Resource Allocation Optimization for Secure Multi-device Wirelessly Powered Backscatter Communication with Artificial Noise

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Abstract—Wirelessly powered backscatter communications (WPBC) is an emerging technology for providing continuous energy and ultra-low power communications. Despite some progress in WPBC systems, resource allocation for multiple devices towards secure backscatter communications (BC) and efficient energy harvesting (EH) requests a deep-insight investigation. In this paper, we consider a WPBC system in which a full-duplex access point (AP) transmits multi-sinewave signals to power backscatter devices (BDs) and injects artificial noise (AN) to secure their backscatter transmissions. To maximize the minimum harvested energy and ensure fairness and security of all BDs, we formulate an optimization problem by jointly considering the backscatter time, power splitting ratio between multi-sinewave and AN, and signal power allocation. For a single-BD system, we characterize the achievable secrecy rate-energy region with a non-linear energy harvester and propose two algorithms to solve an energy maximization problem. We then analyze the effect of multi-sinewave and AN signals on BD’s secrecy rate and harvested energy through simulations and proof-of-concept experiments. For a multi-BD system, we propose an iterative algorithm by leveraging block successive upper-bound minimization (BSUM) techniques to solve the non-convex problem of fair resource allocation and show its convergence and complexity. Numerical results show the proposed algorithm achieves optimal and equitable harvested energy for all BDs with satisfying the security constraint.

Index Terms—Physical Layer Security, Wirelessly Powered Backscatter Communications (WPBC), Nonlinear Energy Harvesting, Resource Allocation.

I. INTRODUCTION

Green and sustainable communication technology has drawn a huge amount of attention from both industry and academia, such as simultaneous wireless information and power transfer (SWIPT) [1], [2] and backscatter communications [3]. SWIPT makes use of radio waves for the joint purpose of wireless information transfer (WIT) and wireless power transfer (WPT) [4]. It is a promising technology to prolong the lifetime of Internet of Things (IoT) devices by allowing them to continuously harvest energy from radio frequency (RF) signals. Compared to magnetic induction and resonant coupling with a short distance of up to one meter [5], RF-based power transfer can support a longer distance up to several meters, which is more suitable for IoT applications. Backscatter communication can be viewed as a significant supplement communication technology for IoT devices due to its ultra-low power consumption [3]. It enables IoT backscatter devices (BDs) to transmit data by reflecting and modulating incident RF signals without any costly and power-hungry RF transmitters [3]. By seamlessly synthesizing SWIPT and backscatter communication, wirelessly powered backscatter communication (WPBC) was proposed to transmit unmodulated/modulated signals to power small devices, which can harvest energy from the RF signals and backscatter signals to a receiver for information transmission [6].

Due to the capability of supporting continuous energy supply and ultra-low-power communications, WPBC can be widely applied into various IoT systems with resource-limited devices. However, in WPBC systems, the broadcast nature of backscatter communication makes it easy for illegal devices to intercept information contents, which could lead to data interception and privacy leakage. Since BDs possess limited computation and energy resources, it could be problematic and undesirable for them to directly apply complex cryptography approaches for securing backscatter communications [7]. The deployment of BDs is potentially in large numbers, which also brings serious difficulty to distribute and manage secret keys. The literature still lacks lightweight schemes for secure backscatter communications against eavesdropping. This will seriously hinder widespread applications of backscatter communications and their integration into WPBC systems.

To address the security issues of backscatter communications, physical layer security has been proposed as an important complement and replacement to the cryptographic approaches [8]. It brings information-theoretic security and low complexity to secure backscatter communication for resource-limited BDs. Thus, the RF signals of an access point (AP) can be designed to secure backscatter communications in the WPBC system by utilizing physical layer security techniques, such as beamforming and artificial noise (AN) injection [9]. In [10], [11], the signal waveform of the AP, i.e., multi-sine, has been optimized to improve the harvested energy at the BD in WPT systems. In [12], [13], the signal waveform has been studied to consider the trade-off between energy
harvesting and backscatter rate in WPBC systems. But these works have not yet considered the security of backscatter communications, which is a key issue in WPBC systems. On the other hand, an AN injection strategy was proposed to improve the secrecy capacity of backscatter transmission in a point-to-point WPBC system [14], [15]. However, injecting AN into carrier signals could worsen the energy harvesting efficiency of BDs because of their non-linear model of energy harvesting [4]. This negative effect has been demonstrated in our previous work with real experiments [16]. As a result, the signal waveform, including AN and multi-sine, should be further investigated regarding its impact on energy harvesting and backscatter communication security of BDs.

Besides, in a multi-BD WPBC system, it is important to improve system performance by optimally allocating system resources, while realizing backscatter security with AN injection. Clerckx et al [17] discussed a multi-sine waveform to maximize the total harvested energy of BDs with a backscatter transmission constraint. It is suitable for high signal-noise-ratio (SNR) scenarios, by assuming a system model where all BDs backscatter information to an AP simultaneously. But in low SNR scenarios, it significantly increases the complexity of signal processing at the AP, and even induces the degradation of data reception. As the results are shown in [12], [18], the performance of power-splitting is inferior to time-sharing architecture in a low SNR regime (< 30dB). By assuming that BDs perform backscattering in a time-division manner, some researchers analyzed the performance of backscatter transmission by allocating time, signal power and reflection ratio of each BD [19], [20]. The reflection ratios of BDs cannot yet be changed in practice, since they are fixed when the BDs are deployed. Besides, due to significant signal attenuation, a BD far from the AP harvests lower energy and only supports a lower backscatter rate than a BD near the AP. The coupled effect is referred to as the doubly near-far problem [1], which could result in very low secrecy throughput and harvested energy for far BDs, if the multiple access scheme is not properly designed with signal allocation. Thus, to the best of our knowledge, none of the existing works considered the security of backscatter transmission while realizing resource allocation optimization. It remains a serious challenge in multi-BD WPBC systems to optimize resource allocation for satisfying both backscatter security and energy requirements of all BDs.

In this paper, we consider a WPBC system with multiple BDs and a full-duplex AP for simultaneous signal transmission and reception. Especially compared with the system model in [17], we assume all BDs alternately perform backscatter transmission in a time-division access manner. In such a multi-BD WPBC system, we propose to inject AN signal into the multi-sine signal to improve the secrecy capacity of backscatter and analyze its impact on a non-linear energy harvester. In addition, we investigate the optimization of system resource allocation in a multi-BD WPBC system, in order to achieve sufficient secrecy throughput and harvested energy. To avoid a doubly near-far problem, we aim to maximize the minimum harvested energy of all BDs, by jointly optimizing backscatter time, signal power allocation and power splitting ratio between multi-sine and AN, subject to the security throughput of backscattering.

Specifically, the main contributions of this paper are summarized as follows:

- We are the first to propose AN signal injection into the carrier signal to improve the security of backscatter communications in WPBC systems. Based on the non-linear rectenna model in [12], we model the achievable secrecy backscatter rate and the non-linear energy harvester with the injected AN and multi-sine signal. In contrast to the work in [12] that only refers to the multi-sine waveform for power transfer and backscatter communication, we inject AN signal into the multi-sine signal to gain sufficient enough backscatter security and investigate its effect on energy harvesting.
- For a single-BD, we characterize the achievable secrecy rate-energy region and formulate an optimization problem to analyze the trade-off between the achievable secrecy rate and harvested energy. Compared to optimization in [2], [12], the power of AN is a key variable in our paper that brings non-convex constraints, i.e., upper bounding a ratio between two posynomials. Thus, we apply the single condensation method [21] with successive convex approximation (SCA) [22] to solve the non-convex posynomial problem, and propose a simplified suboptimal algorithm with low complexity based on the uniform power allocation of multi-sine in [4].
- For multi-BDs, we formulate an optimization problem to maximize the minimum harvested energy by jointly considering resource allocation together with the secrecy throughput requirement. In comparison with the waveform in [17] designed only for backscatter communication and energy harvesting, we consider the security of backscatter transmission while realizing resource allocation optimization for multiple BDs in a time-division manner. An iteration algorithm by leveraging block coordinate descent (BCD) and SCA optimization is proposed to jointly optimize backscatter time, signal power allocation and power splitting ratio between multi-sine and AN. Then, We prove the convergence of this algorithm and analyze its complexity.
- We conduct extensive simulations to analyze the performance of WPBC systems. Firstly, we conduct simulations to show the trade-off between backscatter secrecy and harvested energy with different numbers of multisine wave and the different power of AN in the single-BD case. And we evaluate the impact of AN power on harvested energy and backscatter secrecy with a proof-of-concept experimental WPBC system. Secondly, in the multi-BD case, numerical results show that the fair performance of the harvested energy and secrecy throughput can be achieved with our resource optimization, as compared to equal resource allocation.

The rest of the paper is organized as follows. We introduce related work in Section II. A system model is given in III about the secrecy rate of backscatter communications and the non-linear energy harvester. Section IV characterizes the
achieved secrecy rate-energy region of one BD and presents two algorithms to solve the energy maximization problem. Section V presents the max-min optimization problem and proposes the iterative algorithm to solve it. In Section VI, the simulation and proof-of-concept experimental results are reported. Finally, Section VII concludes the whole paper.

Notations: Bold letters stand for vectors or matrices whereas a symbol not in a bold font represents a scalar. $|.|$ and $||.||$ refer to the absolute value of scalar and the 2-norm of a vector. $\Re$ refers to the real number of signals.

II. RELATED WORK

One of the key challenges of SWIPT systems is the optimal signal waveform or beamforming design of downlink signals to maximize the SNR-energy region. The non-linearity of the energy harvester was mostly exploited to design the signal waveforms, such as multi-sine and chaotic signal [2], [4], [12]. Besides, secure signal waveforms were designed based on the channel information to enhance the secrecy capacity of downlink transmission in SWIPT systems [23], [24]. For instance, energy beamforming and/or AN can be utilized to jam eavesdroppers to achieve backscatter secrecy [25], [26]. On the other hand, since backscatter communication does not require active RF components, it has received renewed interest with the advances in communication theory including coding [3], beamforming [27]. It can be integrated into the SWIPT systems as WPBC for uplink transmission with ultra-low power consumption. For securing backscatter communication, Hou et al. [28] and Hassanieh et al. [29] both randomized backscatter channels via a designed modulation to reduce the possibility of being eavesdropped. Besides, the authors of [14], [15] proposed a noise-injection precoding strategy to improve the secrecy capacity of a backscatter channel for securing backscatter communications, but limited to point-to-point communications.

For the WPBC systems, existing works mainly focus on studying how to make a trade-off between energy harvesting and backscatter communication. For instance, Clerckx et al. [12], [17] presented how to design multi-sine wave signals that affect the harvested energy and backscatter transmission in both single-BD and multi-BD scenarios. Beamforming with multi-antenna was designed to maximize total harvested energy with backscatter rate constraints [30]. Besides, Xiao et al [31] studied resource allocation for cognitive backscatter networks by formulating an optimization problem to maximize the backscatter throughput. These works mainly focused on improving the performance of the energy harvesting and backscattering by analyzing the waveform of the downlink signals from the AP and solving an optimization problem. However, these works do not consider any security issues of backscatter communications and the effect of injecting AN into downlink signals on a non-linear energy harvester. Compared to the system model applied in [17], where BDs backscatter at the same time, Yang et al. [20] applied a system model where BDs backscatter RF signals in a time-division manner. And they investigated ambient backscatter communication and its performance regarding backscatter time and reflection ratio of BDs. Lu et al. [32] also modeled the wireless-powered ambient D2D communication to discuss the performance regarding time allocation and reflection ratio. But the reflection ratio cannot be changed in practice, since it is fixed when a BD is deployed. In particular, backscatter communication security has not yet been explored in the prior arts with resource optimization taken into consideration at the same time. Obviously, backscatter communication security is crucially important to support its future wide applications. Our work is the first study to secure multi-device wirelessly powered backscatter communication with artificial noise injection and resource optimization.

Different from conference version: Preliminary results of this paper have been published in a previous conference version [16] (IEEE INFOCOM). Compared with the conference version, we adopted a non-linear energy harvester (EH) in this paper, which is much closer to the energy harvesting behaviors in practice, instead of the linear model by assuming a constant RF-to-Direct Current (DC) conversion coefficient. With the non-linear EH model, the effect of AN injection in multi-sine is analyzed with a geometric program problem in this paper. Besides, the factors that impact the performance of multi-BD WPBC systems are comprehensively investigated, including the number of multi-sinewave and the injected AN power.

III. SYSTEM MODEL

In this section, we first introduce the system model for multi-user WPBC systems, and then present the mathematical model of non-linear energy harvester and the achievable secrecy rate of backscatter communication.

A. System Description

In this section, we provide a system model for the multi-BD WPBC system as shown in Fig. 1. It consists of a full-duplex AP with two antennas, and $K (K \geq 1)$ legitimate BDs with a single antenna. The AP continuously transmits RF signals to power the legitimate BDs and receives backscatter signals from BDs at the same time. It can perfectly separate its received signals from the transmitted signals without any leakage. The assumption of perfect signal separation is commonly used in many existing literature of backscatter communication systems [33]. As the transmitted signal deviates from the carrier signal, the difficulty of signal separation at the AP increases. But it can still be solved with an advanced transceiver that can keep the signal leakage at a minimal level [14], [33]. Each BD contains a backscatter antenna, a switched load impedance, an information receiver, an energy harvester, and other modules (e.g., micro-controller, battery, and sensors). It converts the incoming RF signal into direct current (DC) power with the energy harvester and transfers information to the AP through backscattering modulation. Here, as typically considered in a backscatter system, we assume that the BDs are semi-passive devices that can store the harvested energy in a battery for circuit operations.

We are only interested in uplink backscatter transmission in which each BD transmits its data over the incident RF signals.
With multiple BDs in the WPBC system, we adopt a frame-based protocol to schedule the backscatter transmission of all BDs. The time duration of each frame is given as $T$ seconds, each of which consists of $K$ slots for all BDs in a time-division manner. Each BD is allocated with a time duration $T_k$, and can only perform backscattering during its allocation duration to avoid interference. Besides, when BDs backscatter information to the AP, we assume there is an illegal eavesdropper Eve that intercepts the backscatter transmission because of its open and broadcast feature. But Eve is passive and does not actively interfere with the backscatter communication in order to avoid being discovered.

We define the forward channel from the AP to the $k$-th BD as $h_k$ and the backward channel from the $k$-th BD to the AP as $h_r,k$, respectively. We assume that each BD backscatters the incident RF signals to the AP, so that the AP can obtain the perfect knowledge of the forward channel and the backward channel, i.e., channel gains. Let $h_{k,e}$ and $h_e$ denote the channel from the $k$-th BD to Eve and the channel from the AP to Eve, respectively. All channels in the multi-BD WPBC system are modeled as frequency-flat and quasi-static, which means the channel gains remain constant over a period of a frame.

### B. Transmit Signal

To secure the transmission, the AP injects AN signal into the carrier signals to improve the secrecy capacity of the backscatter channel. The AN is statistically identical to the additive white Gaussian noise (AWGN). Thus, the transmitted signals of AP to the $k$-th BD can be expressed as $w_k = s_k + z_k$, where $s_k$ and $z_k$ indicate the dedicated carrier signal and the AN, respectively. The dedicated carrier $s_k$ is designed as a multisine signal (with $N$ sinewaves) to facilitate energy harvesting with the non-linear model at BDs [2], [4]. The transmitted signals for the $k$-th BD by the AP is
\[
  w_k(t) = \sum_{n=0}^{N-1} s_{k,n} \cos(2\pi f_n t + \phi_{k,n}) + z_k(t)
\]

\[
  = \Re\{ \sum_{n=0}^{N-1} x_{k,n} e^{j2\pi f_n t} \} + z_k(t)
\]

with $x_{k,n} = s_{k,n} e^{j\phi_{k,n}}$ where $s_{k,n}$ and $\phi_{k,n}$ refer the amplitude and phase of the $n$-th sinewave at frequency $f_n$ for the $k$-th BD, respectively. We assume for simplicity that the frequencies are evenly spaced, i.e., $f_n = f_0 + n\Delta f$ with the frequency space $\Delta f$. The magnitudes and phases of the sinewaves can be collected into vectors $s_k$ and $\phi_k$. The $n$-th entry of $s_k$ and $\phi_k$ are written as $s_{k,n}$ and $\phi_{k,n}$, respectively. The transmitted signals are subject to a transmit power constraint $E\{|w_k|^2\} = \frac{1}{2}|s_k|^2 + \frac{1}{2}|z_k|^2 = P_{k,s} + P_{n,k} \leq P_k$, where $P_k$ is the allocated power for the $k$-th BD.

After downlink propagation with the slow frequency-flat fading channel with the same amplitude and phase for all sinewaves (i.e., $(N-1)\Delta f$ much smaller than the channel bandwidth), the received signal at the $k$-th BD with a single antenna can be written as
\[
y_k(t) = \Re\{ h_k \sum_{n=0}^{N-1} x_{k,n} e^{j2\pi f_n t} + z_k(t) \} + n_k(t)
\]

\[
  = |h_k| \left[ \sum_{n=0}^{N-1} s_{k,n} \cos(2\pi f_n t + \psi_{k,n}) + z_k(t) \right] + n_k(t)
\]

(2)

where $h_k = |h_k| e^{j\psi_k}$ is the frequency response of the channel between the AP and the $k$-th BD, $\psi_{k,n} = \phi_{k,n} + \psi_k$, $n_k(t)$ is AWGN. We ignore the noise $n_k(t)$ at BDs for simplicity in the remainder of the paper, because its power is much smaller than the power of carrier signal $w_k(t)$, including either the power of the multisine signal or the power of the AN. Besides, when the receivers, AP or Eve, receive the backscattered noise $n_k(t)$ from the BD, it has experienced two-way channel attenuation making it negligible for the receivers. Thus, it has a negligible effect on the harvested energy and backscattered communication.

### C. Backscatter Signal

We consider that each BD employs a simple block binary modulation to backscatter information to AP as in [12]. Binary 0 refers to a perfect impedance mismatch that completely absorbs the incoming signal, i.e., the reflection coefficient is 0. Binary 1 refers to a perfect impedance mismatch that completely reflects the incoming signal, i.e., the coefficient is 1. The signal absorbed during binary 0 is conveyed to the rectifier for energy harvesting, while the signal reflected during binary 1 operation is backscattered to the AP for data transmission. Thus, BDs will harvest almost half the whole duration of operations when they are performing backscatter communication, since each information 0 and 1 will hold half of the time with enough long number of the bit sequences. When BDs are backscattering, the AP performs information detection of bit 0 and 1 from the incoming backscattered signal. With the received signal, we model the SNR for information detection at the AP and Eve, respectively and then formulate the achievable secrecy rate.

The received signal at the AP is given as
\[
y_{r,k}(t) = m_k \Re\{ h_{r,k} h_k \left[ \sum_{n=0}^{N-1} x_{k,n} e^{j2\pi f_n t} + z_k(t) \right] \} + n_r(t)
\]

(3)
where \( n_r \) is the AWGN at frequency component \( f_n \), whose period is much longer than that of multisine signal \( s_k \) for arbitrary \( k \).

After applying a product detector to each frequency and assuming ideal low pass filtering, the baseband signal of \( k \)-th BD on each frequency \( f_n \) is given by

\[
y_{r,k,n} = m_k h_{r,k} x_{r,k,n} + n_r.
\]

where \( m_k \) is the binary information for \( k \)-th BD, and \( m_k \) is the frequency response of the backscatter channel between \( k \)-th BD and AP.

For more details about the rectenna model, the interested readers can refer to the description in [2], [4].

In our energy harvester, we will assume the same rectenna model as in [2], [4]. The rectenna is made of an antenna and rectifier. The received power is transferred from the antenna to the rectifier through a matching network. Following [2], the maximization of the harvested energy, namely \( i_{out} \), is equivalent to maximizing the DC current approximation as

\[
z_{DC,k} = A_2 R_{ant} \mathcal{E} \{ y_k(t)^2 \} + A_4 R_{ant}^2 \mathcal{E} \{ y_k(t)^4 \}
\]

where \( A_u = \frac{u(t_{av})}{i_{max}} \), \( u \) is the reverse bias saturation current, \( t_{av} \) is the thermal voltage and \( \alpha \) is the ideality factor. For more details about the rectenna model, the interested readers can refer to the description in [2], [4].

Applying (2), and using the fact that \( \mathcal{E} \{ s_k(t) z_k(t) \} = 0 \), \( \mathcal{E} \{ s_k(t)^3 z_k(t) \} = 0 \), \( \mathcal{E} \{ s_k(t)^2 z_k(t)^2 \} = \mathcal{E} \{ s_k(t)^2 \} \mathcal{E} \{ z_k(t)^2 \} \), we can obtain

\[
\mathcal{E} \{ y_k(t)^2 \} = |h_k|^2 \left( \mathcal{E} \{ s_k(t)^2 \} + \mathcal{E} \{ z_k(t)^2 \} \right).
\]

\[
\mathcal{E} \{ y_k(t)^4 \} = |h_k|^4 \left( \mathcal{E} \{ s_k(t)^4 \} + \mathcal{E} \{ z_k(t)^4 \} \right)
+ 6 |h_k|^4 \mathcal{E} \{ s_k(t)^2 \} \mathcal{E} \{ z_k(t)^2 \}.
\]

Besides, due to the characteristic of the frequency flat channel, it is clear that choosing \( \varphi_k = \psi_k/2 \) is optimal for any frequency \( f_n \) [4], thus not considering the phase of the sine wave in the sequel. Recalling the power expression \( \frac{1}{2} |s_k|^2 = \frac{1}{2} \sum_{n=0}^{N-1} |s_{k,n}|^2 = P_{s,k} \) and \( |z_k|^2 = P_{z,k} \), we can then write the expression of \( z_{DC,k} \) as

\[
z_{DC,k} = 2 A_2 R_{ant} |h_k|^2 (P_{s,k} + P_{z,k})
+ A_4 R_{ant}^2 |h_k|^4 \left( \frac{3}{8} F_k + 4 P_{z,k}^2 + 24 P_{s,k} P_{z,k} \right).
\]
where
\[ F_k = \sum_{n_0, n_1, n_2, n_3} s_{k, n_0} s_{k, n_1} s_{k, n_2} s_{k, n_3}. \] (13)

In the sequel, (12) is called the nonlinear model of the energy harvester over the received signal consisting of the multisine signal and AN. The linear model of the energy harvester, which is utilized in our conference version [16] (IEEE INFOCOM), is obtained as a special case by ignoring the second term on the right-hand side (r.h.s) of (12). Under the linear model, since \( A_2 R_{ant} \) is a constant independent of the input signal power and shape, it has been used extensively through the WPBC and SWIPT literature [1], [20], [36], [37]. For the non-linear model, finding the best transmit strategy so as to maximize the \( z_{DC,k} \), subject to an AP transmit power constraint, does not lead to the same solution as the one with the linear model. This non-linear model accounts for the dependency of the RF-to-DC conversion efficiency of the rectifier on the input signal (power of the multisine signals and the AN).

**E. CSI Assumption**

We assume that the AP has a perfect knowledge of CSI of the two-way channel \((h_{r,k} h_k, \forall k)\). The two-way channel can be estimated with a pilot signal delivered by the AP. And in the presence of channel reciprocity, \( h_k = h_{r,k} \), the AP can also easily obtain the forward channel \( h_k \) and backward channel \( h_{r,k} \). This process of channel estimation has been performed in WPBC systems to improve communication performance. Thus, the AP can directly utilize it for AN injection and resource allocation without consuming extra energy. If not, the AP can apply pilot signals at the beginning of each frame to measure the two-way channel information. The process will not introduce lots of energy consumption at the AP and especially at BDs, while it only requires a backscatter action at BDs within a number of frame periods.

Besides, we also assume that the AP can obtain the full CSI of the eavesdropper in the following scenarios, i) the eavesdropper is active so that the AP can monitor its behavior and obtain its CSI, ii) even a passive eavesdropper’s CIS can be obtained through its local oscillator power leaked from the received RF front end of RF receiver using the methods specified in [38], [39]. This assumption is widely adopted in the physical-layer security literature (see [40], [41]). If the AP cannot get the whole CSI of eavesdroppers, it can still obtain the partial CSI through statistics, i.e., CSI distribution. Though, measuring the CSI of Eve consumes extra energy at the AP, it does not impact the energy consumption of the BDs. It is worth noting that this paper focuses on secure backscatter communication and resource allocation. The problem of accurate channel estimation and its influence on the optimization problem will be further studied in the future.

**IV. JOINT RESOURCE ALLOCATION IN A SINGLE-DEVICE WPBC SYSTEM**

In this section, we consider a special case which there is only one BD in the WPBC system, i.e., \( K = 1 \), then formulate the achievable secrecy rate-energy region and discuss the effects of power allocation of the multi-sinewave and AN.

**A. Problem Formulation**

For brevity, the subscript \( k = 1 \) is omitted in this section. With the achievable secrecy rate and the harvested energy as described above, the resource allocation for backscatter communication, mainly consisting of power allocation of each sinewave and AN, is subject to a tradeoff between maximizing achievable secrecy rate at the AP and maximizing the harvested energy at BDs. Characterizing this secrecy rate-energy tradeoff and the corresponding power allocation is the objective of this section.

We can now define the achievable secrecy rate-energy region as
\[ C_{SC-1DC}(s, z) \triangleq \{(C_{th}, I_{DC}) : C_{th} \leq C^s(s, z), I_{DC} \leq z_{DC}(s, z), \frac{1}{2}\|s\|^2 + \frac{1}{2}\|z\|^2 \leq \bar{P} \}, \] (14)
where \( C_{th}, I_{DC} \) and \( \bar{P} \) are the constraints of the secrecy capacity, harvested energy and AP’s transmission power. Optimal value \( s^* \) and \( z^* \) are to be found in order to enlarge the region \( C_{SC-1DC} \). And \( C^s(s, z) \) and \( z_{DC}(s, z) \) are as following,
\[ C^s(s, z) = \log(1 + \frac{|h_{r,k}|^2 |h|^2 \|s\|^2}{\kappa |h_{r,k}|^2 |h|^2 \|z\|^2 + \sigma_e^2}) - \log(1 + \frac{|h_{r,k}|^2 |h|^2 \|s\|^2}{|h_{r,k}|^2 |h|^2 |z|^2 + \sigma_e^2}), \] (15)
\[ z_{DC}(s, z) = A_2 R_{ant} |h|^2 (\|s\|^2 + |z|^2) + A_4 R_{ant}^2 |h|^4 \sum_{n_0, n_1, n_2, n_3} \frac{3}{8} s_{n_0} s_{n_1} s_{n_2} s_{n_3} \] (16)

In order to identify the achievable secrecy rate-energy region, we formulate an optimization problem as an energy maximization problem subject to the transmission power and secrecy rate constraints
\[ \max_{s, z} z_{DC}(s, z) \] (17a)
\[ \text{s.t.} \quad C^s(s, z) \geq C_{th}, \] (17b)
\[ \frac{1}{2}\|s\|^2 + \frac{1}{2}\|z\|^2 \leq \bar{P}. \] (17c)

**B. Optimal injected AN with multi-sine**

From [21], [22], a function \( f : \mathbb{R}^n \to \mathbb{R} \) with \( \text{dom} f = \mathbb{R}^{n+1}_+ \), defined as \( f(x) = cx_{a_1}^{x_{a_2}} \cdots x_{a_n}^{x_{a_n}}, \) where \( c > 0 \) and \( a_i \in \mathbb{R} \), is called a monomial function. A sum of monomials is called a posynomial function and can be written as \( f(x) = \sum_{k=1}^K c_k x_{1}^{a_{1,k}} x_{2}^{a_{2,k}} \cdots x_{n}^{a_{n,k}}, \) where \( c_k > 0 \). As we can see from (16), \( z_{DC}(s, z) \) is a posynomial. Thus, it maximizes a posynomial subject to the transmission power and secrecy rate constraints. Unfortunately, the optimization problem is not a standard Geometric Program (GP). Thus,
we first transform problem (17) to an equivalent problem by introducing an auxiliary variable \( t_0 \)

\[
\begin{align*}
\min_{s, z, t_0} & \quad 1/t_0 \\
\text{s.t.} & \quad f(s, z) / g(s, z) \leq 1 / 2^{C_{th}}, \\
& \quad t_0 / z_{DC}(s, z) \leq 1, \\
& \quad 1 / 2 ||s||^2 + 1 / 2 ||z||^2 \leq \bar{P}.
\end{align*}
\]  

(18a)\hspace{1cm}(18b)\hspace{1cm}(18c)\hspace{1cm}(18d)

where

\[
f(s, z) = \left( 1 / 2 \kappa |h_r|^2 |h_1|^2 ||s||^2 + \sigma_s^2 \right) \\
\times \left[ 1 / 2 |h_c|^2 |h_1|^2 |s|^2 + 1 / 2 |h_c|^2 |h_1|^2 ||s||^2 + \sigma_s^2 \right],
\]

(19)

and

\[
g(s, z) = \left( 1 / 2 |h_c|^2 |h_1|^2 ||s||^2 \right) \\
\times \left[ 1 / 2 |h_r|^2 |h_1|^2 ||s||^2 + 1 / 2 \kappa |h_r|^2 |h_1|^2 ||s||^2 + \sigma_s^2 \right].
\]

(20)

Note that the secrecy rate constraint (17b) is converted into upper bounding a ratio between two posynomials as the inequality (18b), which is affected by the power of AN and the multi-sine. And the original objective function (17a) is transformed to the constraint (18c), a ratio between a monomial to a posynomial. Both the objective and constraint functions are associated with posynomials. The problem (18) is known as Complementary GP [21], which is an intractable NP-hard problem. However, it can be turned into a standard GP by approximating \( g(s, z) \) and \( z_{DC}(s, z) \) with the arithmetic-geometric mean inequality, respectively. The idea is to obtain the lower bound \( g(s, z) \) and \( z_{DC}(s, z) \), respectively, with a monomial \( \tilde{g}(s, z) \) and \( \tilde{z}_{DC}(s, z) \). As a result, the original problem (17) can be solved with the single condensation method in [21] with SCA.

Let \( g_m(s, z) \) be the monomial terms in the posynomial \( g(s, z) = \sum_{m=1}^{M} g_m(s, z) \). For a given choice of \( \{ \alpha_m \} \) with \( \alpha_m \geq 0 \) and \( \sum_{m=1}^{M} \alpha_m = 1 \), we have \( g(s, z) \geq \prod_{m=1}^{M} \left( g_m(s, z) \right)^{\alpha_m} = \tilde{g}(s, z) \) due to the arithmetic-geometric mean inequality. Similarly, we can obtain \( z_{DC}(s, z) \geq \prod_{m=1}^{M'} \left( z_{DC}(s, z) \right)^{\beta_{m'}} = \tilde{z}_{DC}(s, z) \) with \( \beta_{m'} \geq 0 \) and \( \sum_{m'=1}^{M'} \beta_{m'} = 1 \), where \( \rho_{m'}(s, z) \), \( \forall m' \) are the monomial terms of \( z_{DC}(s, z) \). Therefore, we perform the single condensation method [21] on the denominators of both constraints and write a standard GP by replacing (18b) and (18c)

\[
\begin{align*}
\min_{s, z, t_0} & \quad 1/t_0 \\
\text{s.t.} & \quad f(s, z) \prod_{m=1}^{M} \left( g_m(s, z) / \alpha_m \right) \leq 1 / 2^{C_{th}}, \\
& \quad t_0 \prod_{m'=1}^{M'} \left( z_{DC}(s, z) / \beta_{m'} \right) \leq 1, \\
& \quad 1 / 2 ||s||^2 + 1 / 2 ||z||^2 \leq \bar{P}.
\end{align*}
\]  

(21a)\hspace{1cm}(21b)\hspace{1cm}(21c)\hspace{1cm}(21d)

It is important to note that the choice of \( \{ \alpha_m, \beta_{m'} \} \) plays a great impact on the tightness of the arithmetic-geometric mean inequality. An iterative procedure can be used to tighten the bound, while the standard GP (21) is solved with an updated set \( \{ \alpha_m, \beta_{m'} \} \) at each iteration. Assuming a feasible solution \( (s(i-1), z(i-1)) \) at iteration \( i - 1 \), we can compute a new value \( \alpha_m(i-1) = g_m(s(i-1), z(i-1)) / g(s(i-1), z(i-1)) \), \( \forall m \) and \( \beta_m(i-1) = \rho_{m'}(s(i-1), z(i-1)) / z_{DC}(s(i-1), z(i-1)), \forall m' \). Then, we solve the problem (21) to obtain new solution \((s, z)\). We summarize the whole procedure in Algorithm 1, in which this approximation technique is also known as a successive convex approximation (SCA). The solutions of this iterative approximating converge to a point satisfying the Karush-Kuhn-Tucker (KKT) conditions of original problem [42], and has been shown by simulation that such an iterative algorithm often is convergent [21].

C. Simplified Algorithm

From the optimization problem (17) with the frequency-flat channel model, we found that secrecy rate is affected by the power of the multi-sine and AN, instead of the waveform \((s, z)\), which only affects \( F \) in \( z_{DC}(s, z) \). And the optimal value \( s^* \) and \( z^* \) always satisfy \( ||s^*||^2 + ||z^*||^2 = 2 \bar{P} \).

Based on these characteristics, we propose another suboptimal algorithm to reduce complexity in this subsection. We defined \( \frac{1}{2} ||s||^2 = P_s = \rho \bar{P} \) and \( \frac{1}{2} ||z||^2 = P_z = (1 - \rho) \bar{P} \) by introducing an auxiliary variable \( \rho \) as the power splitting ratio between the multi-sine wave and AN. The low bound of \( F \) can be obtained as

\[
F \geq \sum_{n=0}^{N-1} s_n^4 + \sum_{n_0 \leq n_1} s_{n_0}^2 s_{n_1}^2 = 4P_s^2 + 2 \sum_{n_0 \leq n_1} s_{n_0}^2 s_{n_1}^2 .
\]

(22)

Subject to the power constraint of the multi-sine wave, the lower bound is maximized by allocating power uniformly across sinewaves [4], i.e., \( s_n = \sqrt{2P_s / \sqrt{N}} \). We will denote the uniform power (UP) waveform strategy as UP characterized by \( s = \sqrt{2P_s / \sqrt{N}} \). UP is optimal for \( N = 2 \) for which the inequality is replaced by an equality, and suboptimal for \( N \geq 2 \), for which UP almost reaches the optimum obtained with Algorithm 1, as also confirmed in simulation.

The value of \( z_{DC}(s, z) \) with the UP strategy, simply denoted as \( z_{DC, UP}(s, z) \), can be thought of as a lower bound of optimum \( z_{DC}(s^*, z^*) \) with optimal waveform in our frequency-
flat channel model. Thus, with \( s = \sqrt{2P_s}/\sqrt{N} \), we can obtain,
\[
z_{DC,UP}(\rho) = 2A_2R_{ant}|h|^2\rho + A_4R_{ant}^2|h|^4\left(\frac{2N^2 - 40N + 1}{2N}\rho^2 + 16\rho + 4\right)^2P^2, \quad (23)
\]
since that there are \( N(2N^2 + 1)/3 \) terms in the sum of (13).

With UP strategy of multi-sinewaves and the determined transmission power \( \bar{P} \), we can transform the optimization problem (17) as
\[
\begin{align*}
\max_{\rho} & \quad z_{DC,UP}(\rho) \quad (24a) \\
\text{s.t.} & \quad C_k^s(\rho) \geq C_{th}, \quad (24b) \\
& \quad 0 \leq \rho \leq 1, \quad (24c)
\end{align*}
\]

The objective function in (24) is a convex function, and all constraints only limit the interval of \( \rho \), so the optimum \( z_{DC}(\rho^*) \) can be easily obtained at the optimal value \( \rho^* \) [21]. And, the suboptimal waveform is \( z^* = \sqrt{2(1-\rho^*)}\bar{P} \) and \( s^* = \sqrt{2P^2}/\sqrt{N} \). Thus, we can obtain a suboptimal solution for the problem (17) with much lower complexity.

V. JOINT RESOURCE ALLOCATION IN A MULTIPLE-BD WPBC SYSTEM

In this section, we consider multiple BDs and formulate an optimization problem to analyze joint resource allocation in multi-BD WPBC systems.

A. Problem Formulation

The WPBC system with multiple BDs operates in a frame-based protocol as shown in Fig. 1. The frame duration \( T \) (seconds), each of which consists of \( K \) slots, is within the channel block length of our frequency-flat and quasi-static model. In each slot, the AP simultaneously transmits downlink RF signals to all BDs and receives uplink backscattered signals from all BDs in a time-division manner. The \( k \)-th slot with duration \( \tau_k T \) (with proportion \( \tau_k \) \( 0 \leq \tau_k \leq 1 \)) is assigned to the \( k \)-th BD for backscatter communication, and \( \tau = [\tau_1, \tau_1, \ldots, \tau_K] \) denotes time allocation vector for all BDs. In the \( k \)-th slot, the signal power allocated to the \( k \)-th BD is denoted by \( P_k \), and \( P = [P_1, P_2, \ldots, P_K] \) denotes the power allocation vector for all BDs. For the \( k \)-th BD, the allocated power \( P_k \) will be split to multi-sinewave \( s_k \) and AN \( z_k \).

The time and power vector need to be appropriately allocated to satisfy the security throughput and energy harvest requirement of each BD by jointly considering waveform designing (consisting of \( s_k \) and \( z_k \)). We assume that BDs will harvest almost half of the incident RF signal power while backscattering in their own slot \( \tau_k \) presented at the Section III-C, and harvest all power of incident wireless signals in other slots. Thus, the total energy harvested by the \( k \)-th BD during all slots is
\[
z_{total,k}(\tau, P, S, z) = \frac{1}{2}\tau_k z_{DC,k}(s_k, z_k) + \sum_{i=1,i\neq k}^{K} \tau_i z_{DC,i}(s_i, z_i), \quad (25)
\]
where \( S = [s_1, s_2, \ldots, s_K] \) and \( z = [z_1, z_2, \ldots, z_K] \). The total energy harvested by all BDs in WPBC systems is \( z_{total} = \sum_{k=1}^{K} z_{total,k} \).

Besides, from the achievable secrecy rate defined in (8), the secrecy throughput of the \( k \)-th BD normalized to the frame duration \( T \) is
\[
R_k(\tau_k, s_k, z_k) = \tau_k C_k^s(\tau_k, s_k, z_k). \quad (26)
\]

Our objective is to optimally allocate resources with the tradeoff between the achievable secrecy throughput and harvested energy for a multi-BD backscatter system. However, it will bring the serious “doubly near-far” problem [36] by only maximizing the total harvested energy \( z_{total} \). That is, because the AP will allocate more resources to closer BDs than the far BDs to maximize \( z_{total} \), thus resulting in unfair performance among different BDs. Therefore, to provide sufficient fairness, we formulate an optimization problem by maximizing the minimum energy harvested by BDs, instead of maximizing \( z_{total} \). Given a normalized secrecy throughput constraint at each BD and the transmission power constraint, the optimization problem is mathematically formulated as follows,
\[
\begin{align*}
\max_{\tau, P, S, z} & \quad \min_{1 \leq k \leq K} z_{total,k}(\tau, P, S, z) \quad (27a) \\
\text{s.t.} & \quad R_k(\tau_k, s_k, z_k) \geq R_{th,k}, \quad \forall k \quad (27b) \\
& \quad 1/2||s_k||^2 + 1/2||z_k||^2 \leq P_k, \quad \forall k \quad (27c) \\
& \quad \sum_{k=1}^{K} \tau_k P_k \leq \bar{P}, \quad (27d) \\
& \quad 0 \leq P_k \leq P_{peak}, \quad \forall k \quad (27e) \\
& \quad \sum_{k=1}^{K} \tau_k \leq 1, \quad (27f) \\
& \quad 0 \leq \tau_k \leq 1, \quad \forall k. \quad (27g)
\end{align*}
\]

where \( R_{th,k} \) indicates the common secrecy throughput constraint for each BD, \( P \) is the AP’s total transmission-power constraint in one frame duration; \( P_{peak} \) is the non-negative and peak-power constraint for each BD; \( P_{peak} \) is the total backscatter time constraint in one frame; \( P_{peak} \) is the non-negative constraint for each backscatter time.

Note that there are some conflicting goals in the above joint optimization problem. On the one hand, from the secrecy capacity point of view, according to Eq. (8), the injected AN at Eve is desired to be as large as possible. However, it reduces the power for the multi-sinewave that will reduce the efficiency of energy harvesting. On the other hand, from the perspective of the resources allocation, by allocating longer backscatter time and more transmission power, the secrecy backscatter throughput of BDs can be largely improved. Hence, a suitable resource allocation policy, including backscatter time \( \tau \), transmission power vector \( P \), signal waveform \( (S, z) \) should be selected with different application scenarios and requirements. But the non-convex problem in Eq.(27) is challenging to solve since the backscatter time vector \( \tau \), transmission power vector \( P \), signal waveform \( (S, z) \) are all coupled in the objective function and the non-convex secrecy throughput constraints.
B. Iterative Algorithm

In general, there is no standard method for optimally and efficiently solving the non-convex optimization problem in Eq. (27). Hence, we propose an iterative algorithm to solve it sub-optimally by applying the block coordinate descent (BCD) method or tools, such as CVX [42].

Functions are all linear. Thus, this problem is linear programming by introducing a slack variable [22], since constraint (28c) can be decomposed into

\[ \max_{\tau} \min_{1 \leq k \leq K} z_{\text{total},k}(\tau, P^j, S^j, z^j) \]  
\[ \text{s.t.} \quad \tau^*_k C_k(s^*_k, z^*_k) \geq R_{\text{th},k}, \quad \forall k \]  
\[ \sum_{k=1}^{K} \tau_k P_k^j \leq \bar{P}, \]  
\[ \sum_{k=1}^{K} \tau_k \leq 1, \]  
\[ 0 \leq \tau_k \leq 1, \quad \forall k. \]  

The problem can be converted to reduced linear programming by introducing a slack variable [22], since constraint functions are all linear. Thus, this problem is linear programming and can be solved efficiently by existing optimization methods or tools, such as CVX [42].

2) Waveform Design: At iteration \( j (j \geq 1) \), given a power vector \( P^j \) and time allocation vector \( \tau^j \), the waveform design \((S^j, z^j)\) can be optimized by solving the following problem

\[ \max_{S, z} \min_{1 \leq k \leq K} z_{\text{total},k}(\tau^j, P^j, S, z) \]  
\[ \text{s.t.} \quad \tau^*_k C_k(s^*_k, z^*_k) \geq R_{\text{th},k}, \quad \forall k \]  
\[ \frac{1}{2}||s_k||^2 + \frac{1}{2}||z_k||^2 \leq P_k^j, \quad \forall k. \]  

With determined \( P_k^j \) in (29c), designing the multi-sinewave and AN signal of each BD will not affect each other. This problem (29) can be decomposed into \( K \) independent subproblems, each of which can be solved with Algorithm 1 to obtain the optimal \( S^* \) and \( z^* \). Besides, we introduce an auxiliary splitting ratio vector \( \rho = [\rho_1, \rho_2, \ldots, \rho_K] \) as introduced in Section IV.

For a given vector \( P^j \) and \( \tau^j \), we can first obtain the optimal ratio vector \( \rho \), so as to obtain the suboptimal multi-sinewave and AN like the simplified algorithm. Nevertheless, the power splitting ratios for all BDs are independent of each other. This is, because the ratio \( \rho_k \) for \( k \)-th BD only affects their own secrecy capacity \( C_k^\rho \) and \( \frac{2K^2-40N+1}{2K^2} \rho_k^2 + 16\rho_k + 4 \) in

Algorithm 1: Overall iterative algorithm for solving problem (27)

1: Initialize \( \beta^0, \rho^0, \tau^0 \). Set \( j = 0 \) and a small threshold constant \( \epsilon > 0 \).
2: repeat
3: \( j \leftarrow j + 1 \).
4: Obtain the optimal solution \( \beta^j \) by solving the problem (28) under given \( \rho^{j-1} \) and \( P^{j-1} \).
5: Obtain the optimal solution \( \rho^j \) by solving the problem (29) under given \( \beta^j \) and \( P^{j-1} \).
6: Obtain the optimal solution \( P^j \) by solving the problem (31) under given \( \beta^j \) and \( \rho^j \).
7: until The fractional increase of the objective value of the original problem (27) is smaller than a threshold \( \epsilon \).
8: Return the optimal solution \( \beta^*, \rho^* \) and \( P^* \).

Therefore, we can solve all subproblems independently with the method applied in the single-device WPBC case. With optimal vector \( \rho^* \), we can sub-optimally obtain \( s^*_k = \sqrt{2\rho_k^* P_k^*/\sqrt{N}1_N} \) and \( z^*_k = \sqrt{2(1-\rho_k^*) P_k^*/\sqrt{N}} \). With each sub-optimal solution of each subproblem, \( s^*_k \) and \( z^*_k \), we can obtain the waveform \( S^* \) and \( z^* \).

3) Power Allocation: At iteration \( j (j \geq 1) \), given a time allocation vector \( \tau^j \) and the power splitting ratio vector \( \rho^j \), the power allocation vector \( P \), which also changes the power of multi-sinewave and AN \( (s_k^j = \sqrt{2\rho_k^* P_k^*/\sqrt{N}1_N} \) and \( z_k^j = \sqrt{2(1-\rho_k^*) P_k^*/\sqrt{N}} \)), can be optimized by solving the following problem

\[ \max_{P} \min_{1 \leq k \leq K} z_{\text{total},k}(\tau^j, P, \rho^j) \]  
\[ \text{s.t.} \quad \tau^*_k C_k^\rho(s^*_k, z^*_k) \geq R_{\text{th},k}, \quad \forall k \]  
\[ \sum_{k=1}^{K} \tau_k P_k \leq \bar{P}, \]  
\[ 0 \leq P_k \leq P_{\text{peak}}, \quad \forall k. \]  

The problem in Eq. (31) is non-convex, since all secrecy capacity functions \( C_k^\rho(s_k^j, z_k^j) \) are non-convex with respect to \( P_k \) and all \( P_k \) are coupled with each other in (31c). Since the objective function is a pointwise minimum of all energy functions \( z_{\text{total},k} \), we introduce a slack variable. The problem can be converted as follow,

\[ \min_{P} \frac{1}{t_0} \]  
\[ \text{s.t.} \quad (1 + \gamma_{c,k})/(1 + \gamma_{r,k}) \leq 1/(R_{\text{th},k}/\tau^*_k), \quad \forall k \]  
\[ t_0/z_{\text{total},k}(\tau^j, P, \rho^j) \leq 1, \quad \forall k \]  
\[ \sum_{k=1}^{K} \tau_k P_k \leq \bar{P}, \]  
\[ 0 \leq P_k \leq P_{\text{peak}}, \quad \forall k. \]
To handle the non-convex constraints in the complementary GP problem (32), we transform to a standard GP by approximating all $\hat{z}_{\text{total}, k}(P)$ and $g(P_k)$ \( (f(P_k)/g(P_k)) = (1 + \gamma_{r,k})/(1 + \gamma_{r,k}) \). As the description in Section IV-B, we can obtain all $g(P_k) \geq \hat{g}(P_k) = \prod_{m=1}^{M'} (\frac{g_m(P_k)}{\alpha_m})^{\rho_k}$ and $z_{\text{total}, k}(P) \geq \hat{z}_{\text{total}, k}(P) = \prod_{m=1}^{M'} (\frac{g_m(P)}{\alpha_m})^{\rho_k}$ due to the arithmetic-geometric mean inequality. Thus, we write the standard GP as,

$$
\begin{align}
\min_{P, t_0} & \quad 1/t_0 \\
\text{s.t.} & \quad f(p_k) \sum_{m=1}^{M'} (\frac{g_m(P_k)}{\alpha_m})^{-\alpha_m} \leq 1/2(R_{th,k}/\tau_k^k), \forall k \\
& \quad t_0 \sum_{m=1}^{M'} (\frac{g_m(P_k)}{\alpha_m})^{-\alpha_m} \leq 1, \forall k \\
& \quad \sum_{k=1}^{K} \tau_k^k P_k \leq \bar{P}, \\
& \quad 0 \leq P_k \leq P_{\text{peak}}, \forall k.
\end{align}
$$

(33a)

(33b)

(33c)

(33d)

(33e)

that can be be solved efficiently with CVX. And more importantly, the lower bound functions adopted in (33b) and (33c) imply that their feasible set are always a subset of that of the function (31b) and (31c), respectively. The solution to the problem (33) is also a feasible solution to the problem (31) [43]. As a result, the maximal objective value (\( t_0 \)) obtained from the problem in (33) is a lower bound of the one in (31).

4) Overall Algorithm: By applying the BCD technique, we summarize Algorithm 2 for problem (27), which cyclically and iteratively solve the problems (28), (29) and (31) until it converges. For SCA, the solution of Algorithm 1 is used as an initial point of power ratio \( \rho_k \) in Algorithm 2, such that \( \rho_k = P_{\text{sec}, k}/P_k \) for satisfying the security requirement. And for time and signal power variables, we set the average allocation policy with $P_k = \bar{P}/K$, $\tau_k = T/K$ as a feasible initial point. In each iteration, we optimize one of the three-block variables, including the backscatter time allocation vector \( \tau \), the multi-sinewave \( (\text{S}) \) and AN \( (z) \) designing with an auxiliary splitting ratio vector \( \rho \), and the power allocation vector \( P \), while keeping the other two fixed. The obtained solution in each iteration is used as the input of the next step.

5) Convergence Proof: For the classic BCD method with cyclic block coordinate descent, the search along with any block coordinate direction is required to yield a unique optimal solution so as to guarantee the convergence [43]. However, in Algorithm 2, with the power allocation problem approximation and the waveform design replaced by a power splitting ratio problem, we only solve an approximating problem of (27) optimally. Thus, we need to prove the convergence of our algorithm to solve the original problem.

The max-min problem (27) can be converted to maximize a slack variable $Z$ that is smaller than all $z_{\text{total}, k}(\tau, P^j, S^j, z^j), \forall k$ [22]. The Lagrangian for problem (27) is given as (34), where nonnegative vector \( a = [a_1, a_2, \ldots, a_K] \), \( b = [b_1, b_2, \ldots, b_K] \), \( c = [c_1, c_2, \ldots, c_K] \) and scale $d \geq 0$ and

**Algorithm 3. BSUM algorithm for obtaining Lagrange dual function**

1: Find a feasible point $x^{(0)}$ and set $j=0$. Define a set $\Gamma^j$ as the block-variable indices at iteration $j$.
2: repeat
3: \quad pick index set $\Gamma^j$.
4: \quad let $x^{i^j} \in \arg\max\{u_i(x^{i-1}), i \in \Gamma^j\}$.
5: \quad Set $x^i = x^{i-1}$, $i \notin \Gamma^j$.
6: \quad $j \leftarrow j + 1$.
7: until convergence criterion is met.

$$
\begin{align}
& f \geq 0 \text{ are Lagrange multipliers. Thus, Lagrange dual function is then given by} \\
& \mathcal{G}(a, b, c, d, f) = \max_{\tau, \rho, P} L(\tau, \rho, P, a, b, c, d, f). \\
& \text{The dual problem is thus given by} \\
& \min_{a, b, c, d, f} \mathcal{G}(a, b, c, d, f).
\end{align}
$$

Since the objective is a non-convex function, optimization problem (27) cannot be directly solved by applying Karush-Kuhn-Tucker (KKT) conditions [43].

For obtaining the Lagrange dual function, we just simplify the Lagrange $L(\tau, \rho, P)$ by not considering the Lagrange multipliers $a, b, c, d, f$. Based on the BSUM algorithm [44], at the previous iteration feasible point $x^{i-1}$ ($x \triangleq [x_0, x_1, x_2] \triangleq [\tau, \rho, P]$), let us select $u_i(x_i, x^{i-1}_j)$ as an upper bound approximate function of $L(\tau, \rho, P)$ for each block coordinate \( i = (j \bmod 3) + 2 \).

Each iteration, the part $C^i_k$ in the $u_i(x_i, x^{i-1}_j)$ is replaced by $C^i_k$ if the block variable is picked, otherwise keeping the same $C^i_k$. If the $\tau$, $\rho$ and $P$ are alternately selected as $x_i$, the Algorithm 3 is the same as Algorithm 2. Since each $u_i(x_i, x^{i-1}_j)$ is continuous and differentiable, each iteration has a unique and regular solution.

Based on the Theorem 1 in [44], the sequence $\{x^i\}_j=1$ generated by Algorithm 3 will converge to an accumulation point that is the global optimal solution of Lagrange dual function.

Besides, in step 4 and step 5 of the Algorithm 2, since both of the subproblems are linear problems and the unique optimal solution can be obtained, we have the inequality on the objective value as $Z(\tau^j, \rho^j, P^j) \leq Z(\tau^{j+1}, \rho^{j+1}, P^{j+1})$.

And in the step 6, we can obtain

$$
\begin{align}
Z(\tau^{j+1}, \rho^{j+1}, P^{j+1}) = & Z(\tau^{j+1}, \rho^{j+1}, P^{j+1}) \\
\leq & Z(\tau^{j+1}, \rho^{j+1}, P^{j+1}) \\
\leq & Z(\tau^{j+1}, \rho^{j+1}, P^{j+1}).
\end{align}
$$

With the two inequalities, we can further have $Z(\tau^j, \rho^j, P^j) \leq Z(\tau^{j+1}, \rho^{j+1}, P^{j+1})$, which implies that the objective value of problem (27) is non-decreasing. In the above analysis, the sequence $\{x^i\}_j=1$ will converge to an stationary point of the problem (27). Therefore, the objective value $Z(\tau^j, \rho^j, P^j)$ will converge to an optimal solution and the convergence of the Algorithm 2 is guaranteed.

6) Complexity Analysis: For the complexity of Algorithm 2, we theoretically analyze the complexity of three subproblems in it, respectively. First, the complexity of solving the subproblem (28) is given $O(K^{2.5})$ since it is a reduced LP linear programming [43]. In addition, the optimal ratio vector $\rho_k$ can be obtained individually by the Simplified Algorithm,
\[
L(\tau, \rho, P, a, b, c, d, f) = Z - \sum_{k=1}^{K} a_k (z_{total,k} - Z) - \sum_{k=1}^{K} b_k (R_k - R_{th,k}) + \\
\sum_{k=1}^{K} c_k \left( \frac{1}{2} ||s_k||^2 + \frac{1}{2} ||z_k||^2 - P_k \right) + d(\sum_{k=0}^{K} \tau_k P_k - \bar{P}) + f(\sum_{k=0}^{K} \tau_k - 1).
\]

(34)

and so the complexity is \(O(K)\) for the sub-problem (29). And for the sub-problem (31), it can be solved efficiently with CVX by transforming it to a standard GP problem and then to a convex problem. The complexity is polynomial in \(K\) for \(O(K^q)\), where \(q\) is constant and equal to 2 for the ellipsoid method [43]. As a result, the overall complexity of Algorithm 2 is \(O(K^{2.5} + K + K^q)\), which is polynomial. Therefore, our algorithm can be practically implemented with fast convergence for a multi-BD WPBC system. As numerically shown in Section VI, it converges typically in a few iterations, which is quite fast for our simulation setup.

VI. SIMULATION AND EXPERIMENTAL RESULTS

In this section, we firstly provide numerical and experimental results to evaluate the validity and the performance of the single BD case. Then, we evaluate the performance of the proposed algorithm in the multi-BD case with optimal resource allocation. In the simulation setup, we considered a WPBC system with \(K\) BDs and one eavesdropper that are located in a cell with random distances to the AP. The forward and backward channel gains are set as \(10^{-2} d^{-2}\), where \(d\) denotes the distance. In the multi-BD WPBC system, we study the resource allocation policy for BDs at different positions, which determine the total harvested energy and secrecy capacity of BDs. And the channel power delay profile is obtained from the work [46], with a normalized channel power gain. The total transmission power budget for AP is set to \(P = 20\) dBm and the received noise power is assumed to be \(\sigma^2 = 60\) dBm for both the AP and Eve. The same coefficient of backscatter for all BDs is set as \(\kappa = 0.4\). The center frequency is set as 5.15 GHz, 10MHz bandwidth with both the perfect low-pass filter and load in the energy harvester, whose parameters are taken as \(A_2 = 0.0034\), \(A_4 = 0.3829\) and \(R_{stat} = 50\Omega\) [4]. Thus, in the simulation, we mainly consider the effect of the AN power on the energy harvesting and secure backscatter transmission. The simulation is conducted by MATLAB R2020a and all convex problems are efficiently solved by the CVX tool.

A. Single-BD Case

In the single-BD case, we set \(d_1 = 3, d_e = 3.1\) for the distances between the BD, Eve and the AP, respectively, and \(d_{1,e} = 0.1\) for the distance between Eve and the BD. Fig. 2 illustrates the achievable secrecy rate-energy region obtained with the GP-based algorithm and the simplified algorithm with different numbers of sinewaves. A first observation is that achievable secrecy rate and harvested energy are indeed subject to a fundamental tradeoff, i.e., increasing the secrecy rate constraint results in a decrease of the harvested energy, and vice versa. A second observation is that growing the number of frequency component \(N\) of the multi-sinewave waveform enlarges the achievable secrecy rate-energy region. Indeed, by increasing \(N\), the waveform exploits the nonlinearity of the rectifier, which is beneficial to energy harvesting. A third observation is that our simplified algorithm is able to solve the optimization problem by only introducing a slight penalty of both the secrecy rate and harvested energy. And for \(N = 2\), it obtains the same \(z_{DC}\) with the GP-based algorithm.

On the other hand, increasing \(N\) boosts the harvested energy under the same secrecy rate constraint by looking at Fig. 3. And the harvested energy of the linear model is significantly outperformed by that of the non-linear model as \(N\) grows large. And, the performance of the simplified algorithm is slightly inferior to the GP-based algorithm, but very close. Besides, we measure the computing time of the GP-based algorithm and the simplified algorithm, as well as their optimal objective value, illustrated in Table I. The results show that the average computational time for the simplified algorithm is far less than the GP-based algorithm, especially for larger \(N\), only with a small performance penalty. Therefore, our simplified algorithm is able to achieve an approximating solution for obtaining optimum objective value through significantly low complexity.

Besides, in the paper, we assume that AP can obtain \(h_k\) and \(h_{r,k}\) with the measured \(h_k h_{r,k}, \forall k\), because of the perfect channel reciprocity \(h_k = h_{r,k}\), denoting channel correlation as \(corr = 1.00\). But due to dynamic environments, the two channels may not be completely reciprocal in practice. There could be a deviation to estimate the two channels with the process above. Thus, in the single-BD case, we further study the secrecy rate-energy region with different channel correlations between the backward channel and forward channel. The results are obtained with the GP algorithm by setting \(N = 2\). From Fig. 4, we observe that when the channel correlation is very large, i.e., 0.99, only a negligible performance loss is incurred. But as the channel correlation decreases, the performance loss increases. Therefore, accurate channel information still needs to be estimated in the WPBC system to improve the backscatter secrecy and harvested energy while injecting AN into the multi-sine signals. For instance, the \(k\)-th BD can first measure the forward channel \(h_k\) and feeds it back to the AP. The AP can measure the two-way channel \(h_k h_{r,k}\) and then calculate the backward channel \(h_{r,k}\). But the estimation process of the forward channel \(h_k\) introduces additional computational overhead to the resource-constrained BD.

To further investigate the multi-sinewave and AN signal design, Fig. 5 details the allocated power for each frequency component of multisine and AN. As we analyzed, the uniform power allocation for multisine is equal to the results obtained from the GP-based algorithm when \(N = 2\). For \(N = 4\), the power of each multisine frequency component could be...
different due to the non-linear feature of the rectifier. But under the same secrecy rate requirement, it will split an identical power for the AN signal to jamming the illegal receiver Eve.

1) Experimental Results of Single BD Case: In existing works, Kim et al. [47] designed and prototyped a WPT system with NI equipment and a fabricated rectifier. They measured the forward channel to design the WPT multi-sine signal to improve the received DC power. The work in [18] established a SWIPT testbed system to discuss the trade-off between information throughput and harvested energy both with the power-splitting and time-sharing architecture. Compared with the experiments above, we mainly consider the effect of the splitting ratio $\rho$ for AN power on the harvested energy and the backscatter communication, especially the secrecy capacity of backscatter with an eavesdropper. As the approach introduced in the paper, we injected AN with different powers in the single-sine signal, but setting a fixed power of the superposition signal. Thus, we measure the harvested voltage at the WISP and the SNR at the AP and the eavesdropper.

To evaluate the validity and the performance of harvested energy and secure backscatter communication in the single BD case, we implemented a single-BD WPBC system, as shown in Fig. 6. It consists of an AP, a BD and a passive eavesdropper, and operates at 900MHz carrier frequency. A USRP N210 is used as the transceiver AP that can transmit carrier signals and receive information and another USRP N210 as the eavesdropper to illegally intercept the backscatter communication. The low-power BD is configured with the wireless identification and sensing platform (WISP) [48], which is controlled by the TI LaunchPad with MSP430G2553. The WISP is an ultra-low-power passive UHF RFID tag and scavenges energy from the RF signal and converts it into DC voltage. Thus, we measured the harvested voltage of the WISP as its performance of energy harvesting. The WISP is controlled by LaunchPad to realize the backscatter transmission at a rate of 4 kbps. As both the AP and Eve receive backscattered information, we measure the information signal and calculate its related SNR.

Therefore, we evaluate the voltage generated at the WISP, whether it is backscattering or not, and the SNRs of the signal received at both USRPs. Through the results in Fig. 7, the voltage at the WISP drops when increasing the proportion of AN power. In addition, the voltage harvested by the WISP declines about 36% while it is backscattering. Fig. 8 shows the SNR of AP and Eve versus the splitting ratio for the artificial noise. Without AN in the downlink signal, the SNR of the eavesdropper is higher than that of the AP’s, because Eve is set closer to the WISP in our experiment. Thus, if the eavesdropper is close to the transmitter and has a very sensitive receiver compared to the legitimate receiver, there is a grave risk of information leakage. But as the power of injected noise increases, the SNR of the eavesdropper reduces faster than the AP’s. Therefore, positive secrecy capacity can be achieved by injecting a suitable power of AN into the downlink signal.
B. Multiple Devices

In the multiple BDs case, we mainly analyze the achievable secrecy throughput-energy region for \( K = 2 \) and \( K = 4 \). We set the distance as \( d_k = [3.00, \sqrt{10}, \sqrt{10}, 3.2] \), \( d_{k,e} = [0.1, \sqrt{10}, \sqrt{10}, 0.1] \) and \( d_e = 3.1 \), respectively. Other parameters are kept the same as in the single BD case. First, Fig. 9 depicts the convergence behavior of the proposed algorithm with \( N = 2, 8, 16 \), comparing with the global optimal value through the exhaustive search. In general, the proposed algorithm almost achieves the global optimality of about 10 iterations within an increment smaller than the threshold \( \varepsilon = 10^{-4} \). And, there are almost the same convergence behaviors for different numbers of multi-sinewave and devices. But in simulation, the case with more sinewaves and more devices needs more time for CVX to solve the optimization problem in each step, since it has more variables in each problem. In addition, we can observe that the max-min harvested energy with larger numbers of sinewaves gets larger, since the energy harvester with non-linear rectifier benefits from multiple sinewaves.

The max-min achievable secrecy throughput-energy region for \( K = 4 \) is shown in Fig. 10. The \( R_{th} \) on the x-axis is the secrecy throughput constraint for all BDs. By looking at the achievable secrecy throughput-energy region, it is observed that the performance of WPBC is subject to a tradeoff between secrecy throughput \( R_{th} \) and the harvested energy \( z_{\text{total}} \). That is, maximizing the \( R_{th} \) would result in a decrease of \( z_{\text{total}} \). Another observation is that, like the single BD case, as the number of sinewaves in the waveform increases, the tradeoff region will be enlarged. This is, because a proper power allocation across multiple sinewaves of each BD can exploit the nonlinear feature of the rectifier, making more power be split to the AN signal to improve the secrecy throughput.

Next, we illustrated the whole system performance with \( K = 4 \) BDs under different resource allocation policies and security requirements, where the distance of each BD from the AP increases with their index \( k \). Fig. 11 depicts the system performance with an equal resource allocation policy for all BDs, while the identical power splitting ratio is set to satisfy the secrecy throughput constraint of all BDs. From these results, the closest BD to the AP, has the highest harvested energy. And, the harvested energy of each BD declines, as the distance between the BD and the AP increases. Significantly, with the same augmentation of allocation power for all BDs, there is the greatest increment or profit of harvested energy on the closest BD. If just maximizing the total throughput of all BDs with the same weight, most of the resources will be allocated to the closest BD, such as the transmission power and time.

![Fig. 5: Power allocation for AN and multi-sine signal with \( C_{th} = 1.3 \).](image)

![Fig. 6: Experimental set-up in the single-user WPBC system.](image)

![Fig. 7: Harvested voltage vs splitting ratio with transmission power.](image)

![Fig. 8: SNRs of AP and Eve vs splitting ratio with transmission power.](image)
After applying our proposed algorithm, each BD has the maximal and identical harvested energy with the same security requirement, as shown in Fig. 12. From the result, AP assigns more power to the second and third BD, since it has higher secrecy throughput profit. This is because, Eve is farther from these two BDs with lower eavesdropping capability, which also means less power is allocated to the AN to meet the security requirement. With the higher allocated power, the splitting ratio can be decreased, as long as the secrecy throughput is satisfied, and the backscatter time is reduced. And due to the highest profit of harvested energy at the closest BD, AP will allocate more power and less backscatter time. The saved time can be allocated to the farther fourth BD and improve its harvested energy.

Then, we increased the total power transmitted by the AP to improve the harvested energy of all the devices, as shown in Fig. 13. As the total transmission power increases, the resource allocation policy will also be updated to optimize the max-min harvested energy. Firstly, the power splitting ratios for all BDs are slightly reduced compared to the result in Fig. 12, since higher signal power leads to higher secrecy capacity. Thus, the AP can allocate less power to AN while keeping the same secrecy capacity while further increasing the minimal harvested energy of all BDs. In addition, as the higher...
harvested energy gain is obtained at the closer BDs with higher transmission power, the AP will allocate less backscatter time to them, while the far BDs will obtain more backscatter time. Fig. 14 demonstrates the system performance and the resource allocation policy with a higher secrecy throughput constraint. Compared with Fig. 12, we can observe that with the growth of the required secrecy throughput, the resource allocated to each BD is totally changed. Firstly, the splitting ratios of all BD are increased and more power is split into the AN signal, especially for the second and third BD. Therefore, the minimal harvested energy of all BDs is slightly decreased compared to the harvested energy in Fig. 12. Besides, in order to maximize the minimal harvested energy at all BDs, more transmission power is allocated to closer BDs, whereas more backscatter time is allocated to the far BDs.

VII. CONCLUSION

This paper proposed AN injection in multi-sine signal to improve the secrecy capacity of the backscatter channel in a multi-BD WPBC system. And we investigated the resource allocation policy by considering fairness for joint backscatter time and signal power allocation, as well as AN power splitting ratio selection. For the single BD case, we formulated an energy maximization problem by considering the secrecy rate constraint and proposed an SCA algorithm to solve the non-convex posynomial problem. For the multiple BDs case, a max-min optimization problem was formulated to maximize the minimum harvested energy of all BDs while satisfying the same secrecy throughput constraint. Then, we presented an efficient iterative algorithm to solve the non-convex joint optimization problem of the multi-BD WPBC system, where the convergence of the algorithm can be guaranteed with the polynomial complexity. The performance of the single-BD WPBC system was evaluated by simulation and proof-of-concept experiments. And numerical simulation results showed that the optimally fair energy for all BDs can be achieved in the multi-BD WPBC system by satisfying the security throughput. Our work can provide a significant perspective of system resource allocation in terms of different limitations and requirements of harvested energy and security in multi-BD WPBC.

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