Ambient BackCom in Beyond 5G NOMA Networks: A Multi-Cell Resource Allocation Framework

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Abstract—The research on non-orthogonal multiple access (NOMA) is extensively used to increase the capacity of beyond fifth-generation networks. The recent merger of NOMA with ambient backscatter communication (BackCom), though opens new possibilities of massive connectivity, poses several challenges in dense wireless networks. One of such challenges is the performance degradation of ambient BackCom in multi-cell NOMA networks under the effect of inter-cell interference. Driven by providing an efficient solution to the issue, this article proposes a new resource allocation framework that uses the dual theory approach. Specifically, the sum-rate of the multi-cell network having backscatter tags and NOMA user equipments is maximized by formulating a joint optimization problem. To find the efficient base station transmit power and backscatter reflection coefficient in each cell, the original problem is first divided into two subproblems and then derived the closed-form solutions. A comparison with the orthogonal multiple access (OMA) ambient BackCom and pure NOMA transmission has been provided. Simulation results of proposed NOMA ambient BackCom indicate a significant improvement over the OMA ambient BackCom and pure NOMA in terms of sum-rate gains.

Index Terms—Beyond fifth-generation (5G), non-orthogonal multiple access (NOMA), ambient backscatter communication (BackCom), spectrum efficiency optimization.

I. INTRODUCTION

Nex generation wireless networks demand high spectral efficiency, low energy consumption, and increased connectivity [1], [2]. Non-orthogonal multiple access (NOMA) is a potential solution to meet these demands in beyond fifth-generation (5G) cellular networks [3], [4]. Its spectrum efficiency over the conventional orthogonal multiple access (OMA) solutions has made it popular among both industry and academia [5], [6]. Multiple users in a system using NOMA technique can access the same spectrum resources at one time [7]. The signals of these users can be successfully multiplexed at transmitter using superposition coding technique. The decoding process takes place at the receivers using successive interference cancellation (SIC) technique [8]. As a favorable technology to improve both the system capacity and user access, the applications

of NOMA have been explored for cognitive radio (CR) [9], millimeter-wave (mmWave) [10], and massive multiple-input-and-multiple-output (MIMO) heterogeneous networks [11]. Besides, some other studies indicate applications of NOMA for grant-free access [12], physical layer security [13], vehicular communication [14] and mobile-edge computing [15]. The rapid evolution of NOMA techniques has now led to the point where researchers have started exploring their applications in backscatter communication.

Lately, backscatter communication (BackCom) is emerging as a power- and spectrum-efficient technology to enable massive connectivity [16]. Generally, BackCom consists of two parts, i.e., an RF source/ reader and a backscatter tag [17]. For the case of mono-static BackCom, the RF source and reader are collocated. The carrier emitted by the RF source is reflected by the backscatter tag. The reflected signal is again received by the reader at the RF source which decodes the information. This principle of BackCom is used in the radio frequency identification (RFID) tags. Nonetheless, several other customized solutions of BackCom have been proposed as a result of the gradual evolution of this technology [18]. One of the more improved versions is bistatic BackCom, which allow efficient communication when RF source and reader are not co-located. Another improved variant is ambient BackCom, which provides a more robust spectrum utilization by removing the need for a dedicated RF source [19]. Specifically, the ambient BackCom enable the exploitation of available RF signals. By proper implementation, the ambient BackCom removes the need of a dedicated RF source [20]. However, this also brings some complexity in the hardware design of the backscatter tag and the receiver [21]. Fig. 1 shows different types of BackCom systems.

A. Literature Review

Recently, researches have been studied BackCom in both OMA and NOMA networks. For example, the authors in [22] have used an optimization technique to enhance the throughput of OMA BackCom network. Guo *et al.* [23] have optimized the successive decoding rate of OMA BackCom system. The work in [24] has investigated the trade-off between energy and spectral efficiency of BackCom system. Jameel *et al.* [25] have studied the applications of BackCom in health-care system. The authors of [26] have proposed a technique for physical layer security of cognitive BackCom system. Tao *et al.* [27] have proposed a new interference cancellation technique for OMA BackCom to investigate the bit error rate of the system. Reference [28] has provided an efficient resource management

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Fig. 1: Types of BackCom systems.

approach to improve the energy efficiency of mobile edge computing BackCom network. Wang *et al.* [29] have designed an energy efficiency BackCom system by optimizing the backscatter tag's reflection coefficient. Moreover, the work in [30] has optimized the power splitting and time switching for BackCom to investigate the rate-energy trade-off. Besides, the researches of [31]–[33] have also studied various applications of OMA BackCom in wireless networks.

Despite extensive research efforts, the studies on NOMA BackCom are still in their nascent stage. In this regard, most of the studies evaluate the performance evaluation aspect of such systems. For instance, the authors of [34] have provided the outage analysis of NOMA BackCom system. Guo *et al.* [35] have used NOMA for both fading-less and faded BackCom scenarios. Besides this, they also provided closed-form expressions of successfully decoded bits. In [36], a new optimization framework has proposed for unmanned aerial vehicles (UAVs) and NOMA BackCom to reduce the power consumption of UAVs while improving the number of successive decoded bits. For the case of multiple-input single-input, the authors of [37] have investigated the outage analysis of NOMA BackCom system. In another study [38], Li *et al.* have focused on the secrecy-rate of BackCom network. To improve the sum-rate, the work in [39] has jointly optimized the reflection coefficient and time allocation of NOMA BackCom network. In a similar study [40], the authors have provided a new approach to enhance the spectral efficiency and outage probability of the NOMA BackCom system. Zhang *et al.* [41] have explored the outage analysis of BackCom system. Reference [42] studied a secrecy optimization problem of BackCom in multi-cell NOMA network. To enhance the physical layer security, the authors of [43] have calculated the transmit power and reflection coefficient in NOMA BackCom system. Of late, Jameel *et al.* [44] have proposed a reliable power allocation scheme for interference management in backscatter heterogeneous networks using reinforcement learning. Moreover, the studies of [45], [46] have optimized the spectral efficiency of NOMA

BackCom system under the perfect and imperfect channel state information (CSI) assumption. Of late, Khan *et al.* [47] have provided a new BackCom framework for NOMA vehicular-to-everything network.

B. Motivation and Contributions

It is evident by the aforementioned discussion that NOMA BackCom is slowly maturing as a feasible technology for the massive connectivity of low-powered devices. It can also be observed that most of the researches have considered single cell scenarios. However, there is still room for improvement before the widespread adoption of BackCom. In this regard, it is critical to evaluate the performance of NOMA BackCom in the multi-cell environment. Such studies may also help in mitigating the impact of inter-cell interference on NOMA BackCom through robust optimization techniques. In this backdrop, our article provides following novel contributions:

- 1) A multi-cell NOMA BackCom architecture has been considered, where user equipments in each cell communicate over the same frequency band using NOMA protocol. The backscatter tag utilizes the superimposed RF signal to reflect its data to nearby NOMA users.
- 2) An optimization framework has been developed to maximize the sum-rate of the network. The original non-convex optimization problem has been decoupled into two subproblems for finding the optimal base station (BS) transmit power and backscatter reflection coefficient. The subproblems are then solved using the dual decomposition approach.
- 3) A comprehensive comparison of the proposed NOMA BackCom framework has been provided with pure NOMA and OMA BackCom frameworks. Results show the significant improvement in the sum-rate of the system using proposed NOMA BackCom over the benchmark pure NOMA as well as conventional OMA systems.

Fig. 2: System model of multi-cell NOMA Ambient BackCom network.

The remainder of the article is structured as follows. Section II discusses the system model of multi-cell network. Section III provides the problem formulation and various steps of the BS power allocation and backscatter reflection coefficient optimization techniques. In Section IV, the performance evaluation is presented along with a discussion on results. Section V highlights the conclusions of the work and possible future research directions.

II. SYSTEM AND CHANNEL MODELS

A downlink multi-cell BackCom¹ network is considered as shown in Fig. 2. In the considered model, the BS is assumed to be located at the center of each cell and communicates with two user equipments using NOMA protocol. Practically, user equipments in the same cell have various channel conditions, thus, we consider that the user equipment located near to the BS has stronger channel gain over the user equipment located far from the BS [48]. For better spectrum utilization, we also assume that all the BSs are sharing the same frequency [49]. The set of BSs can be denoted as $\mathcal{M} = \{m|1, 2, 3, \dots, M\}$, where m index m -th BS. The proposed system also consists of B uniformly distributed backscatter tags, where b index b -th backscatter tag and $\mathcal{B} = \{b|1, 2, 3, \dots, B\}$ represents the set of backscatter tags, respectively. The information of user equipments in each cell is available at their serving BS. A single-input single-output case is considered, where all the devices are equipped with omni-directional antenna. A backscatter tag in each cell also simultaneously receives the RF signal from the BS. It harvests some energy from the RF signal and then reflects it towards user equipments by adding its own information. According to the downlink NOMA protocol, near user equipment can apply SIC to subtract the information of weak user equipment before decoding its own information [38], [50]. In the end, the far user equipment will not apply SIC and decode its information by treating the signal of near user equipment as noise. The superimposed signal of m -th BS

for near user equipment and far user equipment is denoted as x_m and can be given as:

$$x_m = \sqrt{P_m \omega_m} z_m^{(n)} + \sqrt{P_m (1 - \omega_m)} z_m^{(f)}, \quad (1)$$

where $z_m^{(n)}$ and $z_m^{(f)}$ are the transmitted symbols of m -th BS for near user equipment (denoted as n -th) and far user equipment (stated as f -th), respectively. Furthermore, P_m is the power budget of m -th BS and $0 < \omega_m < 0.5$ represents the power allocation coefficient of m -th BS. According to power-domain NOMA, the m -th BS allocates more transmit power to the f -th user equipment compared to the n -th user equipment to ensure the successful operation of SIC at receiver side [51]. As discussed earlier, the b -th backscatter tag modulates s_m symbol, i.e., $\mathbb{E}[|s_m|^2] = 1$, and reflect it towards user equipments. Thus, n -th user equipment receives the following signal:

$$y_m^{(n)} = g_m^{(n)} x_m + \sqrt{\alpha_m^{(b)} g_m^{(b)}} x_m g_m^{(n,b)} s_m + \sum_{m'=1, m' \neq m}^M h_{m'}^{(n)} \sqrt{P_{m'}} x_{m'} + \beta_m^{(n)}, \quad (2)$$

where $g_m^{(b)}$ and $g_m^{(n)}$ are the channel gains from the BS to near user equipment and backscatter tag while $g_m^{(n,b)}$ is the channel gain from the backscatter tag to near user equipment. Similarly, $h_{m'}^{(n)}$ is the interference channel gain from the neighboring BS to near user equipment, $P_{m'}$ denotes the interference power of neighboring BS, and $x_{m'}$ represents the data symbol of neighboring BS. Moreover, the term $\alpha_m^{(b)}$ represents the reflection coefficient of the backscatter tag and $\beta_m^{(n)}$ is the zero mean additive white Gaussian noise (AWGN) with variance σ^2 .

Considering the effect of double fading, the signal of backscatter tag is very weaker compared to the signal of BS. Therefore, n -th user equipment need to apply SIC to decode and remove its own signal as well as the signal of f -th user equipment from m -th BS before decoding its desired signal from the backscatter tag. Thus, the signal to interference plus

¹The term BackCom in this paper refers to ambient BackCom; however, the full name is omitted here for the sake of simplicity.

noise ratio (SINR) at n -th user equipment for decoding the signal of f -th user equipment can be stated as:

$$\gamma_m^{(n,f)} = \frac{|g_m^{(n)}|^2 P_m (1 - \omega_m)}{P_m \omega_m (|g_m^{(n)}|^2 + |g_m^{(n,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2) + \ell_m^{(n)} + \sigma^2}, \quad (3)$$

where $\ell_m^{(n)} = \sum_{m'=1, m' \neq m}^M P_{m'} |h_{m'}^{(n)}|^2$ is the interference from other BSs. After removing $z_m^{(f)}$, the n -th user equipment decodes its own signal. Therefore, the SINR of n -th user equipment to decode its own signal can be given as:

$$\gamma_m^{(n,n)} = \frac{|g_m^{(n)}|^2 P_m \omega_m}{(|g_m^{(n,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2) (1 - \omega_m) P_m + \ell_m^{(n)} + \sigma^2}, \quad (4)$$

Finally, n -th user equipment decodes the signal received from the b -th backscatter tag. Thus, the SINR of n -th user equipment for decoding the signal from backscatter tag can be derived as:

$$\gamma_m^{n,b} = \frac{|g_m^{(n,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 (P_m \omega_m + P_m (1 - \omega_m))}{\ell_m^{(n)} + \sigma^2}. \quad (5)$$

Accordingly, the received signal of n -th user equipment in m -th cell can be given as:

$$y_m^{(f)} = g_m^{(f)} x_m + \sqrt{\alpha_m^{(b)} g_m^{(b)} x_m g_m^{(f,b)} s_m} + \sum_{m'=1, m' \neq m}^M h_{m'}^{(f)} \sqrt{P_{m'} x_{m'}} + \beta_m^{(f)}, \quad (6)$$

where $g_m^{(f)}$ and $g_m^{(f,b)}$ show the channel gains from m -th BS to f -th user equipment and from b -th backscatter tag to f -th user equipment associated with m -th BS, respectively. As such, $h_{m'}^{(f)}$ is the interference channel gain from m' -th BS to f -th user equipment in m -th cell. Finally, the term $\beta_m^{(f)}$ is the zero mean AWGN with variance σ^2 . It is important to note that f -th user equipment in m -th cell decodes its own signal with the interference of n -th user equipment and b -th backscatter tag. Thus, the SINR of f -th user equipment to decode its desired signal can be stated as:

$$\gamma_m^{(f,f)} = \frac{|g_m^{(f)}|^2 P_m (1 - \omega_m)}{P_m \omega_m (|g_m^{(f)}|^2 + |g_m^{(f,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2) + \ell_m^{(f)} + \sigma^2}, \quad (7)$$

where $\ell_m^{(f)} = \sum_{m'=1, m' \neq m}^M P_{m'} |h_{m'}^{(f)}|^2$ denotes the interference from all other BSs.

III. PROBLEM FORMULATION AND PROPOSED SOLUTIONS

We discuss different formulation steps of sum-rate maximization problem followed by the closed-form solutions of BS transmit power and backscatter tag reflection coefficient in this section. Then, we also present the proposed algorithm and complexity analysis.

A. Problem Formulation

In this work, we evaluate the system performance by maximizing the sum-rate of multi-cell BackCom network. In particular, the rate of user equipments from BSs and from the backscatter tags to user equipments. The total rate of backscatter multi-cell network can be then formulated as:

$$R_{tot} = \sum_{m=1}^M (R_m^{(n,n)} + R_m^{(f,f)} + R_m^{(n,b)}), \quad \forall n, \forall f, \forall b, \quad (8)$$

where $R_m^{(n,n)}$, $R_m^{(f,f)}$, and $R_m^{(n,b)}$ are the rates of n -th user equipment from m -th BS, the rate of f -th user equipment from the m -th BS, and the rate of n -th user equipment from b -th backscatter tag in m -th cell², respectively. Moreover, these rates can be given as follow:

$$R_m^{(n,n)} = \log_2(1 + \gamma_m^{(n,n)}), \quad (9)$$

$$R_m^{(f,f)} = \log_2(1 + \gamma_m^{(f,f)}), \quad (10)$$

$$R_m^{(n,b)} \approx \log_2(1 + \gamma_m^{(n,b)}). \quad (11)$$

The target of total rate maximization can be attained by user equipment's transmit power optimization as well as the optimization of reflection coefficient of backscatter tags. This optimization framework is subject to the reflection coefficients of backscatter tags and the transmit power of BSs according to the NOMA protocol³. Mathematically, an optimization problem can be formulated to maximize the sum-rate of multi-cell BackCom network as:

$$\begin{aligned} \text{OP} \quad & \text{Maximize } R_{tot} \\ & \omega_m, \alpha_m^{(b)} \\ \text{s.t.} \quad & C1: 0 \leq \alpha_m^{(b)} \leq \alpha_{max}, \quad \forall m, \forall b, \\ & C2: P_m \omega_m \leq P_m (1 - \omega_m), \quad \forall m, \\ & C3: 0 \leq P_m \leq P_{max}, \quad \forall m, \\ & C4: 0 \leq \omega_m \leq 0.5, \quad \forall m, \end{aligned} \quad (12)$$

where constraint $C1$ limits the reflection coefficient between 0 and α_{max} , where α_{max} is the maximum coefficient power the b -th backscatter tag can reflect. Constraints $C2$ and $C4$ bound BSs to transmit power according NOMA principle. In addition, $C3$ limits each BS transmit power, where P_{max} shows the BS's maximum transmission power threshold.

The above formulated optimization problem of sum-rate is non-convex [54]. Moreover, it also coupled on BS power allocation and backscatter tag reflection coefficient selection, which is very complex and difficult to solve. The complexity of the original problem is reduced by first decoupling it into two subproblems for allocating optimal power at BSs and finding optimal reflection coefficient at backscatter tags. And then provide suboptimal techniques to get the efficient solutions.

²Calculating the exact capacity of BackCom is difficult in practice [52]. Thus, a common approach is to approximate the maximum achievable capacity [22], [53].

³Due to the weak signal of BackCom [34], the interference from backscatter tag to far user equipment is almost non-existent and brings negligible change in its performance.

$$\begin{aligned} \frac{\partial \mathcal{L}(\cdot)}{\partial \omega_m} = \frac{\partial}{\partial \alpha} & \left[\log_2 \left(1 + \frac{|g_m^{(n)}|^2 P_m (1 - \omega_m)}{|g_m^{(n)}|^2 P_m \omega_m + |g_m^{(n,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m + \ell_m^{(n)} + \sigma^2} \right) \right. \\ & + \log_2 \left(1 + \frac{|g_m^{(f)}|^2 P_m (1 - \omega_m)}{|g_m^{(f)}|^2 P_m \omega_m + |g_m^{(f,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m + \ell_m^{(f)} + \sigma^2} \right) \\ & \left. + \log_2 \left(1 + \frac{|g_m^{(n,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m}{\ell_m^{(n)} + \sigma^2} \right) - \mu_m (P_m \omega_m - P_m (1 - \omega_m)) - \eta_m (\omega_m - 0.5) \right] = 0. \end{aligned} \quad (19)$$

$$\begin{aligned} \frac{\partial \mathcal{L}(\cdot)}{\partial \omega_m} = \frac{\partial}{\partial \omega_m} & [\log_2(|g_m^{(n)}|^2 P_m (1 - \omega_m)) - \log_2(|g_m^{(n)}|^2 P_m \omega_m + |g_m^{(n,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m + \ell_m^{(n)} + \sigma^2) \\ & + \log_2(|g_m^{(f)}|^2 P_m (1 - \omega_m)) - \log_2(|g_m^{(f)}|^2 P_m \omega_m + |g_m^{(f,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m + \ell_m^{(f)} + \sigma^2) \\ & + \log_2(|g_m^{(n,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m) - \log_2(\ell_m^{(n)} + \sigma^2) - \mu_m (P_m \omega_m - P_m (1 - \omega_m)) - \eta_m (\omega_m - 0.5)] = 0. \end{aligned} \quad (20)$$

$$\frac{\partial \mathcal{L}(\cdot)}{\partial \omega_m} = \frac{|g_m^{(f)}|^2 P_m}{|g_m^{(n)}|^2 P_m \omega_m} - \frac{|g_m^{(f)}|^2 P_m}{|g_m^{(f)}|^2 P_m \omega_m + |g_m^{(f,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m + \ell_m^{(f)} + \sigma^2} - \mu_m P_m - \eta_m = 0. \quad (21)$$

$$\frac{(|g_m^{(n)}|^2 P_m)(|g_m^{(f)}|^2 P_m \omega_m + |g_m^{(f,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m + \ell_m^{(f)} + \sigma^2) - (|g_m^{(f)}|^2 P_m)(|g_m^{(n)}|^2 P_m \omega_m)}{(|g_m^{(n)}|^2 P_m \omega_m)(|g_m^{(f)}|^2 P_m \omega_m + |g_m^{(f,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m + \ell_m^{(f)} + \sigma^2)} - \eta_m = \mu_m P_m. \quad (22)$$

$$C_m = - \frac{|g_m^{(n)}|^2 |g_m^{(f,b)}|^2 |g_m^{(b)}|^2 P_m^2 \alpha_m^{(b)} + |g_m^{(n)}|^2 P_m \ell_m^{(f)} + |g_m^{(n)}|^2 P_m \sigma^2}{\eta_m}. \quad (26)$$

B. Power Allocation at BSs for the Given Reflection Coefficient of Backscatter Tags

Here we assume that the reflection coefficients of backscatter tags are fixed, and accordingly the subproblem (OP1) can be formulated as:

$$\begin{aligned} \text{OP1} \quad & \underset{\omega_m}{\text{Maximize}} \quad R_{tot} \\ \text{s.t.} \quad & (C2) - (C4), \end{aligned} \quad (13)$$

To solve the optimization problem (OP1) efficiently, we adopt dual theory [55], where the dual-problem of (OP1) can be derived as:

$$\underset{\mu_m, \tau_m, \eta_m}{\text{Minimize}} \quad \Delta(\mu_m, \tau_m, \eta_m), \quad (14)$$

where $\Delta(\cdot)$ is the dual-function while the dual variables include μ_m , τ_m , and η_m . $\Delta(\cdot)$ can be written as:

$$\Delta(\mu_m, \tau_m, \eta_m) = \underset{\omega_m}{\text{Maximize}} \quad \mathcal{L}(\omega_m, \mu_m, \tau_m, \eta_m), \quad (15)$$

where $\mathcal{L}(\omega_m, \mu_m, \tau_m, \eta_m)$ represents Lagrangian function of OP1, and can be defined as:

$$\begin{aligned} \mathcal{L}(\cdot) = R_{tot} - \sum_{m=1}^M \mu_m (P_m \omega_m - P_m (1 - \omega_m)) \\ - \tau_m (P_m - P_{max}) - \eta_m (\omega_m - 0.5). \end{aligned} \quad (16)$$

By expanding R_{tot} , it can be written as:

$$\begin{aligned} \mathcal{L}(\cdot) = \sum_{m=1}^M (R_m^{(n,n)} + R_m^{(f,f)} + R_m^{(n,b)}) \\ - \mu_m (P_m \omega_m - P_m (1 - \omega_m)) \\ - \tau_m (P_m - P_{max}) - \eta_m (\omega_m - 0.5), \end{aligned} \quad (17)$$

Now, we adopt the KKT conditions to calculate a closed-form solution for ω_m as:

$$\begin{aligned} \frac{\partial \mathcal{L}(\cdot)}{\partial \omega_m} = \frac{\partial}{\partial \omega_m} & [\log_2(1 + \gamma_m^{(n,n)}) + \log_2(1 + \gamma_m^{(f,f)}) \\ & + \log_2(1 + \gamma_m^{(n,b)}) - \mu_m (P_m \omega_m - P_m (1 - \omega_m)) \\ & - \tau_m (P_m - P_{max}) - \eta_m (\omega_m - 0.5)] = 0, \end{aligned} \quad (18)$$

Substituting the values of $\gamma_m^{(n,n)}$, $\gamma_m^{(f,f)}$, and $\gamma_m^{(n,b)}$ in (18), we can obtain as (19) on the top of next page. Considering the approximation of high signal to noise ratio [56] and using the log properties, (19) can be rewritten as (20) mentioned at the top of the next page.

After calculating partial derivatives of (20), we obtain (21) at the top of the next page. Now we calculate the least common multiple (LCM) of (21), and arrive at (22), written at the top of the next page. By setting $\mu_m P_m = 0$, and then solving for ω_m , it results in ω_m^* as:

$$\omega_m^* = \left[\frac{-B_m \pm \sqrt{B_m^2 - 4A_m C_m}}{2A_m} \right]^+, \quad (23)$$

$$\begin{aligned} \frac{\partial \mathcal{L}(\cdot)}{\partial \omega_m} = \frac{\partial}{\partial \alpha_m^{(b)}} & \left[\log_2 \left(1 + \frac{|g_m^{(n)}|^2 P_m (1 - \omega_m)}{|g_m^{(n)}|^2 P_m \omega_m + |g_m^{(n,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m + \ell_m^{(n)} + \sigma^2} \right) \right. \\ & + \log_2 \left(1 + \frac{|g_m^{(f)}|^2 P_m (1 - \omega_m)}{|g_m^{(f)}|^2 P_m \omega_m + |g_m^{(f,b)}|^2 \alpha_m^{(b)} |g_m^{(g)}|^2 P_m + \ell_m^{(f)} + \sigma^2} \right) \\ & \left. + \log_2 \left(1 + \frac{|g_m^{(n,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m}{\ell_m^{(n)} + \sigma^2} \right) \right) - \lambda_m (\alpha_m^{(b)} - \alpha_{max}) \Big] = 0. \end{aligned} \quad (35)$$

$$\begin{aligned} \frac{\partial \mathcal{L}(\cdot)}{\partial \alpha_m^{(b)}} = \frac{\partial}{\partial \alpha_m^{(b)}} & \left[\log_2(|g_m^{(n)}|^2 P_m (1 - \omega_m)) - \log_2(|g_m^{(n)}|^2 P_m \omega_m + |g_m^{(n,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m + \ell_m^{(n)} + \sigma^2) \right. \\ & + \log_2(|g_m^{(f)}|^2 P_m (1 - \omega_m)) - \log_2(|g_m^{(f)}|^2 P_m \omega_m + |g_m^{(f,b)}|^2 \alpha_m^{(b)} |g_m^{(g)}|^2 P_m + \ell_m^{(f)} + \sigma^2) \\ & \left. + \log_2(|g_m^{(n,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m) - \log_2(\ell_m^{(n)} + \sigma^2) - \lambda_m (\alpha_m^{(b)} - \alpha_{max}) \right] = 0. \end{aligned} \quad (36)$$

$$\begin{aligned} \frac{\partial \mathcal{L}(\cdot)}{\partial \alpha_m^{(b)}} = & \frac{|g_m^{(n,b)}|^2 |g_m^{(b)}|^2 P_m}{|g_m^{(n,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m} - \frac{|g_m^{(n,b)}|^2 |g_m^{(b)}|^2 P_m}{|g_m^{(n)}|^2 P_m \omega_m + |g_m^{(n,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m + \ell_m^{(n)} + \sigma^2} \\ & - \frac{|g_m^{(f)}|^2 P_m}{|g_m^{(f)}|^2 P_m \omega_m + |g_m^{(f,b)}|^2 \alpha_m^{(b)} |g_m^{(g)}|^2 P_m + \ell_m^{(f)} + \sigma^2} - \lambda_m = 0. \end{aligned} \quad (37)$$

$$\frac{(|g_m^{(n,b)}|^2 |g_m^{(b)}|^2 P_m)(\kappa_m^{(n)})(\ell_m^{(f)}) - (|g_m^{(n,b)}|^2 |g_m^{(b)}|^2 P_m)(\pi_m^{(b)})(\ell_m^{(f)}) - (|g_m^{(f)}|^2 P_m)(\pi_m^{(b)})(\kappa_m^{(n)})}{(\pi_m^{(b)})(\kappa_m^{(n)})(\ell_m^{(f)})} = \lambda_m, \quad (38)$$

where $(\chi)^+ = \max(0, \chi)$, and the values of A_m and B_m are given by

$$A_m = |g_m^{(n)}|^2 |g_m^{(f)}|^2 P_m^2, \quad (24)$$

$$\begin{aligned} B_m = & |g_m^{(n)}|^2 |g_m^{(f,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m^2 + |g_m^{(n)}|^2 P_m \ell_m^{(f)} \\ & + |g_m^{(f)}|^2 P_m \sigma^2 + \frac{|g_m^{(f)}|^4 P_m^2 \sigma^2 - |g_m^{(n)}|^2 |g_m^{(f)}|^2 P_m^2}{\mu_m P_m + \eta_m}, \end{aligned} \quad (25)$$

while the value of C_m is provided in (26) on the next page. At the end, η_m and μ_m are iteratively calculated as [57]:

$$\begin{aligned} \eta_m(1+t) = & \\ \eta_m(t) + \delta(t)(P_m \omega_m - P_m(1 - \omega_m)), \quad \forall i, j, m, \end{aligned} \quad (27)$$

$$\mu_m(1+t) = \mu_m(t) + \delta(t)(\omega_m - 0.5), \quad \forall i, j, m, \quad (28)$$

where t represents the iterations and δ indicates the step size. In each index of t , we find optimal values of μ_m^* and η_m^* using the computed value of ω_m . Then, in further iterations, the values of μ_m^* as well as η_m^* is utilized to obtain optimal ω_m^* . This process is stopped on convergence.

C. Calculating Reflection Coefficient at Backscatter Tags for the Available Transmit Power of BSs

Now we find the reflection coefficient of backscatter tag for a given power allocation at BS. To do so, the original problem (OP) should be simplified as:

$$\begin{aligned} \text{OP2} \quad & \text{Maximize } R_{tot} \\ & \alpha_m^{(b)} \\ \text{s.t.} \quad & (C1), \end{aligned} \quad (29)$$

This optimization problem P2 is convex with respect to $\alpha_m^{(b)}$, thus, similar to the solution of P1, we exploit dual theory. The corresponding dual problem can be formulated as:

$$\text{Minimize}_{\lambda_m} \Delta(\lambda_m), \quad (30)$$

where $\Delta(\cdot)$ in (30) represents the dual-function and λ_m is a dual-variable. The dual-function can be written as:

$$\Delta(\lambda_m) = \text{Minimize}_{\lambda_m} \mathcal{L}(\alpha_m^{(b)}, \lambda_m), \quad (31)$$

where $\mathcal{L}(\alpha_m^{(b)}, \lambda_m)$ represents the Lagrangian-function shown in (OP2), which can be derived as:

$$\mathcal{L}(\cdot) = R_{tot} - \lambda_m (\alpha_m^{(b)} - \alpha_{max}), \quad (32)$$

By expanding R_{tot} , it can be written as:

$$\begin{aligned} \mathcal{L}(\cdot) = & \sum_{m=1}^M (R_m^{(n,n)} + R_m^{(f,f)} + R_m^{(n,b)}) \\ & - \lambda_m (\alpha_m^{(b)} - \alpha_{max}). \end{aligned} \quad (33)$$

To obtain closed-form expression for $\alpha_m^{(b)}$, KKT conditions can be used, thus resulting in following equations:

$$\begin{aligned} \frac{\partial \mathcal{L}(\cdot)}{\partial \alpha_m^{(b)}} = \frac{\partial}{\partial \alpha_m^{(b)}} & \left[\log_2(1 + \gamma_m^{(n,n)}) \right. \\ & + \log_2(1 + \gamma_m^{(f,f)}) + \log_2(1 + \gamma_m^{(n,b)}) \\ & \left. - \lambda_m (\alpha_m^{(b)} - \alpha_{max}) \right] = 0, \end{aligned} \quad (34)$$

By substituting the values of $\gamma_m^{(n,n)}$, $\gamma_m^{(f,f)}$, and $\gamma_m^{(n,b)}$ in (34), we arrive at (35) written on the top of this page. Now considering the approximation for high signal to noise ratio

$$D_m = |g_m^{(n,b)}|^4 |g_m^{(f,b)}|^2 |g_m^{(b)}|^4 P_m^3 + \frac{|g_m^{(n,b)}|^4 |g_m^{(b)}|^4 |g_m^{(f)}|^2 P_m^3}{\lambda_m}, \quad (40)$$

$$\begin{aligned} E_m = & |g_m^{(n,b)}|^4 |g_m^{(b)}|^2 P_m^2 \ell_m^{(f)} + |g_m^{(n,b)}|^4 |g_m^{(b)}|^4 P_m^2 \sigma^2 + |g_m^{(n,b)}|^2 |g_m^{(b)}|^4 |g_m^{(f,b)}|^2 P_m^2 \sigma^2 \\ & + \frac{|g_m^{(n,b)}|^2 |g_m^{(b)}|^2 |g_m^{(f)}|^2 P_m^2}{\lambda_m} + \frac{|g_m^{(n,b)}|^2 |g_m^{(b)}|^2 |g_m^{(f)}|^2 P_m^2 \ell_m^{(n)}}{\lambda_m} + \frac{|g_m^{(n,b)}|^2 |g_m^{(b)}|^2 |g_m^{(n)}|^2 P_m^2 |g_m^{(f)}|^2 \omega_m}{\lambda_m} \\ & + \frac{|g_m^{(n,b)}|^4 |g_m^{(b)}|^4 |g_m^{(f)}|^2 P_m^2 \omega_m}{\lambda_m} - \frac{|g_m^{(n,b)}|^2 |g_m^{(b)}|^2 |g_m^{(f,b)}|^2 P_m^2 \sigma^2}{\lambda_m}, \end{aligned} \quad (41)$$

$$\begin{aligned} F_m = & |g_m^{(n,b)}|^2 |g_m^{(b)}|^2 |g_m^{(f)}|^2 P_m^3 \omega_m + |g_m^{(n,b)}|^2 |g_m^{(n)}|^2 |g_m^{(b)}|^2 P_m^2 \omega_m \ell_m^{(f)} \\ & - \frac{|g_m^{(n,b)}|^2 |g_m^{(b)}|^2 |g_m^{(f)}|^2 |g_m^{(n)}|^2 P_m^3 \omega_m}{\lambda_m} - \frac{|g_m^{(n,b)}|^2 |g_m^{(b)}|^2 P_m^2 \omega_m}{\lambda_m}, \end{aligned} \quad (42)$$

and using the property of the log, the (35) can be formulated as (36).

We compute the partial derivatives of (36) which lead us to (37) on the top of this page. By computing the LCM of (37), we obtain (38), given at the top of this page. Here the values of $\pi_m^{(b)}$, $\kappa_m^{(n)}$, and $\iota_m^{(f)}$ in (38) can be written as:

$$\pi_m^{(b)} = |g_m^{(n,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m,$$

$$\kappa_m^{(n)} = |g_m^{(n)}|^2 P_m \omega_m + |g_m^{(n,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m + \ell_m^{(n)} + \sigma^2,$$

$$\iota_m^{(f)} = |g_m^{(f)}|^2 P_m \omega_m + |g_m^{(f,b)}|^2 \alpha_m^{(b)} |g_m^{(b)}|^2 P_m + \ell_m^{(f)} + \sigma^2.$$

Now calculating for $\alpha_m^{(b)}$, it results in $\alpha_m^{(b)*}$ as:

$$\alpha_m^{(b)*} = \left[\frac{-E_m \pm \sqrt{E_m^2 - 4D_m F_m}}{2D_m} \right]^+, \quad (39)$$

where $(v)^+ = \max(0, v)$, and the values of D_m , E_m , and F_m are respectively presented in (40), (41) and (42) on the top of the next page.

The Lagrangian multiplier λ_m is iteratively updated as:

$$\lambda_m(1+t) = \lambda_m(t) + \delta(t)(\alpha_m^{(b)} - \alpha_{max}), \quad \forall m \forall b \quad (43)$$

where for each index of t in (43), we find optimal λ_m^* using the computed value of $\alpha_m^{(b)}$. Then, using this value of λ_m^* , we find the optimal $\alpha_m^{(b)*}$. This process will be terminated after convergence.

D. Resource Allocation Algorithm and Complexity

In this subsection, we design and discuss an iterative algorithm for the proposed solution of Section III-A and B. As depicted in Algorithm 1, all the system variables and parameters are defined first. Then, for any given value of backscatter tag reflection coefficient $\alpha_m^{(b)}$, we iteratively calculate the optimal value of BS power allocation coefficient ω_m^* and Lagrangian variables η_m and μ_m . Next we substitute the value of ω_m^* in subproblem (29) and calculate the efficient reflection coefficient $\alpha_m^{(b)*}$ of backscatter tag and λ_m . The above iterative process will continue until convergence criterion satisfied.

Algorithm 1: Proposed iterative algorithm.

```

if the iteration number is zero,  $t = 0$  then
    Define all the variables and parameters of the system,
    i.e., BSs, NOMA user equipments, backscatter tags,
    total power of each BS, reflection coefficients of
    backscatter tags, noise variance, and channel gains.
else
    In the first step, the power allocation coefficient  $\omega_m$ 
    of BS in each cell is calculated for a given value of
    backscatter tag  $\alpha_m^{(b)}$ .
    for  $m = 1 : M$  do
        Find  $\omega_m$  using the formula of (23) and calculate
         $\eta_m$  and  $\mu_m$  iteratively as (27) and (28).
    end
    Now the optimal value of BS power allocation
    coefficient  $\omega_m^*$  is substituted in subproblem (29) first,
    and then find the efficient value of backscatter tag
    reflection coefficient  $\alpha_m^{(b)}$ .
    while not converge do
        for  $m = 1 : M$  do
            Calculate  $\alpha_m^{(b)}$  using the formula (39) and
            iteratively update  $\lambda_m$  using the formula (43).
        end
    end
    Return  $\omega_m^*$ ,  $\alpha_{i,k}^{(b)*}$ .
end

```

For the successful deployment of the considered BackCom system in the future, the complexity of the proposed algorithm is an important aspect. It should be noted that the computational complexity of the proposed algorithm is computed in the form of number of iterations required for the convergence. It should also be noted that the number of BSs, backscatter tags, and their associated user equipments are the factors that dictate the complexity of the proposed technique. The computational complexity of the proposed BackCom algorithm in any given iteration is calculated as $\mathcal{O}[(n+f)BM]$, where n and f denote the near user equipment and far user equipment. Since we have assumed that a BS communicates with two user equipments

Fig. 3: Sum-rate of the proposed multi-cell NOMA BackCom versus number of iterations.

at one time, the computational complexity can also be written as $\mathcal{O}[(2)BM]$. The total number of iterations control the computational complexity of the proposed technique. If the total number iterations needed for the convergence of our algorithm is T . Then the total computational complexity can be expressed as $\mathcal{O}[(2)TBM]$.

IV. NUMERICAL RESULTS

In this section, we provide results for the proposed BackCom technique in multi-cell NOMA network. We perform link-level simulations in MATLAB and use Monte Carlo methods to obtain the average channel gains (10^4 realizations). Specifically, we evaluate the system performance by sum-rate and compare three schemes, i.e., NOMA BackCom scheme, pure NOMA technique and conventional OMA BackCom technique, respectively. Here NOMA refer to the scheme without BackCom while OMA is the time division multiple access (TDMA) scheme. According to TDMA, each BS communicates to only one user equipment in a given time. Accordingly, two users can receive their signals in different time slots. The parameters used in the simulations, unless mentioned otherwise, are as follows: Rayleigh fading is used to model the channels among various devices in the system, such that $g_m^{(n)} \sim \mathcal{CN}(0, \phi_m^{(n)})$, $g_m^{(f)} \sim \mathcal{CN}(0, \phi_m^{(f)})$, $g_m^{(b)} \sim \mathcal{CN}(0, \phi_m^{(b)})$, $g_m^{(n,b)} \sim \mathcal{CN}(0, \phi_m^{(n,b)})$, $g_m^{(f,b)} \sim \mathcal{CN}(0, \phi_m^{(f,b)})$, $h_{m'}^{(n)} \sim \mathcal{CN}(0, \phi_{m'}^{(n)})$, and $h_{m'}^{(f)} \sim \mathcal{CN}(0, \phi_{m'}^{(f)})$, where $\phi = 0.1$. Moreover, all the backscatter tags and user equipments are uniformly distributed among all cells, The number of cells is set as $M = 4$, the maximum power of each BS is set as $P_{max} = 40$ dBm, and the reflection coefficient of backscatter tag is set as $0 \leq \alpha_{max} \leq 1$.

The results in Fig. 3 illustrate the sum-rate achieved by the proposed multi-cell NOMA BackCom scheme against the number of iterations when the number BSs is varied. The value of maximum BS power budget used is $P_{max} = 40$ dBm. The result highlights that the proposed NOMA BackCom scheme has low complexity and converges within few iterations. For

Fig. 4: Sum-rate of multi-cell BackCom versus available transmit power at each BS.

Fig. 5: Sum-rate of multi-cell BackCom versus number of cells in the network.

example, the sum-rate of the network for both cases remains unchanged after 10 iterations. Moreover, a system with more cells can achieve more sum-rate compared to the system with less number of cells. It is because the system with more cells can accommodate more NOMA user equipments and backscatter tags.

Now we present the sum-rate provided by the NOMA BackCom scheme in the multi-cell network as compared to the pure NOMA and OMA BackCom schemes. In this regard, Fig. 4 depicts the impact of BS available power budget on the system sum-rate when setting the number of BSs as $M = 4$, and the backscatter tag's maximum reflection coefficient is considered as $\alpha_{max} = 1$. As expected, both NOMA and OMA schemes increase the system sum-rate when the total power budget of BS is increased. It can be seen from Fig. 4 that the NOMA BackCom technique outperforms the pure NOMA and conventional OMA schemes. For instance, when the transmit power of each BS is $P_{max} = 25$ dBm, the sum-rate of

Fig. 6: Plot of number of iterations versus Lagrangian multipliers of the NOMA BackCom scheme.

our proposed NOMA BackCom scheme is 33.2 b/s/Hz in comparison to the benchmark pure NOMA and OMA schemes, i.e., 27.77 and 22.65 b/s/Hz. Besides, the sum-rate of the proposed technique is significantly enhanced in comparison to the other two schemes in the case when transmission power of BS is increased. This is because the proposed NOMA based technique allocated more efficiently the extra available transmit power at BS. Moreover, the integration of BackCom with NOMA achieves significant gains.

In Fig. 5, the system sum-rate is plotted against the number of cells when the maximum power budget of each BS is $P_{max} = 40$ dBm. As the available power budget for each BS is increased, the proposed NOMA BackCom scheme as well as other schemes achieve higher sum-rate. However, the performance of the NOMA BackCom scheme is significantly better than the pure NOMA and OMA schemes. More specifically, if the total BSs are 4, the sum-rate of NOMA BackCom is 36.41 b/s/Hz. On the other hand, sum-rate achieved by the pure NOMA scheme is 30.37, and OMA scheme provides a sum-rate of 25.32. Furthermore, as the number of BSs varies from 1 to 4, the sum-rate difference between NOMA and OMA techniques is increased. It is because the capability of NOMA to accommodate more user equipments on the same network resources. These observations showed that using NOMA can significantly enhance the system performance and OMA is limited to achieve the high demands of the next-generation network.

Last but not the least, it is important to see the convergence behavior of the Lagrangian multipliers which is involved in the solution of the proposed optimization framework. It can be seen from Fig. 6 that the values of Lagrange multipliers against the iteration number. We can see that all the Lagrangian multipliers converge within limited number of iterations. This shows that the the proposed multi-cell NOMA BackCom technique exhibits low complexity.

V. CONCLUSIONS

NOMA BackCom is gradually maturing with every passing year. However, the performance gains of such systems are not well-explored in the existing literature. In this regard, this article has presented a resource allocation approach to enhance the spectral efficiency of the NOMA BackCom in a multi-cell environment. More specifically, a non-convex sum-rate maximization problem has been formulated with various practical constraints. Subsequently, the problem is divided into two subproblems i.e., optimal reflection coefficient selection and BS power allocation. Both of these problems are then solved using a dual theory approach, and the results have been compared with the conventional OMA multi-cell networks. The simulation results clearly illustrate the performance gains obtained by using our proposed optimization framework.

Although the findings in this work can significantly contribute to the state-of-the-art, yet our work can be extended in various ways. For example, one critical issue in NOMA BackCom is that the reflected signal is broadcast and can be intercepted by a malicious eavesdropper in the network. To solve this issue, our work would be extended to improve the secrecy capacity and reduce the secrecy outage probability of such systems. Another challenge in NOMA BackCom in a multi-cell environment can be the appropriate selection of BS for reflecting the superimposed NOMA signal. Our optimization framework can also be extended to improving the selection of BS in a multi-cell environment. These open research topics will be investigated in the future.

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