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Energy-Efficient and Secure Resource Allocation for Multiple-Antenna NOMA with Wireless Power Transfer

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***Abstract*—Non-orthogonal multiple access (NOMA) is considered as one of the promising techniques for providing high data rates in the fifth generation mobile communication. By applying successive interference cancellation schemes and superposition coding at the NOMA receiver, multiple users can be multiplexed on the same subchannel. In this paper, we investigate resource allocation algorithm design for an OFDM-based NOMA system empowered by wireless power transfer. In the considered system, users who need to transmit data can only be powered by the wireless power transfer. With the consideration of an existing eavesdropper, the objective is to obtain secure and energy efficient transmission among multiple users by optimizing time, power and subchannel allocation. Moreover, we also take into consideration for the practical case that the statistics of the channel state information of the eavesdropper is not available. In order to address the optimization problem and its high computational complexity, we propose an iterative algorithm with guaranteed convergence to deliver an upper bound and a suboptimal solution in more general cases. For some special cases, we identify the optimality condition that ensures the global optimum in our algorithm. Extensive simulation studies demonstrate the competitiveness and effectiveness of the proposed algorithmic solution over conventional OFDMA systems as well as over other existing NOMA resource allocation schemes.**

***Index Terms*—Non-orthogonal multiple access (NOMA), security, wireless power transfer, subchannel allocation, power allocation**

I. Introduction

A. Background and Motivation

Non-orthogonal multiple access (NOMA) has been known as an effective solution to improve data rates for the next generation communication system designs. It has recently received great interest. The key idea of NOMA is to realize multiple access in the power domain which is fundamentally different from conventional orthogonal multiple access technologies (OMA), e.g. OFDMA. The motivation behind this approach lies in the fact that NOMA can use spectrum more efficiently by opportunistically exploiting users' channel conditions [1]. Unlike interference-avoidance multiple access schemes, e.g., OFDMA, multiple users in NOMA can be assigned to the same resource in frequency-time domain so as to improve spectrum efficiency. Although, this may result in intra-cell interference among the multiplexed users, some of the interfering signals in NOMA can be eliminated by multiuser detection (MUD) with successive interference cancellation (SIC) at the receiver side. To enable this process, more advanced receiver design and resource allocation techniques should be considered for a NOMA-based system.

Meanwhile, it is envisioned that to solve the energy supplement problem and increase the energy efficiency (EE) of systems, energy harvesting technology is considered as one of promising solutions. Compared with conventional energy sources such as wind and solar, electromagnetic signals are not location-dependent. Therefore, network elements may experience difficulty in accessing conventional energy source. Simultaneous wireless information and power transfer (SWIPT) emerges as an effective way for energy supply. As electromagnetic signals are almost everywhere, SWIPT research recently attracts considerable interests from the academic and industrial communities [2], [3]. As wireless power transfer system enables the device to harvest energy from wirelss signal, it is important to utilize the harvested energy in an efficient way. Therefore, investigating the system performance from energy efficiency point-of-view is considered as an emerging research direction in this line.

In addition to the energy consumption issues, security of the cellular system is also critical as the traditional wireless communications may be vulnerable to increased security threats. Among the design of security mechanisms, physical-layer (PHY) security (PLS) has emerged as a research topic due to its independence of the interception ability of eavesdroppers. The basic idea for enhancing PLS is to exploit the randomness of wireless channel for secure data transmission. Thus, how to design the secure transmission from the PHY perspective is also of significance for the future wireless networks. As mentioned above, PLS has been studied in various scenarios, but there is still a paucity of research contributions on

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investigating the security issues of NOMA, which motivates to investigate the PLS in the NOMA system. Note that the unique features of NOMA makes the analysis of the PLS of NOMA different from that of OMA. However, due to the broadcast nature of the wireless communication, if privacy information is contained in the transmission signals, there still be a chance that passive eavesdropping from external/internal eavesdroppers may occur in NOMA, which motivates us to design corresponding algorithm to enhance the PLS of NOMA.

In this work, we consider a secure and energy-efficient design for NOMA systems. In particular, the focus is on investigating uplink resource allocation algorithms for OFDM-based NOMA systems empowered by wireless power transfer (WPT). In the considered system, there is an eavesdropper with multiple antennas trying to overhear the transmission. At first, the energy transmitter transmits energy to the user equipment (UEs), after which, the UEs utilize all the received energy and transmit information signals to the original energy transmitter. The application scenario can be consider as the BS-user transmission in the cellular networks where BS is the energy transmitter or as the transmission in a wireless sensor network. Considering WPT and wireless information transfer (WIT) in different slots, we propose a time allocation scheme for optimizing the WPT time duration, power and subchannel allocation schemes to obtain secure and energy-efficient uplink transmission among multiple users.

B. Related Work

NOMA has recently received significant attention since it enables the multiplexing of multiple users on the same frequency resource, and thus, improves the system spectral efficiency [4]. In [5], the MIMo application in NOMA is investigated. The authors of [6] study the sum rate maximization problem in the downlink NOMA, and formulate it as a non-convex and intractable optimization problem. By applying a minorization-maximization algorithm, the problem is addressed. The authors in [7] considered a sum-rate utility maximization problem for dynamic NOMA resource allocation. In [8], the authors formulate NOMA resource allocation problems with the objective to optimize the throughput, and further analyze the problem's tractability under various constraints and utility functions. For uplink NOMA, the authors in [10] provided a suboptimal algorithm to solve an uplink scheduling problem with fixed transmission power. In [9], a max-min fairness problem for NOMA has been addressed with user fairness considerations. The fairness in NOMA can be improved by using and adapting the so-called power allocation coefficients. In [11], the authors propose and evaluate user grouping/pairing strategies in NOMA. It has been shown that, from an outageprobability perspective, it is preferable to multiplex users of large gain difference on the same subcarrier. In [12], the authors address subchannel and power allocation as well as user scheduling in NOMA, with the objective of balancing the throughout with the number of scheduled users. Matching theory is applied to address the formulated problem. In [13], a monotonic optimization method is developed for NOMA subcarrier and power allocation. The method potentially approaches the global optimum, at the cost of high complexity in the number of users per subcarrier. In [14], the authors investigate the application of SWIPT in cooperative NOMA, and design the beamforming and power splitting control mechanisms. The authors of [15] study the beamforming and random antenna selection strategies at the Base Station. The users can perform WPT and receive energy from the BS, and then act as the relay for other users. A NOMA cognitive radio network is investigated in [16], where a full-duplex relay assists transmission from a BS to a far user and the BS can also transmit to a near user. The objective of this work is to enlarge the far-near user rate region. In [17] and [18], the authors consider the power allocation in downlink of an OFDM-based NOMA. In [19], the energy efficiency problem of downlink NOMA has been investigated. In this work, the authors propose to optimize subchannel assignment and power allocation to maximize the energy efficiency of the considered system. The authors of [20] present a suboptimal power allocation scheme to maximize the system energy efficiency using statistical channel state information at the transmitter.

As for the wireless power transfer NOMA system, there are several works on throughput optimization solutions. In [21], the authors concentrate on the individual data rate optimization and fairness improvement. It is shown that by linear programming or convex optimization based schemes, the formulated problems can be optimally and efficiently addressed accordingly. In [22], the authors study a wireless powered uplink NOMA system. The authors derive jointly optimal transmit power allocation and time duration of the energy harvesting and information transmission phases in order to maximize the rate region. The authors of [23], propose a SWIPT NOMA protocol, in which near NOMA users that are close to the source act as energy harvesting relays to help far NOMA users. Closed-form expressions for the outage probability and system throughput are derived to characterize the system performance.

For the security consideration, the authors of [24] study physical layer security (PLS) in a single-input single-output (SISO) NOMA system with the objective of maximizing the secrecy sum rate of the system and consider explicitly the users' quality of service (QoS) requirements. In [25] and [26], PLS of NOMA system in large-scale networks is investigated where both the NOMA users and eavesdroppers are spatially randomly deployed. Exact and asymptotic expressions for the security outage probability are derived accordingly. In [27], the authors consider multi-user NOMA network with mixed multicasting and unicasting traffic. The design of beamforming and power allocation are presented to ensure an improved unicasting performance while maintaining the reliability of multicasting. The authors of [28] concentrate on a NOMA system with an external eavesdropper. The design of data rate, decoding order, and power allocation among multiple users are investigated. In [30], secure D2D communication in energy harvesting large-scale cognitive networks is explored. A WPT and an information signal model are introduced to enable wireless energy harvesting and secure information transmission.

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As one may observe, although several recent works have focused on subchannel and power allocation in wireless powered NOMA systems, these papers mainly focus on sum rate maximization without security considerations. However, with the exponential growth of wireless data traffic, energy consumption of wireless networks has been rapidly increasing. Therefore, saving transmit energy while delivering high-speed and secure data rate is an important issue and practical consideration for future communication systems.

C. Contribution

In this paper, with the objective to ensure the secure rate and energy efficiency, we deal with a resource allocation problem for NOMA systems with wireless power transfer. The contribution of this work can be summarized as follows.

- In this paper, we study the EE optimization with considering secrecy data rate for a multiple-antenna multi-user NOMA system empowered by WPT. With the objective to obtain the optimal EE with secrecy rate, we jointly optimize power allocation, time allocation, and subchannel allocation, and formulate the optimization problem as well.
- In the considered system, the whole time slot T is divided into WPT time and WIT time. If more time is allocated to WPT, higher transmit power is available at the UE. However, less time remains for data transmission, which leads to lower system throughput. Therefore, we propose a time allocation scheme to determine the optimal time allocation, along with a scheme to jointly optimize power and subchannel allocations.
- Moreover, we also consider the practical case that the CSI of the eavesdropper cannot be fully obtained by the legitimate nodes of the system. Instead, we investigate the system performance under the consideration to estimate the secrecy rate, based on derived thorough theoretical analysis.
- The formulated optimization problem is nonconvex and contains combinatorial aspects. To address it, we exploit the insights of the problem structure, and establish the theoretical analysis in reformulating the considered nonconvex problem, decomposing difficult constrains by transformation, as well as the convergence and optimality of the proposed solution. Together with all of the developed analytical results, it enables us to develop an iterative algorithm providing promising results, in terms of upper bound, suboptimal or global optimal solutions, for solving the problem. The proposed algorithmic solutions are evaluated and verified through extensive simulations. The performance evaluation demonstrates the effectiveness and superior performance compared with previously proposed scheme.

D. Organization

The paper is organized as follows. The system model is described in Section II. In Section III, we formulate the problem and propose the resource allocation scheme to address it in Section IV. In Section V, extensive simulation are conducted to investigate the effect of the proposed scheme. We finally conclude our work in Section VI.

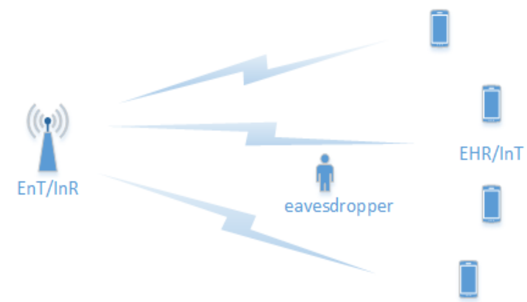

Fig. 1. System Model

II. System Model

A. System Assumption

We consider a wireless network consisting of one energy transmitter (EnT) with $N_T > 1$ antennas, K energy harvesting receivers (EHRs) with $N_R > 1$ antennas and an eavesdropper with $N_E \geq 1$ antennas. The EnT is able to charge the EHRs via WPT. After charging, the EHR can utilize the received energy and then transmit the information data to the EnT. Correspondingly, in the WIT phrase, the EHRs become information transmitter (InTs) and the EnT becomes the information receiver (InR). In the following, InT and EHR, EnT and InR are used interchangeably. For security concerns, we assume $N_R > N_E$. It should be noticed that the eavesdropping capability increases with the number of antennas N_E of the eavesdropper. In practice, the system may not know the number of N_E. Thus, the InT may assume N_E as $N_E = N_R - 1$ to ensure security by considering the worst-case scenario. If the assumption is violated, then the eavesdropper is able to eliminate the artificial noise, resulting in throughput of eavesdropper goes to infinite. Therefore, in this work, we assume $N_E = N_R - 1$ and provide corresponding analysis. Meanwhile, the eavesdropper can passively overhearing the information data. The overall bandwidth B is divided into N subchannels, each with bandwidth $W = B/N$. The set of subchannels is denoted as $\mathcal{N}$ and the set of users that uses subchannel n is denoted as $\mathcal{U}_n$. The considered scenario can be applied to the traditional cellular networks or wireless sensor networks. We assume that the channel state information (CSI) between the EnT/InR and EHRs/InTs are perfectly known, but the one of the eavesdropper is unknown. With SIC, some of the co-channel interference will be treated as decodable signals instead of as additive noise.

B. Wireless Power Transfer

The transmission process of the considered system is depicted in Fig. 2. We consider a quasi-static block fading channel model where the channel between the transmitter and receiver is constant for a given transmission block T, and it can vary independently from one block to another. We assume that the whole transmission process including WPT and WIT phrases. As shown in Fig. 2, in the first time slot τT, the EnT

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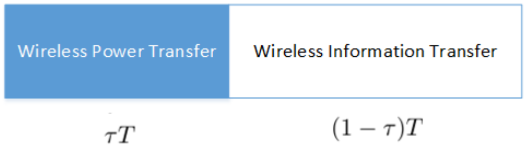

Fig. 2. Wireless Power and Information Transfer

charges EHR k via WPT and the EHR stores the harvested energy in a rechargeable battery. Then, in the time duration $(1-\tau)T$, EHR k becomes the InT and sends its own data to the EnT/InR.

Considering the devices are equipped with wireless energy harvesting capability, the energy harvested by EHR k on subchannel n can be considered as follows [31],

$$E_{k,n} = \vartheta \tau T P_n |\mathbf{B}_{k,n}^H \mathbf{H}_{k,n}|^2 = \vartheta \tau T P_n \|\mathbf{H}_{k,n}\|^2 \quad (1)$$

where τ is the time fraction of WPT. P_n is the transmit power of the EnT on subchannel n. $\mathbf{H}_{k,n}$ is the channel coefficient matrix from the EnT to the EHR k on subchannel n. $0 < \vartheta < 1$ is the receiver efficiency of WPT, which depends on the hardware features of the receiver. In order to maximize the harvested energy, we design the energy beamforming policy as $\mathbf{B}_k = \frac{\mathbf{H}_{k,n}}{\|\mathbf{H}_{k,n}\|}$, which is named as maximum ratio transmission (MRT). In this work, we do not consider circuit activation energy for the energy harvesting circuit in the EHR. The threshold for activating the energy harvesting circuits is usually considered as a fixed value and such assumption has no impact on addressing the considered problem in this work.

C. Transmission protocol

During the data transmission, the received signals at InR and eavesdropper are, respectively, given by,

$$\begin{aligned} \mathbf{y}_{k,n} &= \mathbf{H}_{k,n}\mathbf{x}_{k,n} + \sum_{u \in k}^{U_n} \mathbf{H}_{u,n}\mathbf{x}_{u,n} + \mathbf{n}_{k,n}, \\ \mathbf{y}_{k,n,E} &= \mathbf{G}_{k,n,E}\mathbf{x}_{k,n} + \sum_{u \in k}^{U_n} \mathbf{G}_{u,n,E}\mathbf{x}_{u,n} + \mathbf{n}_{k,n,E}, \end{aligned} \quad (2)$$

where $\mathbf{H}_{k,n} \in \mathbb{C}^{N_T \times N_R}$ and $\mathbf{G}_{k,n,E} \in \mathbb{C}^{N_E \times N_R}$ are the channel coefficient matrices including the path loss effect between the InT k and InR, and between the InT k and eavesdropper, respectively. $\mathbf{x}_{k,n} \in \mathbb{C}^{N_R \times 1}$ denotes the transmitted signal of InT. $\mathbf{n}_{k,n} \in \mathbb{C}^{N_T \times 1}$ and $\mathbf{n}_{k,n,E} \in \mathbb{C}^{N_E \times 1}$ are the additive white Gaussian noise (AWGN) at InR and the eavesdropper, respectively. The noises follow the distribution $\mathcal{CN}(0, \sigma^2 \mathbf{I}_{N_T})$ and $\mathcal{CN}(0, \sigma^2 \mathbf{I}_{N_E})$, respectively. For the sake of simplicity, a normalized noise variance is assumed for all receivers in the following. To prevent the eavesdropper overhearing the information data, the InT can add artificial noise to the transmission signal in the following way:

$$\mathbf{x}_{k,n} = \mathbf{b}_{k,n} u_{k,n} + \mathbf{V}_{k,n}\mathbf{v}_{k,n}, \quad (3)$$

where $u_{k,n}$ is the information bearing signal. Precoding is adopted to improve the system throughput. $\mathbf{b}_{k,n} \in \mathbb{C}^{N_T \times 1}$ is the precoding vector. $\mathbf{v}_{k,n} \in \mathbb{C}^{(N_R-1)\times 1}$ is artificial noise vector whose elements are independent and identically distributed (i.i.d.) complex Gaussian random variables with variance $\sigma^2_{k,n,v}$. Without loss of generality, we define the orthogonal basis $\mathbf{V}_{k,n} \in \mathbb{C}^{N_R \times (N_R-1)}$ for the null space of $\mathbf{H}_{k,n}$ such that $\mathbf{H}_{k,n}\mathbf{V}_{k,n}\mathbf{v}_{k,n} = 0$ and $\mathbf{V}^\dagger_{k,n}\mathbf{V}_{k,n} = \mathbf{I}_{N_R-1}$ where $\mathbf{I}_{N_R-1}$ is a $(N_R-1) \times (N_R-1)$ identity matrix, i.e., artificial noise will do nothing for the desired receiver. We denote $p_{k,n}$ as the transmit power of InT k on subchannel n, where we have $p_{k,n} = \frac{E_{k,n}}{(1-\tau)T}$, and $\beta_{k,n}$ as the fraction of transmit power. Then, choosing $\mathbf{b}_{k,n} = \beta_{k,n} p_{k,n} \mathbf{H}^\dagger_{k,n}/\|\mathbf{H}_{k,n}\|$, such that $u_{k,n}$ lies in the range space of $\mathbf{H}_{k,n}$. As can be seen, the transmitted signal consists of two parts. One is the information bearing signal and the other one the artificial noise. Correspondingly, One important design parameter is the ratio of power allocated to the information bearing signal and the artificial noise. The power of artificial noise vectors can be given by [32],

$$\sigma^2_{k,n,v} = \frac{(1-\beta_{k,n})p_{k,n}}{N_R - 1}. \quad (4)$$

D. Secure Capacity

Let us first consider a fixed decoding order of the InTs' messages at the InR, according to their index k. The InR has capabilities of multi-user detection (MUD) and SIC. We adopt the descending order of channel gains as the decoding order, in order to improve the throughput of weak-channel users and enhance user fairness [10]. We sort all U_n InTs on each subchannel n in descending order of channel gains, $|\mathbf{H}_{1,n}| \geq |\mathbf{H}_{2,n}| \geq \ldots \geq |\mathbf{H}_{U_n,n}|$. The 1st signal (the strongest user) is detected and decoded first by treating all the other users' signals as noise. For the U_nth user (the weakest user), the BS successively decodes and removes all the interference of strong users from 1 to $U_n - 1$, before decoding the signals of the weakest user. In general for the kth user, the BS can remove the received signals from the 1st to the $k-1$th users, and consider the $k+1$th to the U_nth users as noise. Correspondingly, the achievable uplink data rate of k on subchannel n, $C_{k,n}$, can be expressed as

$$C_{k,n} = WT(1-\tau)\log_2(1+\gamma_{k,n}). \quad (5)$$

where $\gamma_{k,n}$ is the uplink SINR of k . It can be given as

$$\gamma_{k,n} = \frac{\beta_{k,n} p_{k,n} \|\mathbf{H}_{k,n}\|^2}{\sigma^2 + \sum_{u=k+1}^{U_n} \beta_{u,n} p_{u,n} \|\mathbf{H}_{u,n}\|^2}, \quad (6)$$

where σ^2 is the noise variance. $p_{k,n}$ is the transmit power of k on subchannel n. In this work, all the harvesting energy can be used for transmitting data. In practice, it may not be easy to know the capabilities of the eavesdropper on overhearing, therefore, here we also consider the case that all the information received at eavesdropper are useful for overhearing. Moreover, in many practical cases, the eavesdropper is passive and the CSI between the InTs and eavesdropper is unknown. Therefore, the data rate of the eavesdropper of $C_{k,n,E}$ should be considered a random variable, which can be given as

$$C_{k,n,E} = WT(1-\tau)\log_2\left(1+\Gamma_{k,n,E}\right). \quad (7)$$

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where $\Gamma_{k,n,E}$ is the SINR. We also assume that the eavesdropper is much closer to the InT than the desired InR, the eavesdropper noise is negligible.Based on (2), (3) and (4) it can be given as

$$\Gamma_{k,n,E} = \frac{N_R - 1}{1-\beta_{k,n}} \tilde{\mathbf{g}}^{\dagger} \left(\widetilde{\mathbf{G}}\widetilde{\mathbf{G}}^{\dagger}\right)^{-1} \tilde{\mathbf{g}}, \tag{8}$$

where $\tilde{\mathbf{g}} = \mathbf{G}_{k,n,E}\mathbf{b}_{k,n}$ and $\widetilde{\mathbf{G}} = \mathbf{G}_{k,n,E}\mathbf{V}_{k,n}$. $\mathbf{G}_{k,n,E}$ is the channel co-efficient between k and eavesdropper on subchannel n. Note the eavesdropper's capability for decoding the message is overestimated here. A worst-case assumption is made for obtaining the data rate of eavesdropper from the legitimate users' perspective. That is, the eavesdropper consider every message is useful and is able to obtain related information of the transmitter before it attempts to decode the message. As a matter of fact, the eavesdropper may or may not know the users' decoding order and the resource allocation policy, and may or may not know the transmitter before it attempts to decode the message. However, the InTs do not have the knowledge about the eavesdropper, since the eavesdropper would not inform its ability and CSI. Thus, the worst-case assumption is adopted here for estimating the data rate of eavesdropper due to the conservativeness mandated by the security studies. Correspondingly, the secrecy capacity of user k on subchannel n can be expressed as

$$C^s_{k,n} = (C_{k,n} - C_{k,n,E})\phi(C_{k,n} > C_{k,n,E}), \tag{9}$$

where

$$\phi(C_{k,n} > C_{k,n,E}) = \begin{cases} 1, & \text{if } C_{k,n} > C_{k,n,E}; \\ 0, & \text{otherwise.} \end{cases} \tag{10}$$

It is worth mentioning that when the CSI of the eavesdropper is known, it is possible to set the target secrecy data rate and control the channel capacity to via power or subchannel allocation to match the channel conditions. However, as $C_{k,n,E}$ should be considered a random variable in this context and we cannot obtain $C^s_{k,n}$ perfectly. Correspondingly, a secrecy outage occurs when a defined target secrecy data rate $R_{k,n}$ exceeds $C^s_{k,n}$, i.e., the message can be delivered securely and successfully when $R_{k,n} < C^s_{k,n}$. Therefore, instead of ergodic capacity, in the following we study the performance w.r.t. the target secrecy data rate $R_{k,n}$ instead of $C^s_{k,n}$, which will be elaborate in the following section.

E. Energy Consumption Model

In this work, we consider the maximum efficiency of energy utilization, that is, all the harvested energy is used for data transmission such that no energy is wasted. We denote $\mathcal{P}(\mathbf{P},\tau)$ as the total energy consumption in a time block T and it can be expressed as

$$\mathcal{P}(\mathbf{P},\tau) = \sum_{n=1}^{N} \tau\nu P_n + P_c T, \tag{11}$$

where $\mathbf{P}$ is a collection of all power elements, and P_c is the static power consumption, such as the power consumption on baseband and RF chain for antenna [33]. ν is the factor standing for the nonlinear power amplifier effect.

III. Problem Formulation

Based on our system model of secrecy data rate and energy consumption, we are able to investigate the secure and energy-efficient resource allocation problem for the considered system. In this Section, we present the formulation of EE problem and also explain the practical constraints. First, to facilitate the presentation of EE formulation, we define a subchannel allocation indicator $\omega_{k,n}$ as follow,

$$\omega_{k,n} = \begin{cases} 1, & \text{if subchannel } n \text{ is allocated to the user } k; \\ 0, & \text{otherwise.} \end{cases} \tag{12}$$

Next, to formulate the optimization problem, we utilize the definition the EE of the considered system in bits/J as follows [34]:

$$\mathbf{\Sigma}(\mathbf{P},\tau,\boldsymbol{\omega}) = \frac{\mathcal{U}(\mathbf{P},\tau,\boldsymbol{\omega})}{\mathcal{P}(\mathbf{P},\tau,\boldsymbol{\omega})}, \tag{13}$$

where $\mathcal{P}(\mathbf{P},\tau,\boldsymbol{\omega})$ is interchangeable with $\mathcal{P}(\mathbf{P},\tau)$, and

$$\mathcal{U}(\mathbf{P},\tau,\boldsymbol{\omega}) = \sum_{k=1}^{K}\sum_{n=1}^{N} \omega_{k,n} R_{k,n} \mathbf{Pr}\{R_{k,n} < C_{k,n} - C_{k,n,E}|\Delta\}, \tag{14}$$

where Δ is the CSI of user k on subchannel n. To this end, we jointly optimize duration τ, allocation indicators $\boldsymbol{\omega}$, and power allocation $\mathbf{P} = \{P_1,\ldots,P_n,\ldots,P_N\}$. The optimization problem can be formulated as follows:

$$\textbf{P1:} \quad \max_{\mathbf{P},\tau,\boldsymbol{\omega}} \mathbf{\Sigma}(\mathbf{P},\tau,\boldsymbol{\omega}), \tag{15}$$

$$\begin{aligned}
&\textbf{s.t.}\\
&\textbf{C1}: \quad \mathbf{Pr}\{R_{k,n} \geqslant C_{k,n} - C_{k,n,E}|\Delta\} \leqslant \varepsilon, \forall k \in \mathcal{K}, \forall n \in \mathcal{N}\\
&\textbf{C2}: \quad \sum_{n=1}^{N} P_n \leqslant P_{b,max},\\
&\textbf{C3}: \quad \sum_{n=1}^{N} \frac{\vartheta\tau P_n \|\mathbf{H}_{k,n}\|^2}{(1-\tau)} \leq P_{u,max}, \ \forall k \in \mathcal{K}\\
&\textbf{C4}: \quad \sum_{n=1}^{N} R_{k,n} \geqslant R_{min}, \ \forall k \in \mathcal{K}\\
&\textbf{C5}: \quad \sum_{k=1}^{K} \omega_{k,n} \leq L, \ \forall n \in \mathcal{N}\\
&\textbf{C6}: \quad \omega_{k,n} \in \{0,1\}, \text{ and } P_n \geq 0,\\
&\textbf{C7}: \quad 0 < \tau \leq 1,
\end{aligned} \tag{16}$$

Our goal is to maximize the system EE under a set of practical constraints. **C1** is the QoS metric for communication security, where ε denotes the maximum tolerable secrecy outage probability. **C2** and **C3** impose limitations on the power consumption and ensure the feasibility of power allocation solutions. Specifically in **C2**, total transmit power for WPT at EnT is no larger than a maximum power limit $P_{b,max}$. In **C3**, we use $\frac{\vartheta\tau P_n\|\mathbf{H}_{k,n}\|^2}{(1-\tau)}$ to represent the power value of UE k on subchannel n, i.e., $p_{k,n}$. Each user's transmit power for uplink data transmission cannot exceed its maximum power limit $P_{u,max}$. In **C4**, R_{min} is the minimum system secrecy rate requirement, and a balance between EE and secrecy outage capacity can be achieved by varying R_{min}. Constraint **C5** indicates that the maximum number of allocated users on each subchannel is up to L. Note that parameter L is an integer value no less than $\frac{K}{N}$, otherwise the problem is infeasible. Constraints **C6** to **C7** are the boundary for optimization variables. We remark that in **P1** we do not explicitly impose an extra constraint to indicate the connection between variables P_n and $\omega_{k,n}$. It reads, for any subchannel n, if $\sum_{k=1}^{K}\omega_{k,n}>0$ then $P_n>0$, and $\sum_{k=1}^{K}\omega_{k,n}=0$ indicates $P_n=0$. Note that both of the unwanted decisions, $\sum_{k=1}^{K}\omega_{k,n}>0$ with $P_n=0$ and $\sum_{k=1}^{K}\omega_{k,n}=0$ with $P_n>0$, will not be presented in the optimum. This is because, either the case of that InTs have been allocated to subchannels but with zero assigned power and zero rate, or power has been consumed but no rate value contributes to the objective, is clearly not optimal.

We remark that the optimization of user grouping is an important aspect in NOMA resource allocation. In this work, determining which users to be assigned to which subcarrier is an outcome of optimization, i.e., decided by the binary variables $\omega_{k,n}$. This is different from some previous works in the literature, in which the co-channel allocated users are predefined in prior of optimization. In the above optimization of problem, the constraints in secrecy outage probability $\mathbf{C1}$, users' power constraints $\mathbf{C3}$, minimum-rate constraints $\mathbf{C4}$, and constraints $\mathbf{C5}$ together with the objective function provide major effect in determining user-subcarrier allocation.

It can be noticed that the formulated problem is with a non-convex structure. The objective function in a fractional program is a ratio of two functions of the optimization variables. In order to make the problem solvable, we transform the objective function and approximate the transformed objective function. In the following, we first transform the the optimization problem by utilizing the idea from fractional programming and then address the transformed problem.

IV. Proposed Resource Allocation Scheme

A. Transformation of the Optimization Problem

In order to make the problem tractable, we utilize the idea from the fractional programming and transform the objective function and approximate the transformed objective function in order to simplify the problem. We can apply the nonlinear fractional programming method to solve the formulated problem [36]. As can be found in the Sec. IV-B, it can be found that $\boldsymbol{\Sigma}(\mathbf{P},\tau,\boldsymbol{\omega})$ can be transformed to a quasi-concave function over the decision variable, then we define the maximum energy efficiency q^* of the considered system and the following theorem can be arrived.

Theorem 1. *The maximum EE q^* can be achieved if and only if*

$$\mathbf{U}(\boldsymbol{P}^*,\tau^*,\boldsymbol{\omega}^*)-q^*\mathcal{P}(\boldsymbol{P}^*,\tau^*,\boldsymbol{\omega}^*)=0, \tag{17}$$

The proof is similar to the one in [34]. To find the optimal q^*, the iterative algorithm with guaranteed convergence in [36] can be applied. To make it adapted for solving our problem, we use the framework, and adjust the procedure, as shown in Algorithm 1. The proof of convergence of Algorithm 1 can be found in [36]. During each iteration, we need to solve the following problem for a given q,

Algorithm 1 Iterative Algorithm for Obtaining q^*

Set maximum tolerance δ;
while (not convergence) **do**
  Solve the problem (18) for a given q and obtain subchannel, power and time allocation $\{\mathbf{P}',\tau',\boldsymbol{\omega}'\}$;
  if $\mathcal{U}(\mathbf{P}',\tau',\boldsymbol{\omega}')-q\mathcal{P}(\mathbf{P}',\tau',\boldsymbol{\omega}')\le\delta$ **then**
    Convergence $=$ true;
    return $\{\mathbf{P}^*,\tau^*,\boldsymbol{\omega}^*\}=\{\mathbf{P}',\tau',\boldsymbol{\omega}'\}$ and obtain q^* by (17);
  else
    Convergence $=$ false;
    return Obtain $q=\frac{\mathcal{U}(\mathbf{P}',\tau',\boldsymbol{\omega}')}{\mathcal{P}(\mathbf{P}',\tau',\boldsymbol{\omega}')}$;
  end if
end while

$$\begin{aligned}\textbf{P2:}\ &\max_{\mathbf{P},\tau,\boldsymbol{\omega}}\mathbf{U}(\mathbf{P},\tau,\boldsymbol{\omega})-q\mathcal{P}(\mathbf{P},\tau,\boldsymbol{\omega}),\\ &\text{s.t. } \mathbf{C1}-\mathbf{C7}.\end{aligned} \tag{18}$$

We are able to replace the "$\leqslant$" in **C1** by a "=" sign and substitute it into the optimization problem, and the resulting optimization problem can be viewed as a restricted version of the original problem since it has a smaller feasible set [35]. In order to address the formulated problem, next, we aim at obtaining the secrecy capacity $R_{k,n}$. Correspondingly, the following conclusion can be achieved.

Theorem 2. *Assuming the channel between the InT and eavesdropper is Rayleigh fading, the equivalent secure data rate for InT k is given by*

$$R_{k,n}=WT(1-\tau)\Big[\log_2(1+\gamma_{k,n})-\log_2\left(\frac{\beta_{k,n}^*\Omega_E^{1/2}}{1-\beta_{k,n}^*}\right)\Big]^+, \tag{19}$$

where

$$\begin{aligned}\Omega_E&=(N_R-1)F_{z_h}^{-1}(\varepsilon),\\ \beta_{k,n}^*&=\frac{1}{\sqrt{2\Omega_E}}.\end{aligned} \tag{20}$$

We also assume that $\gamma\gg1$. $F_{z_h}^{-1}(\varepsilon)$ is the inverse function of $F_{z_h}(z)=\varepsilon$, and ε denotes the maximum tolerable secrecy outage in $\mathbf{C1}$. *$F_{z_h}(z)$ is given by*

$$\begin{aligned}F_{z_h}(z)=&\frac{\sum_{n=0}^{N_E-1}\binom{N_R-1}{n}2z^n}{(1+z)^{N_R-1}}\\ &-\frac{\sum_{n=0}^{N_E-1}\sum_{m=0}^{N_E-1}\binom{N_R-1}{n}\binom{N_T-1}{m}z^{m+n}}{(1+z)^{2N_R-2}}.\end{aligned} \tag{21}$$

Proof. The proof is given in Appendix A. □

From Theorem 2, it can be found that the SINR from the InT to the eavesdropper becomes a constant value at high SNR and it is independent of the decision variables, which simplifies the derivation of the resource allocation scheme. With the above analysis, in the following, we can address the transformed optimization problems.

B. Proposed Algorithmic Solution

The transformed problem **P2** is still with a non-convex structure. Tackling the mixed non-convex and combinatorial optimization problem requires a prohibitively high complexity. Although a possible solution can be obtained when addressing such problem in the dual domain. However, for the formulated optimization problem, it may result in a large duality gap between the primal and the dual problem as the non-linear mixed integer programming is involved. In addition, directly solving the whole problem **P2** by developing simple heuristics, e.g., greedy algorithms, may also lead to a large optimality loss in the optimization process. In this paper, we investigate the problem's insights, and derive analytical results for solving **P2**. We firstly relax the problem and decompose the whole optimization process, then we design an iterative search method with guaranteed convergence, and solve the problem to the optimum at each iteration. The developed algorithm reuses the optimal solution of each iteration as much as possible. Next, we present the algorithm design in details.

The proposed algorithmic solution is based on the following analytical results. Firstly, one can observe that from Theorem 2, the entity $\log_2\left(\frac{\beta^*_{k,n}\Omega_E^{1/2}}{1-\beta^*_{k,n}}\right)$ in $R_{k,n}$ is approximately a constant. Constraint $\mathbf{C1}$ can be absorbed into objective function in **P2** or **P1**, without loss optimality. Hence, we can rewritten $R_{k,n}$ as $WT(1-\tau)\Big[\log_2(1+\gamma_{k,n})-\tilde{V}_{k,n}\Big]^+$, where $\tilde{V}_{k,n}=\log_2\left(\frac{\beta^*_{k,n}\Omega_E^{1/2}}{1-\beta^*_{k,n}}\right)$ is seen as a parameter. Secondly, if we consider the rate function in uplink NOMA, also shown in other existing works, e.g., [10], [21], the summation of $\log_2(1+\gamma_{k,n})$ over users on each subchannel can be represented as the following form.

Lemma 3. *In uplink NOMA,* $\sum_{k=1}^{K}\log_2(1+\gamma_{k,n}) = \log_2\frac{\sum_{k=1}^{K}\beta_{k,n}p_{k,n}\|\mathbf{H}_{k,n}\|^2}{\sigma^2}$, $\forall n\in\mathcal{N}$.

Proof. For an arbitrary subchannel n, $\sum_{k=1}^{K}\log_2(1+\gamma_{k,n}) = \log_2(1+\frac{\beta_{1,n}p_{1,n}\|\mathbf{H}_{1,n}\|^2}{\sum_{k=2}^{K}\beta_{k,n}p_{k,n}\|\mathbf{H}_{k,n}\|^2+\sigma^2})+\ldots,+\log_2(1+\frac{\beta_{K,n}p_{K,n}\|\mathbf{H}_{K,n}\|^2}{\sigma^2})$ reads

$$\log_2\Big(\frac{\sum\limits_{k=1}^{K}\beta_{k,n}p_{k,n}\|\mathbf{H}_{k,n}\|^2+\sigma^2}{\sum\limits_{k=2}^{K}\beta_{k,n}p_{k,n}\|\mathbf{H}_{k,n}\|^2+\sigma^2}\times\frac{\sum\limits_{k=2}^{K}\beta_{k,n}p_{k,n}\|\mathbf{H}_{k,n}\|^2+\sigma^2}{\sum\limits_{k=3}^{K}\beta_{k,n}p_{k,n}\|\mathbf{H}_{k,n}\|^2+\sigma^2}\times,\ldots,\times\frac{\sum_{k=K-1}^{K}\beta_{k,n}p_{k,n}\|\mathbf{H}_{k,n}\|^2+\sigma^2}{\beta_{K,n}p_{K,n}\|\mathbf{H}_{K,n}\|^2}\times\frac{\beta_{K,n}p_{K,n}\|\mathbf{H}_{K,n}\|^2}{\sigma^2}\Big) \quad (22)$$

Eliminating the same entities in the denominator and numerator, (22) is equal to $\log_2\frac{\sum_{k=1}^{K}\beta_{k,n}p_{k,n}\|\mathbf{H}_{k,n}\|^2}{\sigma^2}$, hence the conclusion. Note that the result holds for arbitrary decoding orders, and it is independent with the optimization outcome of user allocation on subchannel n. □

Based on the above two observations, we can have our next analytical result. For any given τ and q, if $\mathbf{C5}$ is temporarily removed or relaxed from **P2**, also replacing all entities $\log_2\left(\frac{\beta^*_{k,n}\Omega_E^{1/2}}{1-\beta^*_{k,n}}\right)$ and $\log_2(1+\gamma_{k,n})$ by the derived new forms, we formulate a relaxed version of **P2** in **P3**. We next show **P3** can be solved efficiently.

$$\begin{aligned}
\textbf{P3:}\ \max_{\mathbf{P}\succeq 0}\ & WT(1-\tau)\sum_{n=1}^{N}\log_2\Big(\frac{\sum_{k=1}^{K}\alpha_{k,n}P_n}{\sigma^2}\Big)-\sum_{k=1}^{K}\sum_{n=1}^{N}\tilde{V}_{k,n}\\
& -q\Big(\sum_{n=1}^{N}\tau\nu P_n+P_cT\Big),\\
\text{s.t. } \mathbf{C2}:\ & \sum_{n=1}^{N}P_n\leqslant P_{b,max},\\
\mathbf{C3}:\ & \sum_{n=1}^{N}\frac{\vartheta\tau P_n\|\mathbf{H}_{k,n}\|^2}{(1-\tau)}\le P_{u,max},\ \forall k\in\mathcal{K}\\
\mathbf{C4}:\ & \sum_{n=1}^{N}WT(1-\tau)\log_2\Big(1+\frac{\alpha_{k,n}P_n}{\sigma^2+\sum_{u=k+1}^{K}\alpha_{u,n}P_n}\Big)\\
& -\tilde{V}_{k,n}\geqslant R_{min},\ \forall k\in\mathcal{K}
\end{aligned} \quad (23)$$

where $\alpha_{k,n}=\beta_{k,n}\vartheta\tau/(1-\tau)\|\mathbf{H}_{k,n}\|^2\|\mathbf{H}_{k,n}\|^2$, and $WT(1-\tau)\log_2(1+\frac{\alpha_{k,n}P_n}{\sigma^2+\sum_{u=k+1}^{K}\alpha_{u,n}P_n})-\tilde{V}_{k,n}=R_{k,n}$ in $\mathbf{C4}$. Note that only power is the optimization variable in **P3**, and the binary indicators $\omega_{k,n}$ are no longer needed due to the absence of $\mathbf{C5}$. We then show the convexity of **P3** below.

Lemma 4. ***P3** is convex.*

Proof. For the objective function, one can observe its concavity. Constraints $\mathbf{C2}$ and $\mathbf{C3}$ are linear. For $\mathbf{C4}$, we derive the second derivative for function $f(P_n)=\log_2(1+\frac{\alpha_{k,n}P_n}{\sigma^2+\sum_{u=k+1}^{K}\alpha_{u,n}P_n})$. According to the fact that $f''(P_n)<0$, we therefore conclude the convexity of **P3**. □

The global optimum of a convex problem, e.g., **P3**, can be obtained efficiently by either using standard convex optimization tools or by applying Karush-Kuhn-Tucker (KKT) conditions. Towards the optimum of **P2**, two aspects can be considered from **P3**. First, given the same q, if the optimal solution in **P3** does not violate $\mathbf{C5}$, it is also optimal for **P2**. This is typically observed in many cases that the maximum number of allocated InTs per subchannel, i.e., parameter L, is not too restricted. On the other side, even if $\mathbf{C5}$ is violated, the similar structure in both problems could lead to high correlation between optimal solutions in **P2** and **P3**, namely, the optimal decisions in **P3** would also be favorable in **P2**. This motivates us to consider that, instead of directly addressing **P1** or **P2**, we can approximate it through **P3** firstly, then derive a near-optimal solution by reusing the optimal solution of **P3** as much as possible.

Based on aforementioned considerations and derived results, we propose an iterative searching scheme in Algorithm 2 to solve the original problem **P1**. Algorithm 2 is based on the framework of Algorithm 1. It updates q iteratively, and for each scanned q, the algorithm finds τ by applying bisection search in Line 3 to 6. In each iteration of bisection search, a convex problem **P3** is efficiently solved in Line 4 when τ and q have been updated. The majority of Algorithm 1 is integrated in Line 11 to 18, to decide whether the optimal q is achieved in Line 13, or update suboptimal q in Line 16. According to the proof of [36], and observing the same algorithmic structure between Algorithm 1 and 2, we can conclude the following observation.

Corollary 5. *Convergence is guaranteed in Algorithm 2.*

When the major loop terminates at Line 18, if there is no violation for **C5** during iterations, the outcome, $\mathbf{P}^*, \tau^*, \boldsymbol{\omega}^*$, of the algorithm in Line 20 is an optimal solution for **P1**. Otherwise, the power solution $\mathbf{P}'$ and the corresponding allocation indicator $\boldsymbol{\omega}'$ will provide an upper bound for the global optimum of **P1**. This conclusion is formalized blow.

Lemma 6. *At the termination of Algorithm 2, solution $\{\boldsymbol{P}', \tau', \boldsymbol{\omega}'\}$ is an upper bound for the optimum of* ***P1***.

Proof. Let τ^1, V^1 denote the globally optimal τ and the objective value in **P2**, respectively. Suppose q^1 is optimal, according to Theorem 1, q^1 will lead to the equivalence between **P2** and **P1**. If we set τ^1 and q^1 as the input in **P3**, the resulting optimal objective value of **P3**, denoted as V^2, has $\mathrm{V}^2 \geq \mathrm{V}^1$, because **P3** is a relaxed version of **P2**. In Algorithm 2, the finalized τ' and q in Line 22 corresponds to a resulting objective value in **P3**, denoted as V^3. We then conclude $\mathrm{V}^3 \geq \mathrm{V}^2$. The reason behind is that the optimization procedure for searching τ and q in Algorithm 2 is optimal. If τ^1 and q^1 are not obtained by Algorithm 2 at the termination, it means τ^1 and q^1 are not the best choice in optimization, and will not lead to higher objective value than obtained τ' and q. Thus, from the results of $\mathrm{V}^3 \geq \mathrm{V}^1$ and the equivalence between **P1** and **P2** in EE, the finalized solution $\{\mathbf{P}', \tau', \boldsymbol{\omega}'\}$ in Algorithm 2 enables an upper bound of **P1**. □

Finally, in Line 23, $\mathbf{P}'$ and $\boldsymbol{\omega}'$ can be adjusted by simple heuristic steps, e.g., the method used in [7], to provide a feasible solution, in general suboptimal, for **P1**. The proposed Algorithm 2 has polynomial-time complexity. The majority of the computations are in two nested loops. The outer loop (also refer to as the framework of Algorithm 1 in Sec. IV. A) can be proved to have a linear-time complexity [35]. The inner loop of Algorithm 2 consists of one-dimension bisection search for τ, associated with solving a convex problem P3 in each iteration. The convex problem P3 can be solved by the barrier-based interior-point method with polynomial-time complexity in the worst case [36]. The complexity of bisection search is much moderate than solving a convex problem. Hence, overall the proposed Algorithm 2 is of polynomial-time complexity.

We remark that identifying the solution existence for an optimization problem is an important aspect in algorithm design. If the original problem P1 is infeasible, by solving the relaxed convex problem P3, Algorithm 2 can efficiently provide a simple feasibility check for the solution existence, which is much more easier than solving a non-convex problem P1 to answer the feasibility. In general the proposed Algorithm 2 is able to provide feasible solutions for solving the formulated problem if the original problem P1 is feasible, i.e., at least one feasible solution exists. This is because in Algorithm 2, instead of relying on heuristic procedures, the majority of the optimization is to iteratively and optimally solve a convex problem P3 which is a relaxed version of the original non-convex problem P1. If the solution exists for P1, then solving its relaxed problem P3 is feasible since the feasible region becomes larger.

Algorithm 2 Iterative Algorithm for Solving **P1**

1: **Initialize**: tolerance δ, $Converge$ = false, $Violate$ = false, and $q = 0$;
2: **while** $Converge$ = false **do**
3: **Bisection search** for τ **do**
4: Solve **P3** for current q and τ
5: Obtain optimal power solution **P** for **P3**
6: **until** Maximum EE under the current q is achieved at τ' and $\mathbf{P}'$
7: Convert $\mathbf{P}'$ to its corresponding channel indicators $\boldsymbol{\omega}'$
8: **if** (**C5** is violated in $\boldsymbol{\omega}'$ and $\mathbf{P}'$) **then**
9: $Violate$ = true
10: **end if**
11: **if** $\mathcal{U}(\mathbf{P}', \tau', \boldsymbol{\omega}') - q\mathcal{P}(\mathbf{P}', \tau', \boldsymbol{\omega}') \leq \delta$ **then**
12: $Converge$ = true
13: **return** $\{\mathbf{P}^*, \tau^*, \boldsymbol{\omega}^*\} = \{\mathbf{P}', \tau', \boldsymbol{\omega}'\}$ and update q by (17)
14: **else**
15: $Converge$ = false
16: Update $q = \frac{\mathcal{U}(\mathbf{P}', \tau', \boldsymbol{\omega}')}{\mathcal{P}(\mathbf{P}', \tau', \boldsymbol{\omega}')}$
17: **end if**
18: **end while**
19: **if** $Violate$ = false **then**
20: **Output 1:** Optimal solution $\{\mathbf{P}^*, \tau^*, \boldsymbol{\omega}^*\}$ for **P1**
21: **else**
22: **Output 2:** Upper bound $\{q, \mathbf{P}', \tau', \boldsymbol{\omega}'\}$ for **P1** or **P2**
23: For τ' and q up to date, convert $\mathbf{P}', \boldsymbol{\omega}'$ to a feasible solution $\bar{\mathbf{P}}, \bar{\omega}$ for **P1**
24: **Output 3:** Suboptimal solution $\bar{\mathbf{P}}, \bar{\omega}$ for **P1**
25: **end if**

V. Performance Evaluation

In this section, the performance of the proposed scheme is evaluated and illustrated. In the simulations, we consider one energy transmitter/information receiver and multiple users (EHRs/InTs) and the distance between the EnT and users are about 200m. The bandwidth is 3 MHz. Some key power consumption parameters related to P_c are mainly from [33] and are also given in Table I. As for wireless power transfer,

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TABLE I
SIMULATION PARAMETERS

Parameter	Value
N	64 for OFDMA case
L	3
$P_{b,max}$	$46dBm$
$P_{u,max}$	$23dBm$
R_{min}	$0.1bit/s/Hz$
η	0.5
ε	10^{-7}
P_{DAC}, P_{ADC}	$10mW$
P_{filt}, P_{filr}	$2.5mW$
P_{mix}	$30.3mW$
P_{syn}	$50mW$
P_{LNA}	$20mW$
P_{IFA}	$3mW$

we assume that the energy conversion efficiency of WPT is $\vartheta = 0.5$. A distance-depended path loss model is considered. To evaluate the performance of proposed scheme (P-NOMA), we have implemented a previous NOMA power and channel allocation scheme called "fractional transmit power control" (FTPC) and an OFDMA scheme with FTPC (OFDMA) [4] [35]. For the implemented OFDMA scheme, each user can only be assigned to one subchannel. In the FTPC, the set of multiplexed users U_n for each n is determined by a greed-based user grouping strategy, where $|U_n| = M$. Based on the user allocation, the FTPC method is then used for power allocation. In considered fractional power control schemes, the users with inferior channel condition will be allocated with more power for the fairness consideration [4]. In addition, we also compare our proposed scheme with equal transmit power allocation scheme (ETPA) and equal time allocation scheme (ETTA). In ETPA, NOMA system is considered and the transmit power on each subchannel is equal while the other schemes are the same as the proposed one. In ETTA, the proposed power allocation and subchannel allocation are used while overall time slot is divided equally for data transmission and power delivery.

In Fig. 3, we plot the secure data rate (bps/Hz) versus the transmit power of the EnT. In this figure, we compare the performance of the P-NOMA with that of the OFDMA and ETTA to show the necessity and advantages of our proposed scheme in NOMA and the effectiveness of proposing time allocation scheme. It can be observed that the secure data rate is incremented when the transmit power increases. As the transmit power becomes larger, the secure data rate continues to increment. In NOMA systems, our proposed algorithm performs better than ETTA. Both algorithms in NOMA outperforms the OFDMA system. For example, our proposed resource allocation scheme achieves up to 25% better performance than the ETTA and is about 50% better than that of OFDMA.

Fig. 4 shows the secure data rate (bps/Hz) versus the number of users. In this figure, we also compare the performance of the P-NOMA with that of the FTPC and OFDMA to show the advantages of our proposed scheme. In addition, we also plot the optimal solution obtained by exhaustive search and named it as "Optimum". It can be observed that the secure data rate increases when the number of users grows. As the number of users becomes larger, the secure data rate continues to increment, while the rate of growth becomes slower, as expected from the way to obtain the secure data rate. From this figure, the performance of our proposed allocation scheme is better comparing with the other two schemes. For example, our proposed resource allocation scheme achieves 10% better performance than the FTPC when the number of users is 25, and is about 50% better than that of OFDMA.

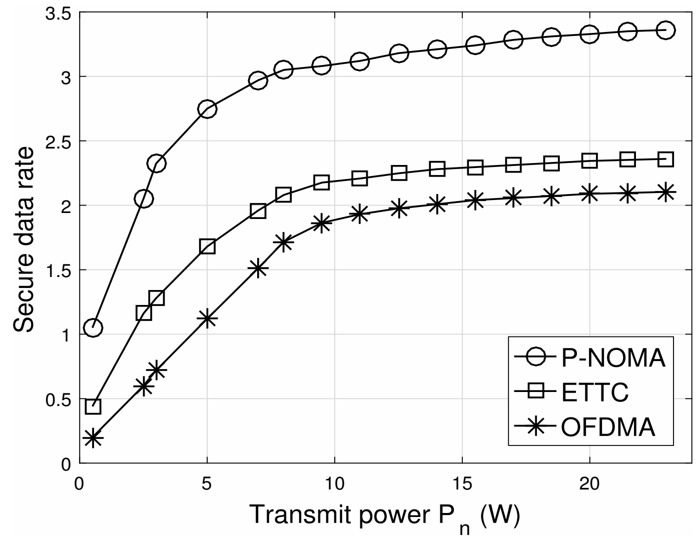

Fig. 3. Secure data rate versus transmit power of the EnT.

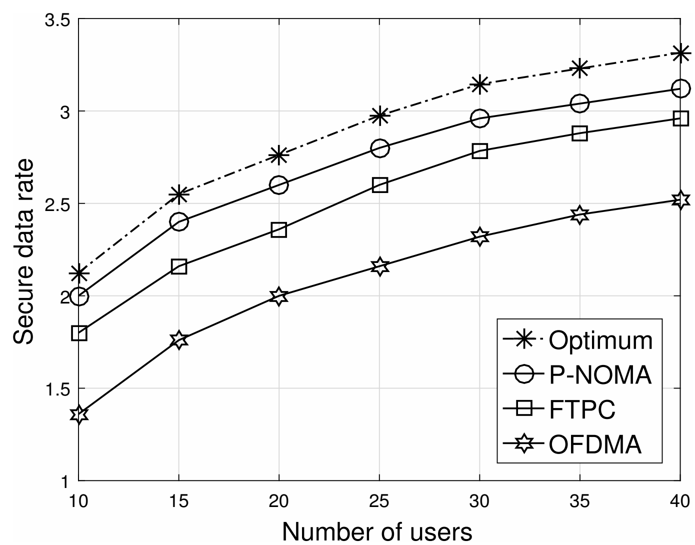

Fig. 4. Secure data rate versus number of users/InTs in the system.

In Fig.5, the performance of EE (bits/J/Hz) is evaluated with the number of users with the same constraints of Fig. 4. To illustrate the advantages of our proposed scheme, we also compare our P-NOMA with the FTPC and OFDMA. It is shown that the EE increases when the number of the users grows. As the number of users grows larger, the EE continues

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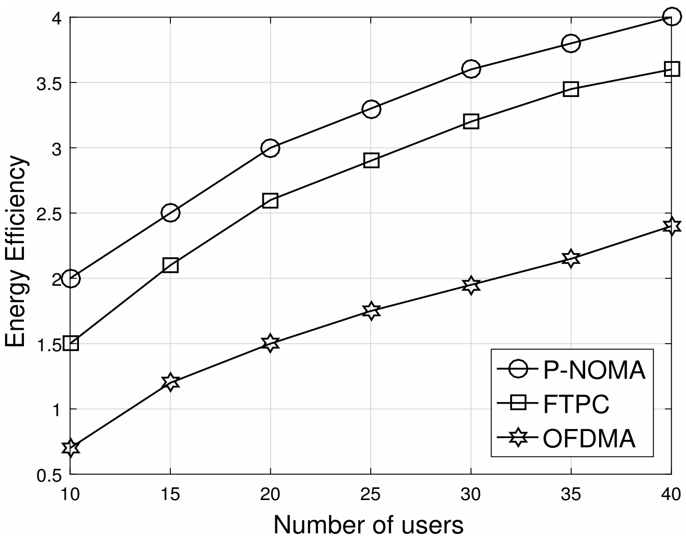

Fig. 5. Energy efficiency versus number of users/InTs in the system.

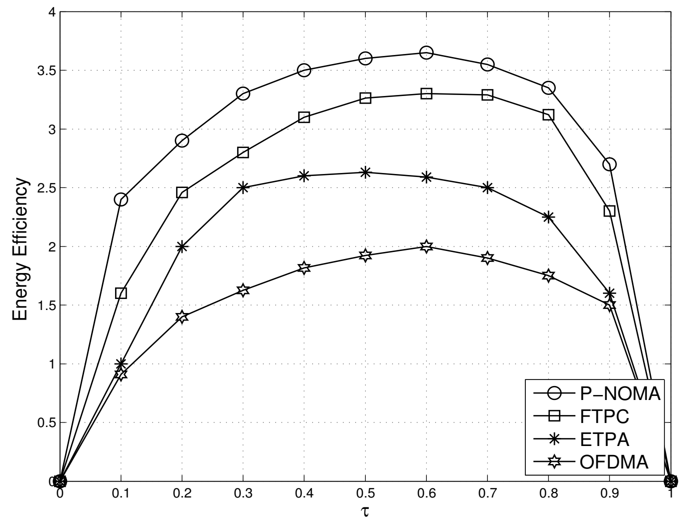

Fig. 7. Energy efficiency versus time allocation.

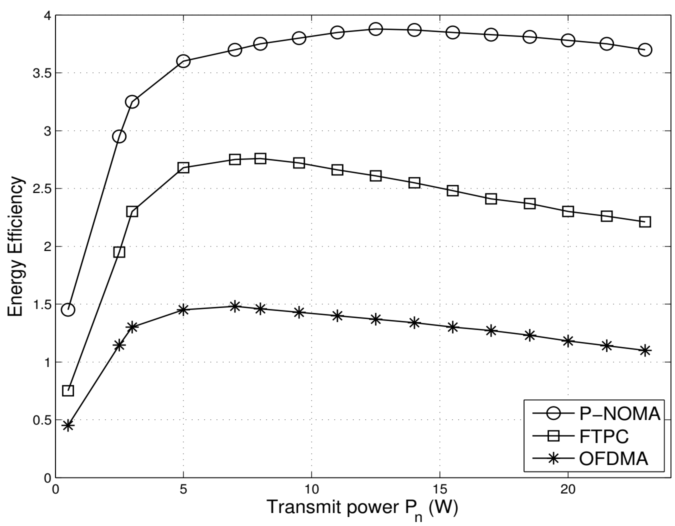

Fig. 6. Energy efficiency versus transmit power of the EnT.

to increase. The trend of the curves is similar to the secure data rate curves in Fig. 4 due to the EE formulation in (13). In addition, from Fig. 5, we can see that the performance of NOMA system with the proposed resource allocation algorithms is better than the OFDMA scheme. For example, when the number of users is 30, the EE of the proposed scheme is about 60% more than that of OFDMA scheme, and is 15% more than that of FTPC scheme. This is mainly due to the fact that in OFDMA scheme, one subchannel can only be used by one user which decrease the efficient usage of frequency bandwidth. Consequently, spectrum resources cannot be fully utilized. For different subchannel power allocation schemes.

Fig. 6 plots the EE by changing the transmit power P_n and allocated time slot τ. The performance of the proposed scheme with optimal time allocation (P-NOMA) is compared with the one of OFDMA with optimal time allocation, and the one of the proposed scheme with equal time allocation (ETTA), e.g. $\tau = 1/2T$. By the comparing these three curves, we can observe that with the increase of transmit power, the EE of the system first ascends and then descends. Similar to the results in other figures, Fig. 6 shows that the transmit power has an optimal value, which confirms the advantages and necessity of power allocation scheme. Moreover, it can be seen that our proposed time allocation scheme can obtain additional EE gain when comparing with the equal time allocation scheme. Last but not the least, we can find that the EE of our proposed scheme is the highest among all three, which shows the advantages of our proposed algorithms over the traditional schemes.

In Fig. 7, we present the total EE in bit/J/Hz versus the time allocation parameter τ. In this figure, we vary the value of first time slot τ and present the EE performance of different resource allocation schemes. Moreover, we also consider the whole time slot $T = 1$ for simplicity. We can observe that there is an optimal value of first time slot τ to maximize the EE. In general, with the increase of time τ, the system EE first increases, then reaches its optimal value and finally decreases. Such phenomenon can be observed for all the cases. In addition, it can be seen that for different algorithms, the optimal EE is different, which evidences the advantages of proposed resource allocation scheme, and the necessity to investigate the time allocation schemes. For example, for the proposed P-NOMA, the optimal EE is higher than the others. The performance difference can be up to 60%, e.g., when comparing the P-NOMA with OFDMA at $\tau = 0.6$. As we can see, our proposed scheme outperforms the other schemes, which confirms the advantages of our proposed schemes.

VI. Conclusion

NOMA is considered as one of the promising techniques for increasing the data rates in the future mobile communication systems. By applying successive interference cancellation schemes and superposition coding at the NOMA receiver, multiple users can be multiplexed on the same subchannel. In this paper, we have investigated secure-rate and energy-efficient resource allocation problem for NOMA systems empowered by the wireless power transfer. With the explicit consideration of an existing eavesdropper, the objective of this work is to obtain secure and energy-efficient transmission among multiple users by investigating time, power and subchannel allocation schemes. In order to solve the formulated problem, we propose an iterative algorithm with guaranteed convergence to deliver a competitive suboptimal solution. The Algorithm is also capable of providing global optimal solutions for some identified cases. Performance evaluations have demonstrated the effectiveness of the proposed algorithm over other resource allocation schemes in NOMA or OFDMA system.

APPENDIX A

Proof of Theorem 2

First, we have the definition of secure data rate $R_{k,n} \approx WT(1-\tau)\log_2(1+\varphi_{k,n})$. Then, the secrecy outage probability

$$\begin{aligned} &\mathbf{Pr}\{R_{k,n} \geqslant C_{k,n} - C_{k,n,E}|\Delta\} = \varepsilon \\ \Rightarrow &\mathbf{Pr}\left\{z \leq \Psi|\Delta\right\} = \varepsilon, \end{aligned} \tag{24}$$

where $z = \frac{\varphi_{k,n}(1-\beta_{k,n})}{1+\beta_{k,n}(N_R-1)}$, $\Psi = \tilde{\mathbf{g}}^{\dagger}(\widetilde{\mathbf{G}}\widetilde{\mathbf{G}}^{\dagger})^{-1}\tilde{\mathbf{g}}$.

The complementary cumulative distribution function (CCDF) is given by

$$\mathbf{Pr}\left\{z \leq \Psi|\Delta_{csi}\right\} = \frac{\sum_{n=0}^{N_E-1}\binom{N_R-1}{n}2z^n}{(1+z)^{N_R-1}}. \tag{25}$$

Therefore, we can obtain

$$\begin{aligned} F_{z_h}(z) = &\frac{\sum_{n=0}^{N_E-1}\binom{N_R-1}{n}2z^n}{(1+z)^{N_R-1}} \\ &- \frac{\sum_{n=0}^{N_E-1}\sum_{m=0}^{N_E-1}\binom{N_R-1}{n}\binom{N_R-1}{m}z^{m+n}}{(1+z)^{2N_R-2}} = \varepsilon. \end{aligned} \tag{26}$$

For a given ε, we have $z = F_{z_h}^{-1}(\varepsilon)$. Then we can have the equivalent secrecy data rate as follows,

$$\begin{aligned} R_{k,n} = &WT(1-\tau)\Big[\log_2(1+\gamma_{k,n}) \\ &- \log_2\left(\frac{\beta_{k,n}(N_T-1)F_{z_h}^{-1}(\varepsilon)}{1-\beta_{k,n}}\right)\Big]^+. \end{aligned} \tag{27}$$

By standard optimization techniques, the asymptotically optimal $\beta_{k,n}^*$ that can minimize the secrecy outage probability is obtained as

$$\beta_{k,n}^* = \frac{-\gamma_{k,n} + \sqrt{2\gamma_{k,n}^2\Omega_E}}{\gamma_{k,n}(2\Omega_E-1)} = \frac{\gamma_{k,n}(\sqrt{2\Omega_E}-1)}{\gamma_{k,n}(2\Omega_E-1)} =\approx \frac{1}{\sqrt{2\Omega_E}}, \tag{28}$$

where $\Omega_E = (N_R-1)F_{z_h}^{-1}(\varepsilon)$.

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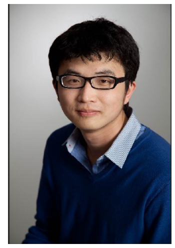

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