar{h}_1\ge\sigma^2\gamma_1^{\min},\\
& C_9: p_2\bar{h}_2\ge p_1\bar{h}_2\gamma_2^{\min}+\sigma^2\gamma_2^{\min},
\end{aligned}\tag{12}$$

where y is a non-negative auxiliary variable. $\bar{h}_1=h_1+\bar{h}\bar{g}_1$, $\bar{h}_2=h_2+\bar{h}\bar{g}_2$, and $\bar{h}=\min(1,\frac{h_1-h_2}{\bar{g}_2-\bar{g}_1})$. For a given p_i, the optimal y is $y^*=\frac{\sqrt{p_2\bar{h}_2}}{p_1\bar{h}_2+\sigma^2}$ which is equivalent to

$$y^*=\begin{cases}\frac{\sqrt{p_2(h_2+g^\mathrm{d}g_2^\mathrm{u})}}{p_1(h_2+g^\mathrm{d}g_2^\mathrm{u})+\sigma^2}, \rho=1,\\ \frac{\sqrt{p_2(g_2^\mathrm{u}h_1-g_1^\mathrm{u}h_2)/(g_2^\mathrm{u}-g_1^\mathrm{u})}}{p_1(g_2^\mathrm{u}h_1-g_1^\mathrm{u}h_2)/(g_2^\mathrm{u}-g_1^\mathrm{u})+\sigma^2},\ \rho=\frac{h_1-h_2}{g^\mathrm{d}(g_2^\mathrm{u}-g_1^\mathrm{u})}.\end{cases}\tag{13}$$

For a fixed y, problem (12) is a convex problem [15], [16] which can be effectively solved by using Lagrange dual theory. The Lagrange function of problem (12) is

$$\begin{aligned}
L(p_1,p_2,y,\alpha,\beta,\lambda)&=\log_2(1+\frac{p_1\bar{h}_1}{\sigma^2})-\eta(\sum_{i=1}^{2}p_i+P_\mathrm{c})\\
&+\log_2\{1+2y\sqrt{p_2\bar{h}_2}-y^2(p_1\bar{h}_2+\sigma^2)\}+\alpha(P-\sum_{i=1}^{2}p_i)\\
&+\beta\Big(p_1\bar{h}_1-\sigma^2\gamma_1^{\min})+\lambda(p_2\bar{h}_2-p_1\bar{h}_2\gamma_2^{\min}-\sigma^2\gamma_2^{\min}\Big),
\end{aligned}\tag{14}$$

where α,β and λ are non-negative Lagrange multipliers. Define the dual objective $D(\alpha,\beta,\lambda)$ as $D(\alpha,\beta,\lambda)=\max_{p_1,p_2,y}L(p_1,p_2,y,\alpha,\beta,\lambda)$, the dual problem is

$$\begin{aligned}
\min_{\alpha,\beta,\lambda}\ & D(\alpha,\beta,\lambda),\\
s.t.\ & \alpha\ge 0,\beta\ge 0,\lambda\ge 0.
\end{aligned}\tag{15}$$

Based on KKT conditions [15], the optimal power is

$$p_1^*=\left[\frac{A_4+\sqrt{A_4^2+4\bar{h}_1\bar{h}_2y^2(A_1\sigma^2-A_3/A_2)}}{2\bar{h}_1\bar{h}_2y^2}\right]^+,\tag{16}$$

$$p_2^*=\left[\frac{B_2^2+4B_3-B_2\sqrt{B_2^2+8B_3}}{8B_1^2\bar{h}_2}\right]^+,\tag{17}$$

where $[x]^+=\max(0,x)$, $A_1=1+2y\sqrt{p_2\bar{h}_2}-y^2\sigma^2$, $A_2=\eta+\alpha+\lambda\bar{h}_2\gamma_2^{\min}-\beta$, $A_3=\bar{h}_1A_1-y^2\bar{h}_2\sigma^2$, $A_4=\frac{2\bar{h}_1\bar{h}_2y^2}{A_2}+y^2\bar{h}_2\sigma^2-\bar{h}_1A_1$, $B_1=\eta+\alpha-\lambda\bar{h}_2$,

Algorithm 1 A Dinkelbach-Based Iterative Algorithm

Input: $h_1, h_2, g^{\mathrm{d}}, g_1^{\mathrm{u}}, g_2^{\mathrm{u}}, P_c, \sigma^2, P, \gamma_1^{\min}, \gamma_2^{\min}$;
Output: Optimal p_1^*, p_2^*, ρ^*.
1: Set $T_{\max}$, ε, $t = 0$, $\eta = 0$.
2: **Initialization**: $\alpha^{(0)}, \beta^{(0)}, \lambda^{(0)}, d_1^{(0)}, d_2^{(0)}, d_3^{(0)}$.
3: **Repeat**
4: **if** $g_2^{\mathrm{u}} > g_1^{\mathrm{u}}$ **then**
5: Obtain $\rho^* = \frac{h_1 - h_2}{g^{\mathrm{d}}(g_2^{\mathrm{u}} - g_1^{\mathrm{u}})}$, $\bar{h}_1$, $\bar{h}_2$, and y^* via (13).
6: **else**
7: Obtain $\rho^* = 1$, $\bar{h}_1$, $\bar{h}_2$, and y^* via (13).
8: **end if**
9: Solve problem (12) with the fixed η.
10: Update p_1, p_2 by (16), (17), and α, β, λ by (18)–(20).
11: **if** $\sum_{i=1}^{2} \log_2(1 + \gamma_{i\to i}) - \eta(\sum_{i=1}^{2} p_i + P_c) \le \varepsilon$ **then**
12: Set Flag=1 and break.
13: **else**
14: Set Flag=0, $\eta = \frac{\sum_{i=1}^{2} \log_2(1+\gamma_{i\to i})}{(\sum_{i=1}^{2} p_i + P_c)}$ and $t = t + 1$.
15: **end if**
16: **until** Flag $= 1$ or $t = T_{\max}$.

$B_2 = B_1(1 - y^2(p_1\bar{h}_2 + \sigma^2))$, and $B_3 = A_1 y \bar{h}_2$. Based on the subgradient method [15], we have

$$\alpha^{t+1} = \left[\alpha^t - d_1^t \times \left(P - \sum_{i=1}^{2} p_i\right)\right]^+, \tag{18}$$

$$\beta^{t+1} = \left[\beta^t - d_2^t \times \left(p_1 \bar{h}_1 - \sigma^2 \gamma_1^{\min}\right)\right]^+, \tag{19}$$

$$\lambda^{t+1} = \left[\lambda^+ - d_3^t \times \left(p_2 \bar{h}_2 - p_1 \bar{h}_2 \gamma_2^{\min} - \sigma^2 \gamma_2^{\min}\right)\right]^+, \tag{20}$$

where t denotes the iteration number. d_1^t, d_2^t and d_3^t denote the positive step sizes for Lagrange multipliers α, β and λ, respectively. If we want to guarantee the convergence of the algorithm, the steps should satisfy $\lim_{t\to\infty} d_j^t = 0$ and $\sum_{t=1}^{\infty} d_j^t = \infty$, $\forall j = \{1, 2, 3\}$ [17]. The procedure of the proposed scheme is outlined in Algorithm 1. When the number of iterations is large enough, η converges to the optimal η^* [14]. Moreover, according to Algorithm 1 and the expressions of (18)–(20), the computational complexity is decided by the Dinkelbach's method. When the convergence precision ε and the maximum iteration number $T_{\max}$ are determined, the computational complexity of the Dinkelbach-based iterative algorithm is $\mathcal{O}\{\frac{1}{\varepsilon^2}\log(T_{\max})\}$ [18].

IV. Simulation Results

In this section, simulation results are provided to demonstrate the effectiveness of the proposed scheme by comparing with the pure NOMA scheme without the BD, the orthogonal multiple access (OMA) scheme with the BD, the proposed scheme with the average power allocation, and the proposed scheme under the average optimal solution. We consider the distance-dependent path-loss model as the large scale fading [3]–[5], [9], [10], where the path-loss exponent is 3, and Rayleigh fading as the small scale fading which follows a unit mean exponential distribution. The transmission radius of the BS is 30 m, the distance between the BD and users is less than 15 m. Other parameters are: $\varepsilon = 10^{-6}$, $\sigma^2 = -100$ dBm, $\gamma^{\min} = \gamma_i^{\min} = 2$ dB, and $P_c = 1$ mW [10].

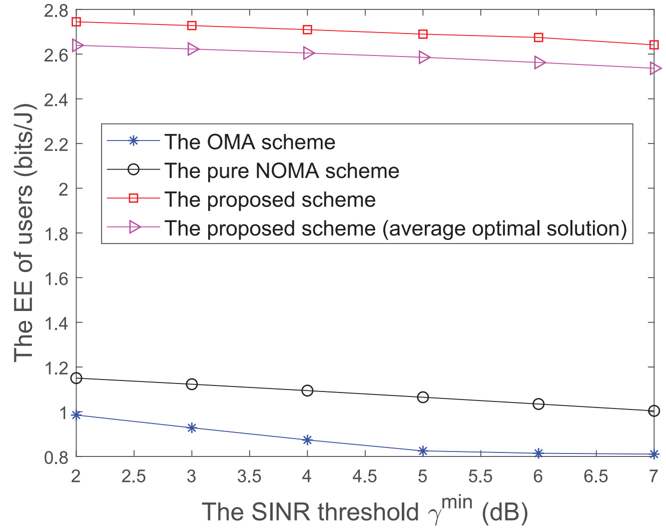

Fig. 2. The EE of users versus the minimum SINR threshold $\gamma^{\min}$ under the fixed power threshold $P = 1$ W.

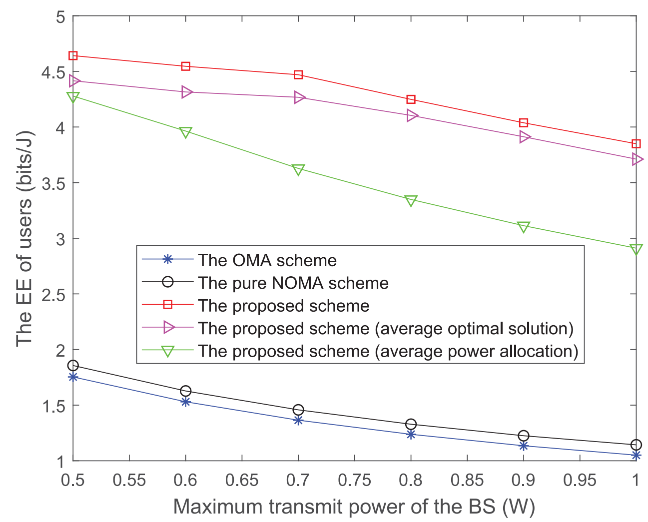

Fig. 3. The EE of users versus the maximum transmit power P under the fixed SINR threshold $\gamma^{\min} = 2$ dB.

Fig. 2 depicts the EE of users versus the minimum SINR threshold of the user $\gamma^{\min}$ under the fixed power threshold $P = 1$ W. From the figure, the EE of users decreases with the increase of the user's SINR threshold. Moreover, the proposed scheme outperforms all other considered schemes in terms of the EE. Because a higher SINR requirement can improve the minimum allocated power to the users. A higher $\gamma^{\min}$ will lead to increase in both transmission rates and the power consumption, however, the energy consumption increases more than rate improvement, which leads to the decline of the EE.

Fig. 3 shows the EE of users versus the maximum transmit power of the BS P under the fixed SINR threshold $\gamma^{\min} = 2$ dB. From the figure, the proposed scheme can obtain a largest EE compared to the pure NOMA scheme and the OMA scheme. Moreover, the EE of users degrades with the increasing P. With the increase of P, the feasible region of transmit power is enlarged, so that the BS is allowed to allocate more power to the NOMA users for a higher rate. But the increase of the power consumption is larger than the increase of the rate. Additionally, the EE of users under the proposed scheme by using the average optimal solution is slightly worse than that under the proposed scheme. However, the performance of the proposed scheme with the average optimal solution is better than that of the proposed scheme with the average power allocation.

V. Conclusion

In this letter, we have investigated the EE-based RA problem for a NOMA-BackComNet with QoS guarantee. We have formulated the EE-based maximization optimization problem of NOMA users by jointly optimizing the transmit power of the BS and the RC of the BD, and proposed a Dinkelbach-type RA algorithm to achieve the optimal solution and the maximum EE. Simulation results have demonstrated the superiority of the proposed scheme by comparing it with the benchmark schemes in terms of the EE of users.

Appendix

Define $F(\rho) = F_1(\rho) + F_2(\rho)$, $F_1(\rho) = \log_2\{1 + \frac{p_1(h_1+\rho\bar{g}_1)}{\sigma^2}\}$, $A = p_1(h_2 + \rho\bar{g}_2) + \sigma^2$, and $F_2(\rho) = \log_2\{1 + \frac{p_2(h_2+\rho\bar{g}_2)}{A}\}$, the first-order derivations are

$$\frac{\partial F_1(\rho)}{\partial\rho} = \frac{p_1\bar{g}_1}{\ln 2(p_1h_1 + p_1\rho\bar{g}_1 + \sigma^2)} > 0, \tag{A.1}$$

$$\frac{\partial F_2(\rho)}{\partial\rho} = \frac{p_2\bar{g}_2\sigma^2}{\ln 2\{A^2 + A(p_2h_2 + p_2\rho\bar{g}_2)\}} > 0. \tag{A.2}$$

Thus, we have the second-order derivations, i.e.,

$$\frac{\partial^2 F_1(\rho)}{\partial\rho^2} = -\frac{(p_1\bar{g}_1)^2}{\ln 2(p_1h_1+p_1\rho\bar{g}_1+\sigma^2)^2} < 0, \tag{A.3}$$

$$\frac{\partial^2 F_2(\rho)}{\partial\rho^2} = -\frac{p_2\sigma^2\bar{g}_2^2\{A(2p_1+p_2)+p_1p_2(h_2+\rho\bar{g}_2)\}}{\ln 2\{A^2+A(p_2h_2+p_2\rho\bar{g}_2)\}^2} < 0. \tag{A.4}$$

$F(\rho)$ is a concave and increasing function with ρ. Thus, the maximum value in problem (9) is determined by the upper bound of ρ. According to $\bar{C}_5 - C_7$, we have $\rho \leq \frac{h_1-h_2}{g^{\mathrm{d}}(g_2^{\mathrm{u}}-g_1^{\mathrm{u}})}$ if $g_2^{\mathrm{u}} > g_1^{\mathrm{u}}$ holds. Accordingly, the optimal RC is $\rho^* = \frac{h_1-h_2}{g^{\mathrm{d}}(g_2^{\mathrm{u}}-g_1^{\mathrm{u}})}$ if $h_1 - h_2 < g^{\mathrm{d}}(g_2^{\mathrm{u}} - g_1^{\mathrm{u}})$ holds. When $h_1 - h_2 > g^{\mathrm{d}}(g_2^{\mathrm{u}} - g_1^{\mathrm{u}})$, the optimal RC is $\rho^* = 1$. When $g_2^{\mathrm{u}} < g_1^{\mathrm{u}}$, the constraint $\bar{C}_5$ is always established since $\rho \geq 0$. Under this case, the optimal RC is $\rho^* = 1$. The proof is complete.

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