

Connection Density Enhancement of Backscatter Communication Systems with Relaying

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Abstract—Backscatter communication is a promising technology for energy-efficient communications. It enables the Internet of things (IoT) devices to send their data by backscattering and modulating the incident radio frequency (RF) signals. In this paper, we propose a scheme for improving the connection density of backscatter communication systems, i.e., increasing the number of backscattering-enabled IoT devices that meet a minimum threshold of the received signal-to-noise ratio (SNR) at the serving base station (BS). The aforementioned goal is achieved by allowing the user equipment (UE) devices to relay the backscattered signals from the IoT devices. A UE superimposes its own uplink data with the data from an associated IoT device using power-domain non-orthogonal multiple access (NOMA). Since the UEs are mobile and have higher transmit power, the IoT devices utilize the nearby UEs to relay their data. In addition, using UEs as relays helps the BS to support more backscattering-enabled IoT devices. We formulate the connection density maximization problem to pair the IoT devices with the available UE relays. The formulated problem is a mixed-integer linear programming (MILP) problem. Although the formulated problem can be solved optimally, it has an exponential complexity. Hence, we propose a suboptimal algorithm which decomposes the original problem into smaller subproblems that can be solved by low complexity algorithms. Simulation results show that the proposed scheme with UEs as relays can increase the connection density by up to 65% compared to deploying fixed relays.

I. INTRODUCTION

The Internet of things (IoT) is an emerging paradigm in which IoT devices communicate with minimal human intervention to provide a wide variety of services, such as home automation and environmental monitoring [1]. Due to its ubiquitous coverage, the fifth generation (5G) cellular network is a strong candidate for enabling the massive IoT (mIoT) use case [2]. mIoT is characterized by a large number of low-cost low-power IoT devices that perform delay-tolerant tasks with relaxed latency requirements in the order of seconds or hours. Due to the difficulty of battery replacement and recharging in many IoT applications, IoT devices are required to maintain a long battery lifetime (up to 15 years), which necessitates energy-efficient communication.

Backscatter communication is a promising energy-efficient communication technology for the IoT devices [3]. It enables the IoT devices to transmit their data without active transmission of radio frequency (RF) signals, thus resulting in lower energy consumption. In backscatter communication, the IoT devices reflect or backscatter an external excitation

signal (i.e., carrier signal or power beacon) using a system of impedances to modulate the frequency, phase, or amplitude of the excitation signal according to their data [4]. Low-power backscatter transmitters and receivers can be implemented with low cost [5]. The performance of backscatter communication systems can further be improved by using relaying [6]–[9].

Relaying enables the receiver to obtain multiple copies of the transmitted signal and combine them to improve the received signal-to-noise ratio (SNR). In [6], user equipment (UE) devices use backscattering to communicate with their peers in device-to-device (D2D) networks and relay information for other D2D pairs. To maximize the aggregate throughput in the aforementioned scenario, an algorithm is proposed to optimize the beamforming of the power beacon signal and the selection of the reflection coefficients for relaying. In [7], a scheme is proposed to maximize the sum rate of a system where decode-and-forward relays are deployed to relay the backscattered data from batteryless IoT devices via active transmission. In [8], the throughput of a system consisting of a backscattering device and a relay is maximized, where the relay can use either active transmission or backscattering based on the availability of embedded power source. In [9], a deep reinforcement learning-based algorithm is proposed to enable UEs to relay data for the IoT devices and enhance the system sum rate. Most previous works focused on maximizing the sum rate of the system as the main objective.

In this work, we aim to improve the connection density (i.e., the number of IoT devices that successfully meet the minimum SNR or data rate requirements [2], [10]) of a backscatter communication system with relaying. We propose a novel scheme in which UEs act as relays for the backscattering-enabled IoT devices. UEs are rewarded (e.g., obtain a monetary reward) when they receive the backscattered signal from an IoT device and relay it to the serving base station (BS) via active transmission. The UE can superimpose the IoT data signal with its own uplink data signal using power-domain non-orthogonal multiple access (NOMA). Power-domain NOMA enables the BS to decode the superimposed signals using successive interference cancellation (SIC). For successful decoding, the UE and IoT data signals should have different power levels at the receiver. The proposed scheme has several advantages. In particular, by utilizing the UEs as relays, the proposed scheme can (a) increase the probability of successful decoding of the

IoT signals at the BS and (b) support a larger number of IoT devices within a given coverage area. The main contributions of this paper are summarized as follows:

- We propose a scheme for connection density enhancement of backscatter communication systems by allowing the UEs to act as relays for the data from the IoT devices.
- We formulate a mixed-integer linear programming (MILP) problem to maximize the connection density of the backscatter communication systems. The optimal solution provides the optimal pairing of the IoT devices and UE relays, as well as the optimal power allocation coefficients for NOMA transmission at the UEs.
- Since the formulated problem is NP-hard, we also propose a suboptimal algorithm to solve the MILP problem with a lower computational complexity. We decompose the original problem into a UE-IoT device pairing subproblem and a power allocation subproblem. These two subproblems can be solved using bipartite weighted matching and linear programming (LP), respectively.
- Simulation results show that the proposed scheme can support a higher connection density in a backscatter communication system by up to 65% when compared with a system with fixed relays. Connection density gains can be achieved with or without channel state information (CSI). In addition, the proposed suboptimal algorithm achieves a close-to-optimal performance.

The remainder of this paper is organized as follows. In Section II, we present our connection density enhancement scheme. In Section III, we formulate the connection density maximization problem as an MILP problem and propose low-complexity algorithms based on bipartite matching and LP to solve it. We evaluate the performance of the proposed scheme in Section IV. Section V concludes the paper.

II. SYSTEM MODEL

Consider a single BS that provides coverage for a set of UEs \mathcal{U} and a set of backscattering-enabled IoT devices \mathcal{D} . Time is divided into slots with equal duration. Each time slot is preallocated to an IoT device $d \in \mathcal{D}$, i.e., TDMA is assumed. Each IoT device $d \in \mathcal{D}$ can be in either communication state or waiting state [11]. When an IoT device d is in the communication state and is allocated a time slot for transmission, it can transmit its data by reflecting a single-tone power beacon from the BS. Other IoT devices $d' \in \mathcal{D} \setminus \{d\}$ are in the waiting state and are refrained from transmission. When an IoT device is in the waiting state, it can perform sensing tasks or harvest necessary energy to power its circuitry.

Each time slot allocated to an IoT device is further divided into two mini time slots as shown in Fig. 1. In the 1st mini slot, the BS sends a power beacon signal to the IoT device. The incident signal is backscattered by the IoT device. The BS can decode the backscattered data from some IoT devices (e.g., nearby IoT devices with good channel conditions). In addition, the UE can act as a decode-and-forward relay and decode the data sent by the nearby IoT device that cannot be served by the BS (e.g., IoT devices far from the BS with

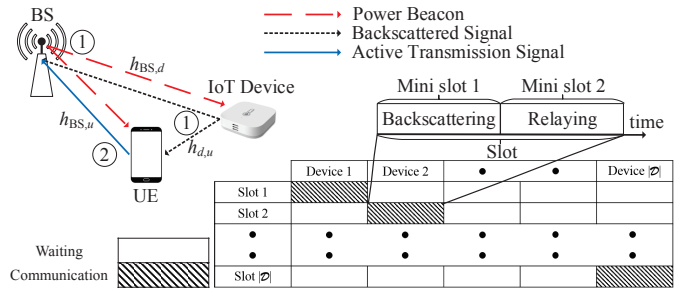


Fig. 1. A backscatter communication system with UEs acting as relays. Each IoT device is preallocated a single time slot which is divided into two mini slots. In the 1st mini slot, the BS transmits a power beacon signal, and the IoT device sends its data by backscattering the incident power beacon signal. In the 2nd mini slot, the UE decodes the data from the associated IoT device, superimposes them with its own data, and transmits the superimposed signal to the BS using power-domain NOMA.

poor channel conditions). UEs are encouraged via economic reward to relay data for the IoT devices in order to enhance the connection density and coverage of the backscatter communication systems. Then, the UE forwards the superimposed signal that includes its own data along with the data of the IoT device by active transmission in the 2nd mini slot using power-domain NOMA.

Throughout this paper, we introduce $h_{a,b} \in \mathbb{C}$ to denote the small-scale channel coefficient (e.g., Rayleigh fading) and $\ell_{a,b} \in \mathbb{R}_+$ to denote the large-scale channel coefficient (e.g., path loss) between device a and device b , where $a, b \in \{\text{BS}\} \cup \mathcal{U} \cup \mathcal{D}$ and $a \neq b$. Since we assume channel reciprocity, then $|h_{a,b}| = |h_{b,a}|$ and $\ell_{a,b} = \ell_{b,a}$.

A. Backscattering of Data

For the BS-IoT device link, the BS transmits a beacon with power level P_{BS} . Hence, the received power at the IoT device $d \in \mathcal{D}$ before backscattering is $P_{\text{BS}}\ell_{\text{BS},d}|h_{\text{BS},d}|^2$. The IoT device transmits its data via backscattering with a reflection coefficient of magnitude $|\zeta_d|$ (i.e., fraction of incident power reflected). Assuming channel reciprocity, the received SNR at the BS $\gamma_{\text{BS},d}$ is given by

$$\gamma_{\text{BS},d} = \frac{|\zeta_d|P_{\text{BS}}\ell_{\text{BS},d}^2|h_{\text{BS},d}|^4}{\sigma_{\text{BS}}^2}, \quad (1)$$

where σ_{BS}^2 is the variance of the noise power at the BS. Note that the channel gain $h_{\text{BS},d}$ can be estimated at the BS side by transmitting a reference or pilot signal and receiving its reflection from the IoT device. For the UE-IoT device link, UE $u \in \mathcal{U}$ receives the backscattered signal from an IoT device $d \in \mathcal{D}$ and the power beacon from the BS. The power beacon signal is assumed to be known at the UE and can be subtracted from the received signal using self-interference cancellation [6], [12]. The received SNR at the UE $\gamma_{d,u}$ is given by

$$\gamma_{d,u} = \frac{|\zeta_d|P_{\text{BS}}\ell_{\text{BS},d}|h_{\text{BS},d}|^2\ell_{d,u}|h_{d,u}|^2}{\sigma_u^2}, \quad (2)$$

where σ_u^2 is the variance of the noise power at UE u . Similar to $h_{\text{BS},d}$, the channel gain $h_{d,u}$ can be estimated by the UE after receiving the reflection of the IoT device for a reference or pilot signal from the BS. Given the received reflected signal

at the UE, the pilot signal, and $h_{\text{BS},d}$, the UE can estimate $h_{d,u}$ and report this estimation to the BS [8].

We introduce a binary variable $z_{d,u}$, which is equal to 1 if UE u and IoT device d are paired (i.e., UE u relays data for IoT device d), and is equal to 0 otherwise. We have

$$z_{d,u} \in \{0, 1\}. \quad (3)$$

For UE u to successfully decode the data from an IoT device d , the received SNR at the UE, denoted as $\gamma_{d,u}$, should exceed a certain threshold $\gamma_{\text{UE}}^{(\text{th})}$.

$$z_{d,u} \frac{|\zeta_d| P_{\text{BS}} \ell_{\text{BS},d} |h_{\text{BS},d}|^2 \ell_{d,u} |h_{d,u}|^2}{\sigma_u^2} \geq z_{d,u} \gamma_{\text{UE}}^{(\text{th})}. \quad (4)$$

Each IoT device $d \in \mathcal{D}$ can only use one UE as a relay, i.e.,

$$\sum_{u \in \mathcal{U}} z_{d,u} \leq 1. \quad (5)$$

B. Relaying of Data

For the BS-UE link, UE u transmits both its own data, denoted by x_u , and the decoded data from the IoT device, denoted by x_d , using power-domain NOMA. Let $\alpha_{d,u}$ and $\beta_{d,u}$ denote the non-negative power allocation coefficients for x_u and x_d , respectively. The received signal at the BS at the 2nd mini slot, denoted by $y_{d,u}$, is given by

$$y_{d,u} = \sqrt{\alpha_{d,u} P_u \ell_{\text{BS},u}} h_{\text{BS},u} x_u + \sqrt{\beta_{d,u} P_u \ell_{\text{BS},u}} h_{\text{BS},u} x_d + n, \quad (6)$$

where P_u is the transmit power of UE u and n is the additive white Gaussian noise. The BS decodes x_u and x_d sequentially using SIC. The data of the UE u is decoded first and the data from the IoT device d is decoded subsequently. Similarly, the channel gain $h_{\text{BS},u}$ is estimated at the BS by receiving a pilot signal from UE u . Since the BS decodes x_u first, the received signal-to-interference-plus-noise ratio (SINR), denoted by $\gamma_{\text{BS},d,u}^{(1)}$, is expressed as follows

$$\gamma_{\text{BS},d,u}^{(1)} = \frac{\alpha_{d,u} P_u \ell_{\text{BS},u} |h_{\text{BS},u}|^2}{\beta_{d,u} P_u \ell_{\text{BS},u} |h_{\text{BS},u}|^2 + \sigma_{\text{BS}}^2}. \quad (7)$$

Subsequently, the BS decodes x_d and the received SNR, denoted by $\gamma_{\text{BS},d,u}^{(2)}$, is given by

$$\gamma_{\text{BS},d,u}^{(2)} = \frac{\beta_{d,u} P_u \ell_{\text{BS},u} |h_{\text{BS},u}|^2}{\sigma_{\text{BS}}^2}. \quad (8)$$

For the IoT devices that are associated with UE relays, we assume that the BS does not perform any combining for the received signals in the two mini slots (i.e., backscattered and relayed signals) and only decodes the relayed signals from the UE relays because $\gamma_{\text{BS},d}$ is very small when compared with $\gamma_{\text{BS},d,u}^{(2)}$. Since the power allocation coefficients $\alpha_{d,u}$ and $\beta_{d,u}$ are non-negative, we have

$$\alpha_{d,u} \geq 0, \quad (9)$$

$$\beta_{d,u} \geq \rho z_{d,u}, \quad (10)$$

where ρ is a small non-negative value that can be adjusted to enforce a minimum value for $\beta_{d,u}$ when $z_{d,u}$ is equal to 1. ρ can be used to mitigate the impact of inaccurate or unavailable CSI. In addition, UE u allocates a portion of its transmit power

for the data of IoT device d (i.e., $\beta_{d,u} > 0$) only if they are paired. Hence,

$$\beta_{d,u} \leq z_{d,u}. \quad (11)$$

The sum of the power allocation coefficients during an allocated time slot for IoT device d cannot be greater than 1 to satisfy the maximum transmit power constraint, i.e.,

$$\alpha_{d,u} + \beta_{d,u} \leq 1. \quad (12)$$

Note that the UE can relay data for the IoT devices even if it does not have any uplink data to transmit by setting $\alpha_{d,u}$ to 0 and using a nonzero value of $\beta_{d,u}$. On the other hand, if the UE has uplink data to transmit, it needs to meet a minimum data rate requirement R_{min}

$$B \log_2 \left(1 + \frac{\alpha_{d,u} P_u \ell_{\text{BS},u} |h_{\text{BS},u}|^2}{\beta_{d,u} P_u \ell_{\text{BS},u} |h_{\text{BS},u}|^2 + \sigma_{\text{BS}}^2} \right) \geq R_{\text{min}}, \quad (13)$$

where B is the communication channel bandwidth. For the UEs that do not have data for uplink transmission, we set $R_{\text{min}} = 0$. It is worth noting that if an IoT device $d' \in \mathcal{D}$ is not paired with UE u (i.e., $z_{d',u} = 0$ and $\beta_{d',u} = 0$), then constraint (13) becomes $B \log_2 \left(1 + \frac{\alpha_{d,u} P_u |h_{\text{BS},u}|^2}{\sigma_{\text{BS}}^2} \right) \geq R_{\text{min}}$. Satisfying constraint (13) for the associated IoT device d implies satisfying the same constraint for all non-associated IoT devices d' . By reordering the terms of (13), the minimum data rate constraints of UEs can be expressed as

$$\alpha_{d,u} \frac{P_u \ell_{\text{BS},u} |h_{\text{BS},u}|^2}{\sigma_{\text{BS}}^2} \geq \left(2^{(R_{\text{min}}/B)} - 1 \right) \times \left(\beta_{d,u} \frac{P_u \ell_{\text{BS},u} |h_{\text{BS},u}|^2}{\sigma_{\text{BS}}^2} + 1 \right). \quad (14)$$

C. Decoding the Data of the IoT Devices

We introduce a binary variable q_d , which is equal to 1 if IoT device d can be successfully served by the BS, and is equal to 0 otherwise. We have

$$q_d \in \{0, 1\}. \quad (15)$$

An IoT device d can be successfully served in one of the following two ways: (a) BS receives the backscattered signal from IoT device d in the 1st mini time slot such that a minimum SNR threshold $\gamma_{\text{BS}}^{(\text{th})}$ is met without requiring a relay. (b) BS receives the successfully decoded superimposed signal from the UE u paired with IoT device d in the 2nd mini time slot such that

$$\frac{|\zeta_d| P_{\text{BS}} \ell_{\text{BS},d}^2 |h_{\text{BS},d}|^4}{\sigma_{\text{BS}}^2} \left(1 - \sum_{u \in \mathcal{U}} z_{d,u} \right) + \sum_{u \in \mathcal{U}} \frac{\beta_{d,u} P_u \ell_{\text{BS},u} |h_{\text{BS},u}|^2}{\sigma_{\text{BS}}^2} \geq q_d \gamma_{\text{BS}}^{(\text{th})}, \quad (16)$$

UE u can successfully decode the data from IoT device d before relaying it if $\gamma_{d,u} \geq \gamma_{\text{UE}}^{(\text{th})}$. Note that for an IoT device d that is paired with UE u , $\gamma_{\text{BS},d,u'}^{(2)} = 0$ for any UE $u' \in \mathcal{U} \setminus \{u\}$ since $\beta_{d,u'} = 0$. If an IoT device d cannot be served due to poor channel conditions or absence of nearby UE relays, it should not be associated with any UE relay, and q_d is equal

to 0. Hence,

$$\sum_{u \in \mathcal{U}} z_{d,u} \leq q_d. \quad (17)$$

III. PROBLEM FORMULATION & PROPOSED ALGORITHM

We formulate an optimization problem to jointly: a) pair the UE relays and the IoT devices and b) allocate power for the NOMA transmission by UEs. We consider a connection density maximization objective $\sum_{d \in \mathcal{D}} q_d$ in which we seek to maximize the number of IoT devices that meet the minimum received SNR threshold $\gamma_{\text{BS}}^{(\text{th})}$ at the BS. The formulated connection density enhancement problem is expressed as follows:

$$\begin{aligned} & \underset{q_d, z_{d,u}, \alpha_{d,u}, \beta_{d,u}}{\text{maximize}} && \sum_{d \in \mathcal{D}} q_d && (18) \\ & \text{subject to} && \text{constraints (3)–(4), (9)–(12), (14),} \\ & && d \in \mathcal{D}, u \in \mathcal{U}, \\ & && \text{constraints (5), (16)–(17),} && d \in \mathcal{D}. \end{aligned}$$

Problem (18) is an MILP problem due to constraints (3) and (15) and it can be optimally solved using different algorithms (e.g., branch-and-bound). However, these algorithms have exponential complexity. In the following subsections, we obtain a suboptimal solution for the problem by decomposing it into two subproblems that can be solved using low-complexity algorithms.

A. UE-IoT Device Pairing Subproblem

In the first subproblem, we pair each IoT device with a UE that can receive the backscattered signal with high SNR in order to decode the data successfully before relaying it in the subsequent mini slot to the BS. The objective of this subproblem is to maximize the number of UE-IoT device pairs. Hence, we formulate the following subproblem

$$\begin{aligned} & \underset{\tilde{z}_{d,u}}{\text{maximize}} && \sum_{d \in \mathcal{D}'} \sum_{u \in \mathcal{U}} w_{d,u} \tilde{z}_{d,u} && (19) \\ & \text{subject to} && \sum_{u \in \mathcal{U}} \tilde{z}_{d,u} \leq 1, && d \in \mathcal{D}', \\ & && \tilde{z}_{d,u} \frac{|\zeta_d| P_{\text{BS}} \ell_{\text{BS},d} |h_{\text{BS},d}|^2 \ell_{d,u} |h_{d,u}|^2}{\sigma_u^2} \geq \tilde{z}_{d,u} \gamma_{\text{UE}}^{(\text{th})}, && d \in \mathcal{D}', u \in \mathcal{U}, \\ & && \tilde{z}_{d,u} \in \{0, 1\} && d \in \mathcal{D}', u \in \mathcal{U}, \end{aligned}$$

where $w_{d,u}$ is a weighting factor assigned to the pair consisting of UE u and IoT device d , and \mathcal{D}' is the set of IoT devices excluding those that (a) can meet the minimum SNR requirement in (16) by backscattering data to the BS without relaying (i.e., $\gamma_{\text{BS},d} \geq \gamma_{\text{BS}}^{(\text{th})}$), or (b) cannot be associated with any UE relay. $\tilde{z}_{d,u}$ is a binary variable that indicates if UE u and IoT device d are associated, and it is used as input to the second subproblem in the next subsection. Problem (19) is a binary integer programming problem. However, it can be reformulated as a weighted bipartite many-to-one matching problem and we solve it by performing multiple iterations of one-to-one maximum cardinality matching (i.e., it can

Algorithm 1: UE-IoT Device Pairing Algorithm

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1 Input:  $\zeta_d, P_{\text{BS}}, \ell_{\text{BS},d}, h_{\text{BS},d}, \ell_{d,u}, h_{d,u}, \sigma_u^2, \gamma_{\text{BS}}^{(\text{th})}, \gamma_{\text{UE}}^{(\text{th})}$ 
2  $\mathcal{D}' \leftarrow \mathcal{D}$ 
3 Evaluate  $\gamma_{\text{BS},d}, d \in \mathcal{D}'$  using (1)
4 // Excluding the IoT devices that do not
  require relaying
5  $\mathcal{D}' := \mathcal{D}' \setminus \{d \in \mathcal{D}' \mid \gamma_{\text{BS},d} \geq \gamma_{\text{BS}}^{(\text{th})}\}$ 
6 Evaluate  $\gamma_{d,u}, d \in \mathcal{D}', u \in \mathcal{U}$  using (2)
7 // Excluding the IoT devices that cannot be
  associated with any UE
8  $\mathcal{D}' := \mathcal{D}' \setminus \{d \in \mathcal{D}' \mid \gamma_{d,u} < \gamma_{\text{UE}}^{(\text{th})} \forall u \in \mathcal{U}\}$ 
9  $w_{d,u} := 0$  for all  $(d,u) \in \{(d,u) \in \mathcal{D}' \times \mathcal{U} \mid \gamma_{d,u} < \gamma_{\text{UE}}^{(\text{th})}\}$ 
10  $\mathcal{N} \leftarrow$  Sort all the values of  $\gamma_{d,u}$  for all
    $(d,u) \in \{(d,u) \in \mathcal{D}' \times \mathcal{U} \mid \gamma_{d,u} \geq \gamma_{\text{UE}}^{(\text{th})}\}$  in an ascending
   order
11  $n := 1, \Delta := \epsilon$ , where  $\epsilon \in \{\epsilon \in \mathbb{R}_{++} \mid 0 < \epsilon < \frac{1}{|\mathcal{N}|-2}\}$  (if
    $|\mathcal{N}| < 2, \Delta := 0$ ).
12 for  $(d,u) \in \mathcal{N}$  do
13    $w_{d,u} := 1 + (n-1)\Delta$ 
14    $n := n + 1$ 
15 end
16 while  $\mathcal{D}' = \emptyset$  do
17   Solve problem (19) as a weighted bipartite one-to-one
   matching problem to obtain  $\tilde{z}_{d,u}$  for all  $d \in \mathcal{D}, u \in \mathcal{U}$ 
18   // Excluding the IoT devices that are
   associated with a UE relay
19    $\mathcal{D}' := \mathcal{D}' \setminus \{d \in \mathcal{D}' \mid \sum_{u \in \mathcal{U}} \tilde{z}_{d,u} = 1\}$ 
20 end
21 Output:  $\tilde{z}_{d,u}$  for all  $d \in \mathcal{D}, u \in \mathcal{U}$ 

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be optimally solved in polynomial time [13]). Algorithm 1 describes the steps of the proposed UE-IoT device pairing algorithm.

In Steps 3 – 5, we evaluate $\gamma_{\text{BS},d}$ and exclude those IoT devices that can transmit their data by backscattering to the BS only. In Steps 6 – 8, we evaluate $\gamma_{d,u}$ and exclude those IoT devices that cannot be associated with any UE relay due to not satisfying the minimum SNR requirement for association $\gamma_{\text{UE}}^{(\text{th})}$. In Steps 9–15, we construct the weighted bipartite graph to match the IoT devices to the UE relays. The weights $w_{d,u}$ are adjusted so that the pairs with higher $\gamma_{d,u}$ are given higher weights. The value of $w_{d,u}$ is equal to 0 when $\gamma_{d,u} < \gamma_{\text{UE}}^{(\text{th})}$. For UE-IoT device pairs with $\gamma_{d,u} \geq \gamma_{\text{UE}}^{(\text{th})}$, the weights $w_{d,u}$ are given non-zero values that are greater than 1. These non-zero weights should be adjusted such that the optimal solution of problem (19) satisfies the following two requirements: (a) obtain the maximum number of UE-IoT device pairs that meet constraint (4) and (b) among those which provide the same maximum number of UE-IoT device pairs, select the pairs with higher $\gamma_{d,u}$. Let the set of candidate UE-IoT device pairs that meet constraint (4) be denoted as \mathcal{N} . Our proposed weight adjusting scheme is to sort the received SNR at UEs $\gamma_{d,u}$ for all UE-IoT device pairs with $\gamma_{d,u} \geq \gamma_{\text{UE}}^{(\text{th})}$ in an ascending order. The first pair is assigned a weight of 1 and the n^{th} pair is assigned a weight of $1 + (n-1)\Delta$ if $|\mathcal{N}| \geq 2$, where $\Delta < \frac{1}{|\mathcal{N}|-2}$. We obtain the solution in Step 17 [13]. After solving problem (19) in one iteration, the IoT devices that are paired with UE relays are excluded from set \mathcal{D}' so that the

one-to-one matching can be repeated until all the remaining IoT devices in set \mathcal{D}' are associated with UE relays as shown in Steps 16 – 20.

B. Power Allocation Subproblem

For each UE-IoT device pair with $\tilde{z}_{d,u}$ that is equal to 1, we need to determine whether UE u can still meet its minimum data rate requirement specified in constraint (14) while acting as a relay for IoT device d . The UE should not act as a relay if it cannot achieve its minimum data rate requirement R_{\min} or the IoT device cannot meet the minimum SNR threshold $\gamma_{\text{BS}}^{(\text{th})}$ for decoding data at the BS (i.e., cannot meet constraint (16) with the help of relaying). There may be cases where $\tilde{z}_{d,u}$ is equal to 1, but $z_{d,u}$ is equal to 0. Hence, we formulate the following problem for each pair of UE u and IoT device d such that $(d, u) \in \{(d, u) \in \mathcal{D} \times \mathcal{U} \mid \tilde{z}_{d,u} = 1\}$.

$$\begin{aligned} & \text{maximize} && q_d \\ & q_d, z_{d,u}, \alpha_{d,u}, \beta_{d,u} \end{aligned} \quad (20a)$$

$$\text{subject to} \quad z_{d,u} \leq q_d, \quad (20b)$$

$$\frac{\beta_{d,u} P_u \ell_{\text{BS},u} |h_{\text{BS},u}|^2}{\sigma_{\text{BS}}^2} \geq q_d \gamma_{\text{BS}}^{(\text{th})}, \quad (20c)$$

constraints (3), (9)–(12), (14), (15).

Algorithm 2 summarizes the steps for the power allocation algorithm. Some IoT devices $d' \in \{d \in \mathcal{D} \mid \sum_{u \in \mathcal{U}} \tilde{z}_{d,u} = 0\}$ do not require relaying because they cannot be paired with any UEs or they can meet their minimum SNR requirement by backscattering their data to the BS. In Steps 3 – 9, we evaluate whether non-paired IoT devices can still be served with backscattering only. For these devices, we set $q_{d'}$ to be equal to 1 if $\gamma_{\text{BS},d'} \geq \gamma_{\text{BS}}^{(\text{th})}$. Otherwise, $q_{d'}$ is set to 0. In Steps 10 – 18, we solve problem (20) where we have two binary variables q_d and $z_{d,u}$. We set $z_{d,u}$ and q_d to be equal to 1 and solve problem (20) as an LP problem to obtain the optimal value of $\alpha_{d,u}$ and $\beta_{d,u}$ if a solution exists. Otherwise, it is not feasible to meet the minimum data rate requirements of UE u when it relays data for IoT device d as in constraint (14). Consequently, we set $z_{d,u}$, q_d , $\alpha_{d,u}$, and $\beta_{d,u}$ to 0. It is worth noting that setting $z_{d,u} = 1$ and $q_d = 0$ is not a solution since it is not beneficial that the UE acts as a relay and obtains a reward without successfully serving the IoT device.

IV. PERFORMANCE EVALUATION

We consider a 100 m \times 100 m coverage area that is served by a single BS, where 30 UEs and 100 IoT devices are placed uniformly (Locations change every simulation run). We assume flat Rayleigh fading channels. The total system bandwidth B is set to 15 kHz. The distance-dependent path loss $PL(D)$ at carrier frequency $f_c = 900$ MHz is calculated by $PL(D) = \frac{4\pi d_o f_c^2}{(3 \times 10^8)^2} \left(\frac{D}{d_o}\right)^\psi$, where d_o is a reference distance of 1 m and ψ is the path loss exponent that is set to 3.5. The distance D takes into account the heights of BS, UEs, and IoT devices which are 25 m, 1.5 m and 1.5 m, respectively [14]. We consider additive white Gaussian noise with power spectral density -174 dBm/Hz and a receiver noise figure of 5 dB and 7 dB at BS and UEs, respectively [14]. The transmit power of

Algorithm 2: Power Allocation Algorithm

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1 Input:  $\zeta_d, P_{\text{BS}}, \ell_{\text{BS},d}, h_{\text{BS},d}, \ell_{\text{BS},u}, h_{\text{BS},u}, \sigma_{\text{BS}}^2, P_u, \gamma_{\text{BS}}^{(\text{th})}, R_{\min}, \tilde{z}_{d,u}$ 
2 Initialize  $q_d := 0, z_{d,u} := 0, \alpha_{d,u} := 0, \beta_{d,u} := 0$ , for all  $(d, u) \in \{\mathcal{D} \times \mathcal{U}\}$ 
3 for  $d' \in \{d \in \mathcal{D} \mid \sum_{u \in \mathcal{U}} \tilde{z}_{d,u} = 0\}$  do
4   if  $\gamma_{\text{BS},d'} \geq \gamma_{\text{BS}}^{(\text{th})}$  then
5      $q_{d'} := 1$ 
6   else
7      $q_{d'} := 0$ 
8   end
9 end
10 for  $(d, u) \in \{(d, u) \in \mathcal{D} \times \mathcal{U} \mid \tilde{z}_{d,u} = 1\}$  do
11    $z_{d,u} := 1, q_d := 1$ 
12   Solve problem (20) as an LP
13   if Solution exists then
14     Obtain  $\alpha_{d,u}, \beta_{d,u}$ 
15   else
16      $q_d := 0, z_{d,u} := 0, \alpha_{d,u} := 0, \beta_{d,u} := 0$ ,
17   end
18 end
19 Output:  $q_d, z_{d,u}, \alpha_{d,u}, \beta_{d,u}$ , for all  $(d, u) \in \{\mathcal{D} \times \mathcal{U}\}$ 

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UEs P_u is equal to 23 dBm [15, p. 481]. The SNR threshold for successful decoding at the BS and the UEs are set such that $\gamma_{\text{BS}}^{(\text{th})} = \gamma_{\text{UE}}^{(\text{th})} = 2$, respectively. We also set $R_{\min} = 100$ kbps, $|\zeta_d| = 0.7$ [11], and $\rho = 0.001$.

We evaluate the connection density $\sum_{d \in \mathcal{D}} q_d$ while varying the BS transmit power, SNR thresholds for decoding, and the number of available UE relays, respectively. We compare the proposed scheme with two baseline schemes. In the first baseline scheme, the IoT devices can only backscatter data to the BS and no UE acts as a relay. In the second baseline scheme, four relays of 10 m height and 23 dBm transmit power are deployed in fixed locations (for all the simulation runs) to relay the data from the IoT devices. We also consider the case, where the BS only obtains information about UE and IoT devices locations and no CSI is available due to the difficulty of estimating $h_{d,u}, h_{\text{BS},d}$ which results in less accurate UE-IoT pairing decisions. In the latter case, we assume that $|h_{d,u}|, |h_{\text{BS},d}|$, and $|h_{\text{BS},u}|$ are equal to 1 and we only depend on the estimates of large scale channel coefficients $\ell_{d,u}, \ell_{\text{BS},d}$, and $\ell_{\text{BS},u}$ to evaluate the SNR expressions in (1), (2), (7), and (8).

In Fig. 2, it can be shown that increasing the transmit power of the BS results in supporting more IoT devices because the received SNR of the backscattered signals from the IoT devices at the UE relays becomes higher. Hence, there is a higher chance of pairing the IoT devices with UE relays to improve the system connection density. The suboptimal algorithm has a very close performance to the optimal algorithm, and both outperform the baseline schemes. In addition, we note that our proposed scheme still outperforms the baseline schemes in the absence of CSI.

In Fig. 3, it can be shown that our proposed scheme uses the transmit power of the available UE relays in the network for improving the received SNR at the BS. Hence, more IoT devices can meet the varying minimum SNR requirement compared to the baseline schemes. As the SNR threshold

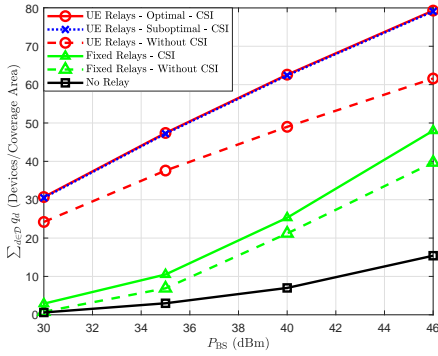


Fig. 2. Connection density versus the BS transmit power P_{BS} ($\gamma_{BS}^{(th)} = \gamma_{UE}^{(th)} = 2$, $|\mathcal{U}| = 30$).

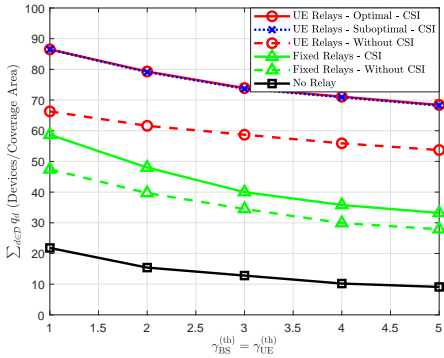


Fig. 3. Connection density versus the SNR decoding threshold $\gamma_{BS}^{(th)}$ ($\gamma_{UE}^{(th)} = \gamma_{BS}^{(th)}$, $P_{BS} = 46$ dBm, $|\mathcal{U}| = 30$).

for decoding increases, a lower number of IoT devices can be supported. We also note that the supported connection density is approximately doubled by using $|\mathcal{U}| = 30$ UE relays compared to having four fixed relays. This large number of UE relays is needed since the SNR of the backscattered signals is low due to the double fading effect (in particular, signal power loss from the BS to the IoT device, and from the IoT device to the relay) [4]. Hence, each IoT device needs to relay data to a nearby relay which makes relay location more effective on the supported connection density than relay count.

Fig. 4 shows the impact of the availability of UE relays as up to 88% of the IoT devices can be served when there are 50 UE relays in the coverage area. The proposed scheme can support more IoT devices than the baseline scheme with a fixed number of relays by up to 65% since UEs can exist in closer proximity to the IoT devices. This facilitates meeting the minimum SNR requirement for decoding the backscattered signals from the IoT devices before relaying them to the BS.

V. CONCLUSION

In this paper, we proposed a scheme for enhancing the connection density of the backscatter communication systems using relaying. In this scheme, the UEs act as relays for the backscattered data by the IoT devices. We formulated a joint UE-IoT device pairing and power allocation problem to maximize the number of IoT devices subject to their minimum SNR requirements. We also proposed low-complexity suboptimal algorithms to solve the problem using bipartite

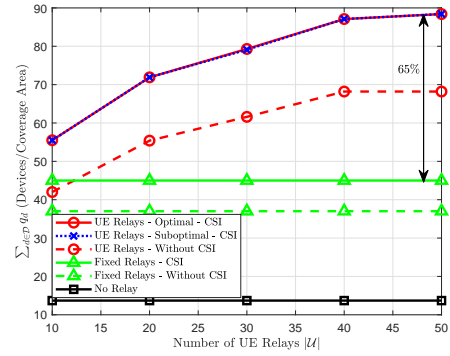


Fig. 4. Connection density versus the number of UE relays $|\mathcal{U}|$ ($P_{BS} = 46$ dBm, $\gamma_{BS}^{(th)} = \gamma_{UE}^{(th)} = 2$).

matching and LP. Simulation results show that the proposed scheme can increase the supported connection density by up to 65% compared to a conventional backscatter system with fixed relays. For future work, we will consider the IoT devices that can operate in both backscattering and active transmission modes according to their battery conditions and enabling each IoT device to use multiple UEs or other IoT devices as relays.

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