Optimal Power Allocation for Superposed Secrecy Transmission in Multicarrier Systems

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***Abstract*—Superposition coding allows secret messages to be delivered stealthily on top of legacy signals. The effective allocation of the limited transmit power at a transmitter is critical to serve the data rate request of a legacy (untrusted) receiver while accomplishing the stealthy and secure transmissions of secret messages to a trusted receiver, which is challenging under OFDM settings due to the non-convexity of the secrecy rate. This paper presents a new iterative algorithm, which optimizes the allocation of the transmit power across the OFDM subcarriers to minimize the transmit power, subject to the data rate request of the (legacy) untrusted receiver and the required secrecy rate of the trusted receiver. The algorithm can also maximize the secrecy rate of the trusted receiver, subject to the data rate request of the untrusted receiver and the total transmit power. In particular, the proposed algorithm decouples the power allocations between the trusted and untrusted receivers. Semi-closed-form solutions are established for the powers, and can be alternately analyzed until convergence with local optimality. Corroborated by simulations, the proposed techniques outperform existing alternatives in terms of power saving and achievable secrecy rate. As the untrusted receiver moves further away from the transmitter, the number of subcarriers carrying superposed signals increases and the secret messages can be delivered unnoticed.**

***Index Terms*—NOMA-OFDM, power allocation, secrecy rate.**

I. Introduction

STEALTHY and secure transmissions of secret messages can be crucial, especially in mission-critical applications [1]–[3]. Consider a multipartite wireless network, e.g., a fleet of vehicles or vessels [4], [5]. One of the parties may wish to send secret messages to its trusted peer, while keeping the messages inaccessible or even unnoticed to the other, untrusted parties. The secret messages could be critical control command, or confidential information. Supposition coding (SC) can be carried out at the transmitter, so that secret messages destined for the trusted receiver can be delivered (unnoticed) on top of other messages destined for an untrusted receiver using the same time and frequency resources [6]–[8]. Successive interference cancellation (SIC) can be utilized at the trusted receiver to recover its secret messages [9]–[11]. In this sense, the transmission and the detection architecture are consistent with the emerging non-orthogonal multiple access (NOMA) [12]–[15], which has been typically known for high throughput and connectivity. In many cases, a wideband multicarrier waveform, such as orthogonal frequency division multiplexing (OFDM), would be used for the transmission to exploit the frequency selectivity of wireless channels, simplify equalization, and achieve high throughput. In other words, a so-called NOMA-OFDM waveform can be a suitable candidate waveform for stealthy and secure transmissions of secret messages.

To the best of our knowledge, the stealthy and secure transmissions of secret messages using the NOMA-OFDM waveform have to date not been studied in the literature. This can be technically challenging because of non-convex constraint of the secrecy rate requirement. The most relevant existing studies [16]–[18] have only focused on single-carrier multiple-input single-output (MISO) NOMA systems or secure beamforming in single-carrier multiple-input multiple-output (MIMO) NOMA systems. It would be non-trivial to extend those studies to the NOMA-OFDM waveform.

This paper presents new power allocation techniques for stealthy and secure transmissions of secret messages using the NOMA-OFDM waveform in a tripartite wireless network. The new techniques minimize the total transmit power of a transmitter (Tx) to both a trusted (near) receiver and an untrusted (far) receiver, or maximize the secrecy rate of the trusted. In particular, we first optimize the power allocation to minimize the transmit power subject to the secrecy rate requirement of the trusted receiver and the data rate request of the untrusted. Further, we optimize the power allocation to maximize the secrecy rate of the trusted receiver, subject to the data rate request of the untrusted and the total transmit power of the Tx. In both cases, the data rate requested by the untrusted receiver is guaranteed. The secret message to the trusted receiver is transmitted on top of the data transmissions to the untrusted, thereby providing stealthiness to the secret transmissions.

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The key contributions of this paper are summarized as follows.

1) We consider new superposed transmissions to deliver secret OFDM signals stealthily and securely, and formulate two problems to separately minimize the total transmit power and maximize the secrecy rate. The problems are non-convex, and each is decomposed into two convex subproblems with alternating optimization.
2) Semi-closed-form solutions are established for the subproblems based on the Karush-Kuhn-Tucker (KKT) conditions. By evaluating the solutions in an alternating manner, local optimal solutions to the considered problems can be achieved with fast convergence.
3) As per the maximization of the secrecy rate, the alternating optimization-based decomposition is non-straightforward due to an indecomposable objective. The necessary condition of the optimality is derived, based on which the problem is decomposed into subproblems with semi-closed-form solutions.
4) The proposed algorithms are extended under a more stringent per-subcarrier power limit.

Corroborated by extensive simulations, the proposed techniques outperform existing OMA-based alternatives in regards of power saving and achievable secrecy rate. We find that, when the secrecy rate constraint becomes stringent, more power is assigned to the trusted receiver. As the distance from the transmitter to the untrusted receiver increases, NOMA is increasingly utilized at different subcarriers (as compared to OMA); in other words, the number of OFDM subcarriers carrying superposed signals increases.

Alternating optimization is employed to solve the considered problem in our paper. Nevertheless, the key contribution of the paper is the rigorous establishment of semi-closed-form solutions for each step of the alternating optimization, not the use of alternating optimization. The benefit of the semi-closed-form solutions is better optimization accuracy or fast convergence (in comparison with a difference-of-convex (DC)-based alternative). As a result, our algorithm converges significantly faster than its DC-based alternative, while they are indistinguishably close in terms of power consumption and secrecy rate, as will be shown in the simulations of this paper.

The remainder of this paper is arranged, as follows. In Section II, related works are surveyed. Section III provides the system model. We elaborate on the new algorithms which minimize the transmit power and maximize the secrecy rate in Sections IV and V, respectively. We extend our proposed algorithm under the per-subcarrier transmit power limit in Section VI. Simulations are provided in Section VII to validate the algorithms in regards of power saving and secrecy rate. In Section VIII, conclusions are drawn.

II. Related Work

Resource allocation of NOMA systems has been extensively studied without security consideration. It was found in [19] that a two-receiver NOMA system with fixed power allocation is better than OMA in terms of sum rate. It was also found that the two receivers which, under substantial channel conditions, can provide better sum rate gain in a fixed power allocation system; while the two receivers which have best channel conditions can provide better sum rate gain in a cognitive-radio-inspired NOMA system. The authors of [20] optimized the resource allocation to maximize the sum rate of multiple receivers NOMA systems, where receiver pairing was optimized by greedy search and power allocation was obtained with an iterative algorithm. These literatures are particularly interested in single-carrier NOMA systems. Recently, multicarrier NOMA, i.e., NOMA-OFDM, has drawn great interest [21]–[23]. In [21], subcarrier pairing and power allocation were jointly optimized to minimize the transmit power under the QoS requirements of the receivers by using the Lagrange dual method in a cooperative two-receiver NOMA-OFDM system. To maximize the system throughput of a NOMA-OFDM system, an iterative power and subcarrier allocation technique were developed in [22] by using transforming the non-convex constraint into linear expressions. Power allocation and subcarrier assignment were jointly optimized to minimize the total transmit power subject to the QoS requirements of multiple receivers in NOMA-OFDM systems [23]. Variable substitution was applied to the power allocation problem.

Resource allocation of NOMA systems with security considerations has been increasingly investigated in the literature. The authors of [24] derived the closed-form solution for the optimal power allocation, which maximizes the sum secrecy rate subject to the quality-of-service (QoS) requirements of the receivers, where there is a transmitter, multiple legitimate receivers and an eavesdropper. In [25], a new NOMA system jointly optimized each receiver's power allocation, decoding order and data rate to minimize the transmit power in the presence of an eavesdropper. In [26], the authors maximized the energy efficiency by considering an eavesdropper among multiple receivers, and optimizing time, power and subchannel allocation. In the existing literature, such as [24]–[26], eavesdroppers have been typically assumed to be external. In contrast, it was assumed the internal eavesdropper in [16]–[18]. The authors of [16] jointly optimized beamforming and power allocation to prevent multicast receivers from overhearing unicast messages. In [17], the authors proposed a power allocation and beamforming strategy in MISO NOMA systems to maximize the sum achievable secrecy rate, where multiple receivers are divided into multiple groups, each group with two receivers, and later extended to MIMO NOMA systems in [18]. In [16]–[18], only single-carrier NOMA transmissions were considered.

Despite single-carrier secure NOMA has been widely investigated [16]–[18], [24], [25], only several known studies [27]–[29] have considered secure communications in multicarrier NOMA systems. Han *et al.* [27] proposed a joint power and sub-channel allocation algorithm to maximize the secrecy capacity of an uplink NOMA channel. Zhang *et al.* [28] maximized the secrecy energy efficiency of amplify-and-forward (AF) two-way relay NOMA networks by optimizing subcarrier assignment and power allocation. In [29], subcarrier allocation, power allocation and beamforming were designed to prevent information leakage in full-duplex (FD) multiple-input single-output (MISO) multicarrier NOMA systems by using a constraint that the data rate of a legitimate user is higher than the capacity of the eavesdropping

link. However, the techniques developed in [27]–[29] cannot solve the problem considered in this paper, because of distinct system models (i.e., uplink in [27], AF two-way relay in [28], and full-duplex in [29] vs. downlink in this paper) and different problem formulations (i.e., secrecy capacity and energy efficiency maximization in the presence of an external pure eavesdropper in [27]–[29], vs. secrecy rate maximization of a fully trusted user under the data rate requirement of a legitimate yet untrusted user (i.e., a potential internal eavesdropper) in this paper).

III. System Model

Consider a scenario consisting of a transmitter (Tx) and two receivers. One is a trusted, near receiver (NRx) by the Tx; and the other is an untrusted, far receiver (FRx). The Tx serves the two receivers over N orthogonal OFDM subcarriers. The channel coefficients from the Tx to the NRx and FRx at subcarrier n are $h_{\mathrm{NRx},n} \triangleq g_{\mathrm{NRx},n} d_{\mathrm{NRx}}^{-\alpha}$ and $h_{\mathrm{FRx},n} \triangleq g_{\mathrm{FRx},n} d_{\mathrm{FRx}}^{-\alpha}$, where $g_{\mathrm{NRx},n}$ and $g_{\mathrm{FRx},n}$ are the small-scale fading (e.g., Rayleigh fading) channel coefficients; d_{NRx} and d_{FRx} are the distances between the NRx and the Tx, and between the FRx and the Tx, respectively; and α denotes the path loss exponent. At the Tx, the superposition coded symbol x_n for the two receivers at subcarrier n is given by

$$x_n = \sqrt{p_{\mathrm{NRx},n}} s_{\mathrm{NRx},n} + \sqrt{p_{\mathrm{FRx},n}} s_{\mathrm{FRx},n}, \tag{1}$$

where $s_{\mathrm{NRx},n}$ and $s_{\mathrm{FRx},n}$ are the data symbols at the n-th OFDM subcarrier destined for the NRx and FRx with unit energy $\mathbb{E}[|s_{\mathrm{NRx},n}|^2] = \mathbb{E}[|s_{\mathrm{FRx},n}|^2] = 1$, respectively; and $p_{\mathrm{NRx},n}$ and $p_{\mathrm{FRx},n}$ are the corresponding transmit powers.

Then, the received signals of both the NRx and FRx at subcarrier n are given by

$$y_{k,n} = h_{k,n}\sqrt{p_{\mathrm{NRx},n}} s_{\mathrm{NRx},n} + h_{k,n}\sqrt{p_{\mathrm{FRx},n}} s_{\mathrm{FRx},n} + w_{k,n}, \tag{2}$$

where $w_{k,n}$, $k \in \{\mathrm{NRx}, \mathrm{FRx}\}$ is a zero-mean additive white Gaussian noise (AWGN) with variance σ^2.

According to [30] and [31], SIC is implemented at the receivers. The NRx first detects s_{FRx} and then cancels s_{FRx} to obtain its own signal s_{NRx}. Thus, the received signal-to-interference-plus-noise ratios (SINRs) for detecting s_{FRx} and s_{NRx} at the NRx are given by

$$\Gamma_{\mathrm{NRx},n}^{\mathrm{FRx}} = \frac{p_{\mathrm{FRx},n} a_{\mathrm{NRx},n}}{p_{\mathrm{NRx},n} a_{\mathrm{NRx},n} + 1}; \ \Gamma_{\mathrm{NRx},n}^{\mathrm{NRx}} = p_{\mathrm{NRx},n} a_{\mathrm{NRx},n}, \tag{3}$$

where $a_{\mathrm{NRx},n} \triangleq \frac{|h_{\mathrm{NRx},n}|^2}{\sigma^2}$ is the carrier-to-noise ratio (CNR) of the direct link. The achievable data rate of the NRx at subcarrier n (in bps/Hz) is given by

$$R_{\mathrm{NRx},n}^{\mathrm{NRx}} = \log_2\left(1 + \Gamma_{\mathrm{NRx},n}^{\mathrm{NRx}}\right). \tag{4}$$

Likewise, the SINRs of s_{FRx} and s_{NRx} at the FRx are:

$$\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}} = \frac{p_{\mathrm{FRx},n} a_{\mathrm{FRx},n}}{p_{\mathrm{NRx},n} a_{\mathrm{FRx},n} + 1}; \ \Gamma_{\mathrm{FRx},n}^{\mathrm{NRx}} = p_{\mathrm{NRx},n} a_{\mathrm{FRx},n}, \tag{5}$$

where $a_{\mathrm{FRx},n} \triangleq \frac{|h_{\mathrm{FRx},n}|^2}{\sigma^2}$. The eavesdropping rate by the FRx (against the NRx) at subcarrier n is given by

$$R_{\mathrm{FRx},n}^{\mathrm{NRx}} = \log_2\left(1 + \Gamma_{\mathrm{FRx},n}^{\mathrm{NRx}}\right). \tag{6}$$

The secrecy rate of the NRx at subcarrier n is given by [17]

$$R_{s,n} = \left[R_{\mathrm{NRx},n}^{\mathrm{NRx}} - R_{\mathrm{FRx},n}^{\mathrm{NRx}}\right]^+, \tag{7}$$

where $[x]^+ = \max(x, 0)$.

The scenario of interest is that, when transmitting the requested data rate to the FRx, the Tx takes the geographical advantage of the NRx and superposes its secret messages intended for the NRx on top of its transmission to the FRx. One purpose is to increase the spectral utilization. More importantly, the Tx can deliver messages secretly to the NRx unnoticed, and also protect the secrecy of the transmissions against the FRx (in case the FRx notices).

IV. Secrecy-Aware Minimization of Transmit Power

In this section, we minimize the transmit power of the Tx, subject to the requested data rate of the FRx and the required secrecy rate of the NRx. The problem is formulated as

$$\min_{p_{\mathrm{NRx},n}, p_{\mathrm{FRx},n}} \sum_{n\in\mathcal{N}} \left(p_{\mathrm{NRx},n} + p_{\mathrm{FRx},n}\right) \tag{8a}$$

$$s.t. \sum_{n\in\mathcal{N}} R_{s,n} \geq R_{\mathrm{NRx}}, \tag{8b}$$

$$\sum_{n\in\mathcal{N}} \log_2\left(1 + \Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right) \geq R_{\mathrm{FRx}}, \tag{8c}$$

$$p_{\mathrm{NRx},n} \geq 0, p_{\mathrm{FRx},n} \geq 0, \forall n \in \mathcal{N}, \tag{8d}$$

where R_{NRx} is the requested minimum secrecy rate of the NRx, and R_{FRx} is the requested minimum data rate of the FRx. Constraint (8 d) indicates that the power allocated to each subcarrier needs to be non-negative. The other constraints, i.e., (8b) and (8c), are self-explanatory.

Constraint (8c) is non-convex and so is problem (8), where $p_{\mathrm{NRx},n}$ and $p_{\mathrm{FRx},n}$, i.e., the per-subcarrier transmit powers allocated for the NRx and FRx, are closely coupled. The problem does not have analytical solutions and cannot be solved by directly using standard convex tools. In [22], a similar constraint to (8c) was considered to specify the minimum data rate requirement of each single-carrier receiver, i.e., $\log_2(1 + \Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}) \geq R_{\mathrm{FRx}}$, which was transformed to a series of linear programs and much tractable than (8c). This is because (8c) involves the summation across all subcarriers and cannot be transformed to linear programs. In [23], there was no constraint on secrecy rates, i.e., (8b), and the transmit powers were rewritten as functions of the data rates by applying variable substitution to (8c). However, the secrecy rate of the NRx (8b) cannot be written as a closed-form function of the data rate of the FRx. Therefore, the variable substitution is not applicable to (8). Problem (8) is challenging and cannot be solved by using current techniques developed to address similar problems, e.g., in [22] and [23].

In the rest of this section, we develop an iterative algorithm to solve the non-convex problem (8). The algorithm consists of two steps. The first step is to optimize $p_{\mathrm{FRx},n}$ to minimize $\sum_{n\in\mathcal{N}} p_{\mathrm{FRx},n}$, given $p_{\mathrm{NRx},n}$. The second step is to optimize p_{NRx} to minimize $\sum_{n\in\mathcal{N}} p_{\mathrm{NRx},n}$, given $p_{\mathrm{FRx},n}$ obtained from the first step. Each of the steps can be converted to a convex

problem with analytical solutions. The two steps repeat in an alternating manner until convergence, as described in the following.

Step 1: Given fixed $p_{\mathrm{NRx},n}$, denoted by $p^*_{\mathrm{NRx},n}$, constraint (8b) is suppressed and the considered problem (8) is rewritten as

$$\min_{p_{\mathrm{FRx},n}} \sum_{n\in\mathcal{N}} \left(p_{\mathrm{FRx},n} + p^*_{\mathrm{NRx},n}\right) \tag{9a}$$

$$s.t. (8\mathrm{c}) \text{ and } p_{\mathrm{FRx},n} \geq 0, \forall n \in \mathcal{N}. \tag{9b}$$

Problem (9) is convex and solvable by using the KKT conditions to find the optimal solution. The KKT conditions of (9) are given by

$$\frac{\partial L\left(p_{\mathrm{FRx},n}, \lambda\right)}{\partial p_{\mathrm{FRx},n}} = 0, n \in \mathcal{N}, \tag{10a}$$

$$\lambda\left(R_{\mathrm{FRx}} - \sum_{n\in\mathcal{N}} \log_2\left(1 + \Gamma^{\mathrm{FRx}}_{\mathrm{FRx},n}\right)\right) = 0, \tag{10b}$$

$$R_{\mathrm{FRx}} - \sum_{n\in\mathcal{N}} \log_2\left(1 + \Gamma^{\mathrm{FRx}}_{\mathrm{FRx},n}\right) \leq 0, \tag{10c}$$

$$\lambda \geq 0, \tag{10d}$$

where λ is the Lagrange dual variable and the Lagrangian is given by

$$L\left(p_{\mathrm{FRx},n}, \lambda\right) = \sum_{n\in\mathcal{N}} p_{\mathrm{FRx},n} + \sum_{n\in\mathcal{N}} p^*_{\mathrm{NRx},n} + \lambda\left(R_{\mathrm{FRx}} - \sum_{n\in\mathcal{N}} \log_2\left(1 + \Gamma^{\mathrm{FRx}}_{\mathrm{FRx},n}\right)\right). \tag{11}$$

By solving (10a), we obtain the optimal solution to (9), as given by

$$p^*_{\mathrm{FRx},n} = \left[\frac{\lambda}{\ln 2} - \frac{p^*_{\mathrm{NRx},n} a_{\mathrm{FRx},n} + 1}{a_{\mathrm{FRx},n}}\right]^+. \tag{12}$$

Clearly, (12) is an increasing function of λ and $\log_2(1 + \Gamma^{\mathrm{FRx}}_{\mathrm{FRx},n})$ is an increasing function of $p_{\mathrm{FRx},n}$. Therefore, $\log_2(1 + \Gamma^{\mathrm{FRx}}_{\mathrm{FRx},n})$ is an increasing function of λ. According to (10b), λ can be solved efficiently by using bisection search until

$$\sum_{n\in\mathcal{N}} \log_2\left(1 + \Gamma^{\mathrm{FRx}}_{\mathrm{FRx},n}\right) = R_{\mathrm{FRx}}. \tag{13}$$

The reason underlying (13) is because, if $\lambda = 0$, (10a) cannot be satisfied; and only λ is positive, (12) is feasible. Therefore, $\sum_{n\in\mathcal{N}} \log_2(1 + \Gamma^{\mathrm{FRx}}_{\mathrm{FRx},n})$ is equivalent to R_{FRx} for the optimal solution to (9), as shown in (13).

Step 2: Given the transmit power allocated for the FRx (12), the power allocation for the NRx in (8) can be transformed into the following univariate optimization problem:

$$\min_{p_{\mathrm{NRx},n}} \sum_{n\in\mathcal{N}} \left(p_{\mathrm{NRx},n} + p^*_{\mathrm{FRx},n}\right) \tag{14a}$$

$$s.t. (8\mathrm{b}) \text{ and } p_{\mathrm{NRx},n} \geq 0, \forall n \in \mathcal{N}. \tag{14b}$$

We confirm that (14) is convex because both the objective of (14) and the constraint $p_{\mathrm{NRx},n} \geq 0$ are linear to $p_{\mathrm{NRx},n}, n \in \mathcal{N}$. Now we only need to confirm the convexity of the secrecy constraint (8b). The second derivative of $R_{s,n}$ with respective to $p_{\mathrm{NRx},n}$ is given by

$$\frac{\partial^2 R_{s,n}}{\partial p^2_{\mathrm{NRx},n}} = \frac{\left(a_{\mathrm{FRx},n} - a_{\mathrm{NRx},n}\right)\left(a_{\mathrm{NRx},n} + a_{\mathrm{FRx},n} + 2a_{\mathrm{NRx,n}} a_{\mathrm{FRx},n} p_{\mathrm{NRx},n}\right)}{\left(1 + p_{\mathrm{NRx},n} a_{\mathrm{NRx},n}\right)^2 \left(1 + p_{\mathrm{NRx},n} a_{\mathrm{FRx},n}\right)^2}, \tag{15}$$

we have $\frac{\partial^2 R_{s,n}}{\partial p^2_{\mathrm{NRx},n}} \leq 0$ for $a_{\mathrm{NRx},n} > a_{\mathrm{FRx},n}$. Thus, $R_{s,n}$ is a concave function of $p_{\mathrm{NRx},n}$. $\sum_{n\in\mathcal{N}} R_{s,n}$ is the sum of multiple concave functions and therefore is a concave function of $p_{\mathrm{NRx},n}$. Therefore, (8b) is a convex constraint and problem (14) is convex.

Given $p^*_{\mathrm{FRx},n}$, we can apply the KKT conditions to derive the optimal solution to problem (14), as given by

$$\frac{\partial L\left(p_{\mathrm{NRx},n}, \mu\right)}{\partial p_{\mathrm{NRx},n}} = 0, n \in \mathcal{N}, \tag{16a}$$

$$\lambda\left(R_{\mathrm{NRx}} - \sum_{n\in\mathcal{N}} R_{s,n}\right) = 0, \tag{16b}$$

$$R_{\mathrm{NRx}} - \sum_{n\in\mathcal{N}} R_{s,n} \leq 0, \tag{16c}$$

$$\mu \geq 0, \tag{16d}$$

where μ is the Lagrange dual variable and the Lagrangian is written as

$$L\left(p_{\mathrm{NRx},n}, \mu\right) = \sum_{n\in\mathcal{N}} p_{\mathrm{NRx},n} + \sum_{n\in\mathcal{N}} p^*_{\mathrm{FRx},n} + \mu\left(R_{\mathrm{NRx}} - \sum_{n\in\mathcal{N}} R_{s,n}\right). \tag{17}$$

By setting $\frac{\partial L(p_{\mathrm{NRx},n},\mu)}{\partial p_{\mathrm{NRx},n}} = 0$ in (16a), we have

$$\mu\left(\frac{a_{\mathrm{NRx},n}}{\left(1 + p_{\mathrm{NRx},n} a_{\mathrm{NRx},n}\right)\ln 2} - \frac{a_{\mathrm{FRx},n}}{\left(1 + p_{\mathrm{NRx}n} a_{\mathrm{FRx},n}\right)\ln 2}\right) = 1, \tag{18}$$

which can be rewritten in the following quadratic form:

$$a_{\mathrm{NRx},n} a_{\mathrm{FRx},n} p^2_{\mathrm{NRx},n} + \left(a_{\mathrm{NRx},n} + a_{\mathrm{FRx},n}\right) p_{\mathrm{NRx},n} - \frac{\mu\left(a_{\mathrm{NRx},n} - a_{\mathrm{FRx},n}\right)}{\ln 2} + 1 = 0, \tag{19}$$

where $p_{\mathrm{NRx},n}$ has the following two roots:

$$p_{\mathrm{NRx},n} = -\frac{\left(a_{\mathrm{NRx},n} + a_{\mathrm{FRx,n}}\right)}{2a_{\mathrm{NRx},n} a_{\mathrm{FRx,n}}} \pm \frac{\sqrt{\left(a_{\mathrm{NRx},n} - a_{\mathrm{FRx},n}\right)^2 + \frac{4\mu}{\ln 2} a_{\mathrm{NRx},n} a_{\mathrm{FRx},n}\left(a_{\mathrm{NRx},n} - a_{\mathrm{FRx},n}\right)}}{2a_{\mathrm{NRx},n} a_{\mathrm{FRx},n}}, \tag{20}$$

Algorithm 1: Joint Power Allocation to Minimize the Total Transmit Power.

Input: R_{NRx}, R_{FRx}, N, the lower and upper bounds λ_1, μ_1 and λ_2, μ_2, threshold ϵ_1, ϵ_2, ϵ_3, $i = 1$;

1 **repeat**
2 **repeat**
3   Update λ by $\lambda = (\lambda_1 + \lambda_2)/2$;
4   Calculate $p_{\mathrm{FRx},n}^{(i+1)}$, $n \in \mathcal{N}$ according to (12);
5   **if** $\sum_{n\in\mathcal{N}} \log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right) < R_{\mathrm{FRx}} - \epsilon_1$ **then**
6    $\lambda_1 = \lambda$;
7   **else if** $\sum_{n\in\mathcal{N}} \log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right) > R_{\mathrm{FRx}} + \epsilon_1$ **then**
8    $\lambda_2 = \lambda$;
9 **until** $\left|\sum_{n\in\mathcal{N}} \log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right) - R_{\mathrm{FRx}}\right| \le \epsilon_1$;
10 Substitute λ into (12) and obtain $p_{\mathrm{FRx},n}^{(i+1)}$;
11 **repeat**
12   Update μ by $\mu = (\mu_1 + \mu_2)/2$;
13   Calculate $p_{\mathrm{NRx},n}^{(i+1)}$ with obtained $p_{\mathrm{FRx},n}^{(i+1)}$, $n \in \mathcal{N}$ according to (22);
14   **if** $\sum_{n\in\mathcal{N}} R_{s,n} < R_{\mathrm{NRx}} - \epsilon_2$ **then**
15    $\mu_1 = \mu$;
16   **else if** $\sum_{n\in\mathcal{N}} R_{s,n} > R_{\mathrm{NRx}} + \epsilon_2$ **then**
17    $\mu_2 = \mu$;
18 **until** $\left|\sum_{n\in\mathcal{N}} R_{s,n} - R_{\mathrm{NRx}}\right| \le \epsilon_2$;
19 $i \Leftarrow i + 1$;
20 **until** $\left|\sum_{n=1}^{N}\left(p_{\mathrm{FRx},n}^{(i+1)}+p_{\mathrm{NRx},n}^{(i+1)}\right)-\sum_{n=1}^{N}\left(p_{\mathrm{FRx},n}^{(i)}+p_{\mathrm{NRx},n}^{(i)}\right)\right| \le \epsilon_3$;

Output: $p_{\mathrm{FRx},n}$ and $p_{\mathrm{NRx},n}$, $n \in \mathcal{N}$.

we take the positive root. If $\mu > \frac{\ln 2}{a_{\mathrm{NRx},n}-a_{\mathrm{FRx},n}}$, then the root is positive and $p_{\mathrm{NRx},n}^{*} = p_{\mathrm{NRx},n}$. If $\mu \le \frac{\ln 2}{a_{\mathrm{NRx},n}-a_{\mathrm{FRx},n}}$, then $p_{\mathrm{NRx},n}^{*} = 0$.

As a result, the optimal power allocation for the NRx at subcarrier n is given by

$$p_{\mathrm{NRx},n} = \begin{cases} p_{\mathrm{NRx},n}^{*}, & \text{if } \mu > \frac{\ln 2}{a_{\mathrm{NRx},n}-a_{\mathrm{FRx},n}}; \\ 0, & \text{if } \mu \le \frac{\ln 2}{a_{\mathrm{NRx},n}-a_{\mathrm{FRx},n}}, \end{cases} \tag{21}$$

where $p_{\mathrm{NRx},n}^{*}$ is given by

$$p_{\mathrm{NRx},n}^{*} = -\frac{(a_{\mathrm{NRx},n} + a_{\mathrm{FRx},n})}{2a_{\mathrm{NRx},n}a_{\mathrm{FRx},n}} + \frac{\sqrt{(a_{\mathrm{NRx},n}-a_{\mathrm{FRx},n})^2+\frac{4\mu}{\ln 2}a_{\mathrm{NRx},n}a_{\mathrm{FRx},n}(a_{\mathrm{NRx},n}-a_{\mathrm{FRx},n})}}{2a_{\mathrm{NRx},n}a_{\mathrm{FRx},n}}, \tag{22}$$

and according to (16b), μ is obtained by running bisection search until

$$\sum_{n\in\mathcal{N}} R_{s,n} = R_{\mathrm{NRx}}. \tag{23}$$

3) Algorithmic Summary: Algorithm 1 summarizes the proposed algorithm involving the above two steps: the power allocation for the FRx, given the power allocation for the NRx, i.e., Steps 2 – 9; and the power allocation for the NRx, given the power allocation for the FRx, i.e., Steps 11 – 18. These two steps alternate and iterate the convergence of the objective $\sum_{n\in\mathcal{N}}(p_{\mathrm{NRx,n}} + p_{\mathrm{FRx},n})$; see Steps 19 – 20.

Algorithm 1 is convergent. The proof is as follows. Despite its non-convexity, the considered problem (8) can be decoupled into two convex subproblems with the same objective and non-overlapping variables. Each subproblem fixes one set of optimization variables (i.e., the power allocation for one of the two receivers, $p_{\mathrm{FRx,n}}$, $\forall n$) and solves the other set (i.e., the power allocation for the other receiver, $p_{\mathrm{NRx,n}}$, $\forall n$). By using alternating optimization, the two subproblems are solved in an alternating manner. In particular, at the i-th iteration of Algorithm 1, we assume that $p_{\mathrm{NRx},n}^{(i)}$ and $p_{\mathrm{FRx},n}^{(i)}$ are the optimized transmit powers of the BS to NRx and FRx, respectively. Since problem (9) is convex, its optimal solution can be obtained by using the KKT conditions at the $(i+1)$-th iteration [32]. With $p_{\mathrm{FRx},n}^{(i+1)}$ being the optimal solution to problem (9) at the $(i+1)$-th iteration, we have $\sum_{n\in\mathcal{N}} p_{\mathrm{FRx},n}^{(i+1)} \le \sum_{n\in\mathcal{N}} p_{\mathrm{FRx},n}^{(i)}$. With the given $p_{\mathrm{NRx},n}^{(i)}$, we have

$$\sum_{n\in\mathcal{N}}\left(p_{\mathrm{FRx},n}^{(i+1)} + p_{\mathrm{NRx},n}^{(i)}\right) \le \sum_{n\in\mathcal{N}}\left(p_{\mathrm{FRx},n}^{(i)} + p_{\mathrm{NRx},n}^{(i)}\right). \tag{24}$$

Likewise, problem (14) is convex and can be optimally solved by using the KKT conditions. With $p_{\mathrm{NRx},n}^{(i+1)}$ being the optimal solution to problem (14) at the $(i+1)$-th iteration, $\sum_{n\in\mathcal{N}} p_{\mathrm{NRx},n}^{(i+1)} \le \sum_{n\in\mathcal{N}} p_{\mathrm{FRx},n}^{(i)}$. With the given $p_{\mathrm{FRx},n}^{(i+1)}$, we have

$$\sum_{n\in\mathcal{N}}\left(p_{\mathrm{FRx},n}^{(i+1)} + p_{\mathrm{NRx},n}^{(i+1)}\right) \le \sum_{n\in\mathcal{N}}\left(p_{\mathrm{FRx},n}^{(i+1)} + p_{\mathrm{NRx},n}^{(i)}\right). \tag{25}$$

Based on (24) and (25), the objective value of (8) satisfies

$$\sum_{n\in\mathcal{N}}\left(p_{\mathrm{FRx},n}^{(i+1)} + p_{\mathrm{NRx},n}^{(i+1)}\right) \le \sum_{n\in\mathcal{N}}\left(p_{\mathrm{FRx},n}^{(i+1)} + p_{\mathrm{NRx},n}^{(i)}\right) \le \sum_{n\in\mathcal{N}}\left(p_{\mathrm{FRx},n}^{(i)} + p_{\mathrm{NRx},n}^{(i)}\right). \tag{26}$$

It is proved that the objective of (8) holds a non-increasing property throughout the execution of Algorithm 1. Since $\sum_{n\in\mathcal{N}}(p_{\mathrm{FRx},n} + p_{\mathrm{NRx},n}) > 0$, the objective of (8) is also lower bounded. Therefore, Algorithm 1 converges, according to[33, Thms. 8.1 & 8.2].

The complexity of Algorithm 1 accounts for solving (9) and (14) recursively. Since the complexity of the subcarrier power allocation for FRx is $\mathcal{O}(N \log \frac{1}{\epsilon_1})$, where ϵ_1 is the required accuracy of FRx. The complexity of the subcarrier power allocation for NRx is $\mathcal{O}(N \log \frac{1}{\epsilon_2})$, where ϵ_2 is the required accuracy of NRx. The overall complexity of solving (8) is $\mathcal{O}(N \log \frac{1}{\epsilon_3}(\log \frac{1}{\epsilon_1} + \log \frac{1}{\epsilon_2}))$, where ϵ_3 is the required accuracy of Algorithm 1.

V. Secrecy Rate Maximization Under Finite Transmit Power

An alternative objective of the problem of interest is to maximize the secrecy rate of the NRx, subject to the minimum data

rate requirement of the FRx and the finite transmit power of the Tx. The problem can be formulated as

$$\max_{p_{\mathrm{NRx},n},p_{\mathrm{FRx},n}} \sum_{n\in\mathcal{N}} R_{s,n} \tag{27a}$$

$$s.t. \sum_{n\in\mathcal{N}} \log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right) \geq R_{\mathrm{FRx}}, \tag{27b}$$

$$\sum_{n\in\mathcal{N}} \left(p_{\mathrm{NRx},n}+p_{\mathrm{FRx},n}\right) \leq P_s, \tag{27c}$$

$$p_{\mathrm{NRx},n} \geq 0, p_{\mathrm{FRx},n} \geq 0, \forall n \in \mathcal{N}, \tag{27d}$$

where P_s is the power budget of the Tx; and the total power allocated must not exceed P_s; see (27c). Problem (27) is still non-convex because of the non-convex constraint (27b).

Lemma 1: The necessary condition of the optimal solution to (27) is that the equality must hold in (27b) and (27c).

Proof: See Appendix A. ■

Problem (27) can be infeasible if the total power P_s is not sufficiently large; see (24b). This is due to the fact that, given the finite transmit power, the FRx may fail to meet its minimum requested data rate if its channel condition is poor. We show that there exists a minimum transmit power, denoted by $P_{\min}$, which guarantees that (24) has a non-empty feasible solution region. $P_{\min}$ can be obtained by solving the following non-convex problem:

$$P_{\min} = \min_{p_{\mathrm{NRx},n},p_{\mathrm{FRx},n}} \sum_{n\in\mathcal{N}} \left(p_{\mathrm{NRx},n}+p_{\mathrm{FRx},n}\right) \tag{28a}$$

$$s.t.\ (24\mathrm{b}), (24\mathrm{d}), \tag{28b}$$

which can be solved in the same way as problem (8), i.e., by revising the constraint $R_{\mathrm{NRx}} \geq 0$ and consequently suppressing the constraint in (8). Given the non-convexity of (27), the solution to (27), i.e., $P_{\min}$, not be the global optimum. As a result, $P_{\min}$ is the sufficient condition of the feasibility of problem (24), not the necessary condition. In the rest of this section, we consider $P_s \geq P_{\min}$, which is the sufficient condition of a non-empty feasible solution region for problem (27).

Based on Lemma 1, we can divide the total transmit power P_s between P_{NRx} and $P_s - P_{\mathrm{NRx}}$, i.e., $\sum_{n\in\mathcal{N}} p_{\mathrm{NRx},n} = P_{\mathrm{NRx}}$ and $\sum_{n\in\mathcal{N}} p_{\mathrm{FRx},n} = P_s - P_{\mathrm{NRx}}$. The objective of (27) is only dependent on $p_{\mathrm{NRx},n}$. Moreover, given $p_{\mathrm{NRx},n}$, constraint (27b) is convex in $p_{\mathrm{FRx},n}$. We can use this property to develop an iterative algorithm which optimally allocates $p_{\mathrm{NRx},n}$, given P_{NRx}; and then optimally allocate $p_{\mathrm{FRx},n}$, given $p_{\mathrm{NRx},n}$ and $P_s - P_{\mathrm{NRx}}$. The algorithm repeatedly optimizes $p_{\mathrm{NRx},n}$ and $p_{\mathrm{FRx},n}$ in an alternating manner until convergence.

Step 1: Given fixed P_{NRx}, denoted by P_{NRx}^*, the subcarrier power allocation for the NRx in (27) can be written as

$$\max_{p_{\mathrm{NRx},n}} \sum_{n\in\mathcal{N}} R_{s,n} \tag{29a}$$

$$\text{s.t.} \sum_{n\in\mathcal{N}} p_{\mathrm{NRx},n} = P_{\mathrm{NRx}}^*, \tag{29b}$$

$$p_{\mathrm{NRx},n} \geq 0, \forall n \in \mathcal{N}, \tag{29c}$$

which is convex and optimally solvable by using the KKT conditions. The KKT conditions of (29) are given by

$$\frac{\partial L\left(p_{\mathrm{NRx},n},\kappa\right)}{\partial p_{\mathrm{NRx},n}} = 0, n \in \mathcal{N}, \tag{30a}$$

$$\kappa\left(\sum_{n\in\mathcal{N}} p_{\mathrm{NRx},n} - P_{\mathrm{NRx}}^*\right) = 0, \tag{30b}$$

$$\sum_{n\in\mathcal{N}} p_{\mathrm{NRx},n} - P_{\mathrm{NRx}}^* \leq 0, \tag{30c}$$

$$\kappa \geq 0, \tag{30d}$$

where κ is the Lagrange dual variable and the Lagrangian is given by

$$L\left(p_{\mathrm{NRx},n},\kappa\right) = -\sum_{n\in\mathcal{N}} R_{s,n} + \kappa\left(\sum_{n\in\mathcal{N}} p_{\mathrm{NRx},n} - P_{\mathrm{NRx}}^*\right). \tag{31}$$

By solving (30a), we obtain the optimal solution to problem (29). The solution is given in (32), shown at bottom of this page, where κ can be obtained by substituting (32) into (29b) and then running bisectional search until (29b) holds with equality.

Step 2: Given $p_{\mathrm{NRx},n}^*$ and $P_s - P_{\mathrm{NRx}}^*$, the subcarrier power allocation for the FRx in (27) can be formulated as

$$\max_{p_{\mathrm{FRx},n}} \sum_{n\in\mathcal{N}} \log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right) \tag{33a}$$

$$s.t. \sum_{n\in\mathcal{N}} p_{\mathrm{FRx},n} = P_s - P_{\mathrm{NRx}}^*, \tag{33b}$$

$$p_{\mathrm{FRx},n} \geq 0, \forall n \in \mathcal{N}, \tag{33c}$$

which is convex. The KKT conditions of (33) are given by

$$\frac{\partial L\left(p_{\mathrm{FRx},n},\eta\right)}{\partial p_{\mathrm{FRx},n}} = 0, n \in \mathcal{N}, \tag{34a}$$

$$\eta\left(\sum_{n\in\mathcal{N}} p_{\mathrm{FRx},n} - P_s - P_{\mathrm{NRx}}^*\right) = 0, \tag{34b}$$

$$\sum_{n\in\mathcal{N}} p_{\mathrm{FRx},n} - P_s - P_{\mathrm{NRx}}^* \leq 0, \tag{34c}$$

$$\eta \geq 0, \tag{34d}$$

$$p_{\mathrm{NRx},n}^* = \left[\frac{-\left(a_{\mathrm{NRx},n}+a_{\mathrm{FRx},n}\right)}{2a_{\mathrm{NRx},n}a_{\mathrm{FRx},n}} + \frac{\sqrt{\left(a_{\mathrm{NRx},n}-a_{\mathrm{FRx},n}\right)^2 + \frac{4}{\kappa\ln 2}a_{\mathrm{NRx},n}a_{\mathrm{FRx},n}\left(a_{\mathrm{NRx},n}-a_{\mathrm{FRx},n}\right)}}{2a_{\mathrm{NRx},n}a_{\mathrm{FRx},n}}\right]^+ \tag{32}$$

Algorithm 2: Joint Power Allocation to Maximize the Secrecy Rate.

Input: P_s, R_{FRx}, N, the lower and upper bounds $P_1 = 0$ and $P_2 = P_s$, threshold ϵ_4;

1 **repeat**
2 Update P_{NRx} by $P_{\mathrm{NRx}} = (P_1 + P_2)/2$;
3 Evaluate $p_{\mathrm{NRx},n}$, $n \in \mathcal{N}$, based on P_{NRx} according to (32);
4 Evaluate $p_{\mathrm{FRx},n}$ based on $p_{\mathrm{NRx},n}$ and P_{NRx}, $n \in \mathcal{N}$ according to (36) ;
5 **if** $\sum_{n=1}^{N} \log_2\left(1+\Gamma_{\mathrm{FRx,n}}^{\mathrm{FRx}}\left(p_{\mathrm{NRx,n}}, p_{\mathrm{FRx,n}}\right)\right) < R_{\mathrm{FRx}} - \epsilon_4$ **then**
6 $P_2 = P_{\mathrm{NRx}}$;
7 **else if** $\sum_{n=1}^{N} \log_2\left(1+\Gamma_{\mathrm{FRx,n}}^{\mathrm{FRx}}\left(p_{\mathrm{NRx,n}}, p_{\mathrm{FRx,n}}\right)\right) > R_{\mathrm{FRx}} + \epsilon_4$ **then**
8 $P_1 = P_{\mathrm{NRx}}$;
9 **until** $\left|\sum_{n=1}^{N} \log_2\left(1+\Gamma_{\mathrm{FRx,n}}^{\mathrm{FRx}}\left(p_{\mathrm{NRx,n}}, p_{\mathrm{FRx,n}}\right)\right) - R_{\mathrm{FRx}}\right| \leq \epsilon_4$;

Output: $\sum_{n\in\mathcal{N}} R_{s,n}$.

where η is the Lagrange dual variable and the Lagrangian is given by

$$L\left(p_{\mathrm{FRx},n}, \eta\right) = -\sum_{n\in\mathcal{N}} \log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right) + \eta\left(\sum_{n\in\mathcal{N}} p_{\mathrm{FRx},n} - P_s + P_{\mathrm{NRx}}^{*}\right). \tag{35}$$

By solving (34a), we finally obtain the optimal solution to (33), as given by

$$p_{\mathrm{FRx},n}^{*} = \left[\frac{1}{\eta \ln 2} - \frac{p_{\mathrm{NRx},n}^{*} a_{\mathrm{FRx},n} + 1}{a_{\mathrm{FRx},n}}\right]^{+}, \tag{36}$$

where η can be obtained by substituting (36) into (33b) and then running bisectional search until (33b) holds with equality. From (36), we see that the subcarriers assigned with low transmit powers for the NRx are assigned with high transmit powers for the FRx.

3) Algorithmic Summary: Algorithm 2 summarizes the proposed algorithm solving (27), which consists of two steps: Optimizing $p_{\mathrm{NRx,n}}$ given P_{NRx}^{*}, i.e., Step 3; and optimizing $p_{\mathrm{FRx,n}}$ given $p_{\mathrm{NRx,n}}^{*}$ and P_{NRx}^{*}, i.e., Step 4. These two steps alternate and iterate the objective value of (33) converges to R_{FRx}, i.e., $|\sum_{n\in\mathcal{N}} \log_2(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}) - R_{\mathrm{FRx}}| \leq \epsilon_4$; see Step 5 – 9. Here, ϵ_4 is the pre-specified accuracy requirement of convergence.

We notice that the semi-closed-form expressions for $p_{\mathrm{NRx,n}}^{*}$, i.e., (22) and (32) and those for $p_{\mathrm{FRx,n}}^{*}$, i.e., (12) and (36), exhibit strong resemblance. (22) and (12) are increasing functions of λ and μ, respectively. (32) and (36) are the decreasing functions of κ and η, respectively. For the problem in Section IV, we first calculate $p_{\mathrm{FRx},n}$, provided $p_{\mathrm{NRx},n}^{*}$; and then optimize $p_{\mathrm{NRx},n}$ iteratively until the objective $\sum_{n\in\mathcal{N}}\left(p_{\mathrm{NRx},n} + p_{\mathrm{FRx},n}\right)$ converges. In contrast, for the problem in this section, we first optimize $p_{\mathrm{NRx},n}$, given P_{NRx}^{*}; and then obtain $p_{\mathrm{FRx},n}$ iteratively until the objective $\sum_{n\in\mathcal{N}} \log_2(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}})$ converges to R_{FRx}.

VI. Extension of the Proposed Algorithms Under Per-Subcarrier Power Limit

In this section, we extend Algorithms 1 and 2 under the per-subcarrier maximum transmit power limit for $p_{\mathrm{NRx,n}}$ and $p_{\mathrm{FRx,n}}$. The per-subcarrier power limit could be a more stringent requirement of the transmitter hardware that the transmit signals need to comply with. The per-subcarrier power limit can also be more practical than the total power limit, despite the total power limit is of research interest and has been widely adopted in the literature, e.g., [21], [23], [34]–[37].

A. Transmit Power Minimization

With the per-subcarrier transmit power limit $P_{\max,n}$ for every subcarrier $n = 1, \ldots, N$, the problem of transmit power minimization can be reformulated as

$$\min_{p_{\mathrm{NRx},n}, p_{\mathrm{FRx},n}} \sum_{n\in\mathcal{N}} \left(p_{\mathrm{NRx},n} + p_{\mathrm{FRx},n}\right) \tag{37a}$$

$$s.t. \sum_{n\in\mathcal{N}} R_{s,n} \geq R_{\mathrm{NRx}}, \tag{37b}$$

$$\sum_{n\in\mathcal{N}} \log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right) \geq R_{\mathrm{FRx}}, \tag{37c}$$

$$p_{\mathrm{NRx},n} \geq 0, p_{\mathrm{FRx},n} \geq 0, \forall n \in \mathcal{N}, \tag{37d}$$

$$p_{\mathrm{NRx},n} + p_{\mathrm{FRx},n} \leq P_{\max,n}, \forall n \in \mathcal{N}. \tag{37e}$$

By extending the proposed algorithm, problem (37) can be solved iteratively in two steps. The first step is to minimize $\sum_{n\in\mathcal{N}} p_{\mathrm{FRx},n}$, given $p_{\mathrm{NRx},n}$. The second step is to minimize $\sum_{n\in\mathcal{N}} p_{\mathrm{NRx},n}$, given $p_{\mathrm{FRx},n}$. Each of the steps can be converted to a convex problem with analytical solutions, as done under the original setting with the total transmit power constraint (as described in Section IV). The two steps repeat in an alternating manner until convergence.

Step 1: Given fixed $p_{\mathrm{NRx},n}$, denoted by $p_{\mathrm{NRx},n}^{*}$, constraint (37b) can be suppressed and problem (37) is rewritten as

$$\min_{p_{\mathrm{FRx},n}} \sum_{n\in\mathcal{N}} \left(p_{\mathrm{FRx},n} + p_{\mathrm{NRx},n}^{*}\right) \tag{38a}$$

$$s.t. \sum_{n\in\mathcal{N}} \log_2\left(1 + \frac{p_{\mathrm{FRx},n} a_{\mathrm{FRx},n}}{1 + p_{\mathrm{NRx},n}^{*} a_{\mathrm{FRx},n}}\right) \geq R_{\mathrm{FRx}}, \tag{38b}$$

$$0 \leq p_{\mathrm{FRx},n} \leq P_{\max,n} - p_{\mathrm{NRx},n}^{*}, \forall n \in \mathcal{N}. \tag{38c}$$

Problem (38) is convex and solvable using the KKT conditions to find the optimal solution. The KKT conditions of (38) are given by

$$\frac{\partial L\left(p_{\mathrm{FRx},n}, \lambda_1, \lambda_{2,n}\right)}{\partial p_{\mathrm{FRx},n}} = 0, n \in \mathcal{N}, \tag{39a}$$

$$R_{\mathrm{FRx}} - \sum_{n\in\mathcal{N}} \log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right) \leq 0, \tag{39b}$$

$$\lambda_1\left(R_{\mathrm{FRx}}-\sum_{n\in\mathcal{N}}\log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right)\right)=0, \tag{39c}$$

$$p_{\mathrm{NRx},n}^{*}+p_{\mathrm{FRx},n}-P_{\max,n}\leq 0, \tag{39d}$$

$$\sum_{n\in\mathcal{N}}\lambda_{2,n}\left(p_{\mathrm{NRx},n}^{*}+p_{\mathrm{FRx},n}-P_{\max,n}\right)=0, \tag{39e}$$

$$\lambda_1\geq 0,\lambda_{2,n}\geq 0,n\in\mathcal{N}, \tag{39f}$$

where λ_1 and $\lambda_{2,n}$ are the Lagrange dual variables associated with (38b) and (38c), respectively; and Lagrangian is given by

$$\begin{aligned}&L\left(p_{\mathrm{FRx},n},\lambda_1,\lambda_{2,n}\right)\\&=\sum_{n\in\mathcal{N}}p_{\mathrm{FRx},n}+\lambda_1\left(R_{\mathrm{FRx}}-\sum_{n\in\mathcal{N}}\log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right)\right)\\&+\sum_{n\in\mathcal{N}}\lambda_{2,n}\left(p_{\mathrm{NRx},n}^{*}+p_{\mathrm{FRx},n}-P_{\max,n}\right).\end{aligned} \tag{40}$$

Based on (39a), we obtain the optimal solution to (38), as given by

$$p_{\mathrm{FRx},n}^{*}=\left[\frac{\lambda_1}{\ln 2\left(1+\sum_{n\in\mathcal{N}}\lambda_{2,n}\right)}-\frac{p_{\mathrm{NRx},n}^{*}a_{\mathrm{FRx},n}+1}{a_{\mathrm{FRx},n}}\right]^{+}. \tag{41}$$

Given $(p_{\mathrm{NRx},n}^{*},p_{\mathrm{FRx},n}^{*})$, the dual variables can be updated with the gradient decent method: At the k-th iteration,

$$\lambda_1{}^{(k)}=\left[\lambda_1{}^{(k-1)}+\varphi_1\left(R_{\mathrm{FRx}}-\sum_{n\in\mathcal{N}}\log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right)\right)\right]^{+}, \tag{42}$$

$$\lambda_{2,n}{}^{(k)}=\left[\lambda_{2,n}{}^{(k-1)}+\varphi_2\left(p_{\mathrm{NRx},n}^{*}+p_{\mathrm{FRx},n}^{*}-P_{\max,n}\right)\right]^{+}, \tag{43}$$

where φ_1 and φ_2 are the step sizes. By iteratively calculating (41), (42) and (43) until convergence, the optimal solution to (38) can be obtained given the convexity of (38).

Step 2: Given the transmit power allocated for the FRx (41), the power allocation for the NRx in (37) can be transformed into the following univariate optimization problem:

$$\min_{p_{\mathrm{NRx},n}}\sum_{n\in\mathcal{N}}\left(p_{\mathrm{NRx},n}+p_{\mathrm{FRx},n}^{*}\right) \tag{44a}$$

$$s.t.\sum_{n\in\mathcal{N}}\left(\log_2\frac{1+p_{\mathrm{NRx},n}a_{\mathrm{NRx},n}}{1+p_{\mathrm{NRx},n}a_{\mathrm{FRx},n}}\right)\geq R_{\mathrm{NRx}}, \tag{44b}$$

$$0\leq p_{\mathrm{NRx},n}\leq P_{\max,n}-p_{\mathrm{FRx},n}^{*},\forall n\in\mathcal{N}. \tag{44c}$$

We confirm that (44) is convex and solvable using the KKT conditions to find the optimal solution. The KKT conditions of (44) are given by

$$\frac{\partial L\left(p_{\mathrm{NRx},n},\mu_1,\mu_{2,n}\right)}{\partial p_{\mathrm{NRx},n}}=0,n\in\mathcal{N}, \tag{45a}$$

$$R_{\mathrm{NRx}}-\sum_{n\in\mathcal{N}}R_{s,n}\leq 0,\mu_1\left(R_{\mathrm{NRx}}-\sum_{n\in\mathcal{N}}R_{s,n}\right)=0, \tag{45b}$$

$$p_{\mathrm{NRx},n}+p_{\mathrm{FRx},n}^{*}-P_{\max,n}\leq 0, \tag{45c}$$

$$\sum_{n\in\mathcal{N}}\mu_{2,n}\left(p_{\mathrm{NRx},n}+p_{\mathrm{FRx},n}^{*}-P_{\max,n}\right)=0, \tag{45d}$$

$$\mu_1\geq 0,\mu_{2,n}\geq 0,n\in\mathcal{N}, \tag{45e}$$

where μ_1 and $\mu_{2,n}$ are the Lagrange dual variables associated with (44b) and (44c), respectively; and Lagrangian is given by

$$\begin{aligned}&L\left(p_{\mathrm{NRx},n},\mu_1,\mu_{2,n}\right)\\&=\sum_{n\in\mathcal{N}}p_{\mathrm{NRx},n}+\mu_1\left(R_{\mathrm{NRx}}-\sum_{n\in\mathcal{N}}R_{s,n}\right)\\&+\sum_{n\in\mathcal{N}}\mu_{2,n}\left(p_{\mathrm{NRx},n}+p_{\mathrm{FRx},n}^{*}-P_{\max,n}\right).\end{aligned} \tag{46}$$

Based on (45a), we obtain the optimal solution to (44), as given by

$$\begin{aligned}p_{\mathrm{NRx},n}^{*}=&-\frac{\left(a_{\mathrm{NRx},n}+a_{\mathrm{FRx},n}\right)}{2a_{\mathrm{NRx},n}a_{\mathrm{FRx},n}}\\&+\frac{\sqrt{\left(a_{\mathrm{NRx},n}-a_{\mathrm{FRx},n}\right)^2+\frac{4\mu_1 a_{\mathrm{NRx},n}a_{\mathrm{FRx},n}}{\ln 2\left(1+\sum_{n\in N}\mu_{2,n}\right)}\left(a_{\mathrm{NRx},n}-a_{\mathrm{FRx},n}\right)}}{2a_{\mathrm{NRx},n}a_{\mathrm{FRx},n}},\end{aligned} \tag{47}$$

where, given$(p_{\mathrm{NRx},n}^{*},p_{\mathrm{FRx},n}^{*})$, the dual variables can be updated with the gradient decent method: At the k-th iteration,

$$\mu_1{}^{(k)}=\left[\mu_1{}^{(k-1)}+\varphi_1\left(R_{\mathrm{NRx}}-\sum_{n\in\mathcal{N}}R_{s,n}\right)\right]^{+}, \tag{48}$$

$$\mu_{2,n}{}^{(k)}=\left[\mu_{2,n}{}^{(k-1)}+\varphi_2\left(p_{\mathrm{NRx},n}^{*}+p_{\mathrm{FRx},n}^{*}-P_{\max,n}\right)\right]^{+}, \tag{49}$$

where φ_1 and φ_2 are the step sizes. By iteratively calculating (47), (48) and (49), the optimal solution to (44) can be obtained given the convexity of (44).

This extension of Algorithm 1 under the per-subcarrier power limit is also convergent. The proof is as follows. At the i-th iteration of the algorithm, we assume that $p_{\mathrm{NRx},n}^{(i)}$ and $p_{\mathrm{FRx},n}^{(i)}$ are the optimized transmit powers of the BS to NRx and FRx, respectively. With the per-subcarrier power limit, problem (38) is still convex and can be optimally solved by using the KKT conditions at the $(i+1)$-th iteration [32]. With $p_{\mathrm{FRx},n}^{(i+1)}$ being the optimal solution to problem (38) at the $(i+1)$-th iteration, we have $\sum_{n\in\mathcal{N}}p_{\mathrm{FRx},n}^{(i+1)}\leq\sum_{n\in\mathcal{N}}p_{\mathrm{FRx},n}^{(i)}$. With the given $p_{\mathrm{NRx},n}^{(i)}$, we have

$$\sum_{n\in\mathcal{N}}\left(p_{\mathrm{FRx},n}^{(i+1)}+p_{\mathrm{NRx},n}^{(i)}\right)\leq\sum_{n\in\mathcal{N}}\left(p_{\mathrm{FRx},n}^{(i)}+p_{\mathrm{NRx},n}^{(i)}\right). \tag{50}$$

Likewise, problem (44) is convex and can be optimally solved by using the KKT conditions. With $p_{\mathrm{NRx},n}^{(i+1)}$ being the optimal solution to problem (44) at the $(i+1)$-th iteration, $\sum_{n\in\mathcal{N}}p_{\mathrm{NRx},n}^{(i+1)}\leq\sum_{n\in\mathcal{N}}p_{\mathrm{FRx},n}^{(i)}$. With the given $p_{\mathrm{FRx},n}^{(i+1)}$, we have

$$\sum_{n\in\mathcal{N}}\left(p_{\mathrm{FRx},n}^{(i+1)}+p_{\mathrm{NRx},n}^{(i+1)}\right)\leq\sum_{n\in\mathcal{N}}\left(p_{\mathrm{FRx},n}^{(i+1)}+p_{\mathrm{NRx},n}^{(i)}\right). \tag{51}$$

Based on (50) and (51), the objective value of (37) satisfies

$$\sum_{n\in\mathcal{N}}\left(p_{\mathrm{FRx},n}^{(i+1)}+p_{\mathrm{NRx},n}^{(i+1)}\right)\leq\sum_{n\in\mathcal{N}}\left(p_{\mathrm{FRx},n}^{(i+1)}+p_{\mathrm{NRx},n}^{(i)}\right)\leq\sum_{n\in\mathcal{N}}\left(p_{\mathrm{FRx},n}^{(i)}+p_{\mathrm{NRx},n}^{(i)}\right). \quad (52)$$

It is proved that the objective of (34) holds a non-increasing property throughout the execution of the algorithm stated in this section. Since $\sum_{n\in\mathcal{N}}\left(p_{\mathrm{FRx},n}+p_{\mathrm{NRx},n}\right)>0$, the objective of (34) is also lower bounded. Therefore, the extended version of Algorithm 1 to the per-subcarrier power limit also converges, according to [33, Thms. 8.1 & 8.2].

B. Secrecy Rate Maximization

With the per-subcarrier transmit power limit $P_{\max,n}$ for every subcarrier $n=1,\ldots,N$, the problem of secrecy rate maximization can be reformulated as

$$\max_{p_{\mathrm{NRx},n},p_{\mathrm{FRx},n}}\sum_{n\in\mathcal{N}}R_{s,n} \quad (53a)$$

$$s.t.\sum_{n\in\mathcal{N}}\log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right)\geq R_{\mathrm{FRx}}, \quad (53b)$$

$$p_{\mathrm{NRx},n}\geq 0, p_{\mathrm{FRx},n}\geq 0, \forall n\in\mathcal{N}, \quad (53c)$$

$$p_{\mathrm{NRx},n}+p_{\mathrm{FRx},n}\leq P_{\max,n}, \forall n\in\mathcal{N}. \quad (53d)$$

Problem (53) is non-convex because of the non-convex constraint (53b). To solve (53), we first put forth the following lemma.

Lemma 2: The necessary condition of the optimal solution to (53) is that the equality must hold in (53b).

Proof: See Appendix B. ■

Based on Lemma 2, we can develop an iterative algorithm with the following two steps to optimize $p_{\mathrm{NRx},n}$ and $p_{\mathrm{FRx},n}$ in an alternating manner until convergence.

Step 1: Given fixed $P_{\max,n}$ and the optimal $p_{\mathrm{FRx},n}$, denoted by $p_{\mathrm{FRx},n}^{*}$, the subcarrier power allocation for the NRx in (53) can be written as

$$\max_{p_{\mathrm{NRx},n}}\sum_{n\in\mathcal{N}}R_{s,n} \quad (54a)$$

$$s.t.\ 0\leq p_{\mathrm{NRx},n}\leq P_{\max,n}-p_{\mathrm{FRx},n}^{*}, \forall n\in\mathcal{N}, \quad (54b)$$

which is convex and optimally solvable by using the KKT conditions. The KKT conditions of (54) are given by

$$\frac{\partial L\left(p_{\mathrm{NRx},n},\kappa_{1,n}\right)}{\partial p_{\mathrm{NRx},n}}=0, n\in\mathcal{N}, \quad (55a)$$

$$P_{\max,n}-p_{\mathrm{NRx},n}-p_{\mathrm{FRx},n}^{*}\geq 0, \quad (55b)$$

$$\sum_{n\in\mathcal{N}}\kappa_{1,n}\left(P_{\max,n}-p_{\mathrm{NRx},n}-p_{\mathrm{FRx},n}^{*}\right)=0, \quad (55c)$$

$$\kappa_{1,n}\geq 0, \quad (55d)$$

where $\kappa_{1,n}$ is the Lagrange dual variable associated with (54b) and the Lagrangian is given by

$$L\left(p_{\mathrm{NRx},n},\kappa_{1,n}\right)=\sum_{n\in\mathcal{N}}R_{s,n}+\sum_{n\in\mathcal{N}}\kappa_{1,n}\left(P_{\max,n}-p_{\mathrm{NRx},n}-p_{\mathrm{FRx},n}^{*}\right). \quad (56)$$

By solving (55a), we obtain the optimal solution to problem (54), as given by

$$p_{\mathrm{NRx},n}^{*}=-\frac{\left(a_{\mathrm{NRx},n}+a_{\mathrm{FRx,n}}\right)}{2a_{\mathrm{NRx},n}a_{\mathrm{FRx,n}}}+\frac{\sqrt{\left(a_{\mathrm{NRx},n}-a_{\mathrm{FRx},n}\right)^2+\frac{4a_{\mathrm{NRx},n}a_{\mathrm{FRx},n}}{\sum_{n\in\mathcal{N}}\kappa_{1,n}\ln 2}\left(a_{\mathrm{NRx},n}-a_{\mathrm{FRx},n}\right)}}{2a_{\mathrm{NRx},n}a_{\mathrm{FRx},n}}, \quad (57)$$

where the dual variables can be updated with the gradient decent method: At the k-th iteration,

$$\kappa_{1,n}{}^{(k)}=\left[\kappa_{1,n}{}^{(k-1)}-\varphi_1\left(P_{\max,n}-p_{\mathrm{NRx},n}^{*}-p_{\mathrm{FRx},n}^{*}\right)\right]^{+}, \quad (58)$$

where φ_1 is the step size. By iteratively calculating (57) and (58) until convergence, the optimal solution to (54) can be obtained given the convexity of (54).

Step 2: Given $p_{\mathrm{NRx},n}^{*}$, the subcarrier power allocation for the FRx in (53) can be formulated as

$$\max_{p_{\mathrm{FRx},n}}\sum_{n\in\mathcal{N}}\log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right) \quad (59a)$$

$$s.t.\ 0\leq p_{\mathrm{FRx},n}\leq P_{\max,n}-p_{\mathrm{NRx},n}^{*}, \forall n\in\mathcal{N}, \quad (59b)$$

which is convex and can be optimally solved using the KKT conditions. The KKT conditions of (59) are given by

$$\frac{\partial L\left(p_{\mathrm{FRx},n},\eta_{1,n}\right)}{\partial p_{\mathrm{FRx},n}}=0, n\in\mathcal{N}, \quad (60a)$$

$$P_{\max,n}-p_{\mathrm{NRx},n}^{*}-p_{\mathrm{FRx},n}\geq 0, \quad (60b)$$

$$\sum_{n\in\mathcal{N}}\eta_{1,n}\left(P_{\max,n}-p_{\mathrm{NRx},n}^{*}-p_{\mathrm{FRx},n}\right)=0, \quad (60c)$$

$$\eta_{1,n}\geq 0, \quad (60d)$$

where $\eta_{1,n}$ is the Lagrange dual variable associated with (59b) and the Lagrangian is given by

$$L\left(p_{\mathrm{FRx},n},\eta_{1,n}\right)=\sum_{n\in\mathcal{N}}\log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right)+\sum_{n\in\mathcal{N}}\eta_{1,n}\left(P_{\max,n}-p_{\mathrm{NRx},n}^{*}-p_{\mathrm{FRx},n}\right). \quad (61)$$

By solving (60a), we finally obtain the optimal solution to (59), as given by

$$p_{\mathrm{FRx},n}^{*}=\left[\frac{1}{\sum_{n\in\mathcal{N}}\eta_{1,n}\ln 2}-\frac{p_{\mathrm{NRx},n}^{*}a_{\mathrm{FRx},n}+1}{a_{\mathrm{FRx},n}}\right]^{+}. \quad (62)$$

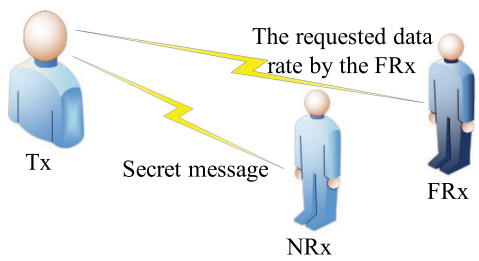

Fig. 1. Illustration of the system of interest, where there is a Tx and two receivers. A trusted, near receiver (NRx) receives secret messages superposed on the messages destined for an untrusted, far receiver (FRx).

where the dual variables can be updated with the gradient decent method: At the k-th iteration,

$$\eta_{1,n}{}^{(k)}=\left[\eta_{1,n}{}^{(k-1)}-\varphi_2\left(P_{\max,n}-p^*_{\mathrm{NRx},n}-p^*_{\mathrm{FRx},n}\right)\right]^+, \quad (63)$$

where φ_2 is the step size. By iteratively calculating (62) and (63) until convergence, the optimal solution to (59) can be obtained given the convexity of (59).

Remark 1: We note that the algorithms under the per-subcarrier power limit share the same structures and flows of the algorithms under the total power limit, i.e., (12) and (22) in Section IV and (32) and (36) in Section V. Semi-closed-form solutions can also be established under the per-subcarrier power limit, i.e., (41) and (47) in Section VI-A and (57) and (62) in Section VI-B. The only difference is that more Lagrange multipliers are involved under the per-subcarrier power limit, associated with different subcarriers. Gradient descent is performed to iteratively update the Lagrange multipliers, e.g., (42) and (43) in Section VI-A.

VII. Simulation Result

In this section, we simulate to evaluate the performance of two proposed algorithms, namely, Algorithms 1 and 2. The simulation parameters are specified in the following, unless otherwise specified. The NRx and FRx are located at the distance $d_{\mathrm{NRx}} = 100$ m and $d_{\mathrm{FRx}} = 300$ m away from the Tx, unless otherwise specified [38]. Independent Rayleigh fading channels are considered. The path loss exponent is set to 3. The average noise spectral density is -174 dBm/Hz, the receiver noise figure is 10 dB, and the bandwidth of each subcarrier is set to 60 kHz [29]. The number of OFDM subcarriers is $N = 16$. We observe that the objective functions of (8) and (24) can be expressed as two differences of two convex functions with the aid of the Lagrange relax method [39]. As result, each of the problems can be convexified with DC programming. The resultant convex problems can be readily solved by convex techniques. For comparison purpose, we simulate the DC-based alternatives to the proposed Algorithms 1 and 2. We also simulate the OMA-based counterparts of the proposed algorithms, where the signals destined for different receivers are transmitted at different subcarriers.

Fig. 2 plots the minimum transmit powers of Algorithm 1 in comparison with its DC-based alternative (solving the same problem (8) in Section IV) and OMA-based counterpart, with the growing data rate request of the FRx, where the secrecy rate requirement of the NRx is $R_{\mathrm{NRx}} = 5$ bps/Hz. The OMA-based counterpart allows only one of the receivers to access a subcarrier by referring to the existing literature on NOMA-OFDM, e.g., [16]–[18]. We see that the proposed Algorithm 1 and its DC-based alternative perform nearly indistinguishably, as they solve the exactly same problem (8) which is a DC program and can be readily solved by DC programming. (Nevertheless, Algorithm 1 is substantially more efficient and converges much faster than the DC-based alternative, as will be shown in Fig. 4.) We also see that Algorithm 1 always surpasses the OMA-based scheme under any given number of subcarriers, N. This is because NOMA adopts SC and SIC to increase the data rate, as long as the channel conditions permit. Furthermore, it is observed that, for both NOMA and OMA, the minimum transmit power $\sum_{n\in\mathcal{N}}\left(p_{\mathrm{NRx,n}}+p_{\mathrm{FRx,n}}\right)$ increases with R_{FRx}.

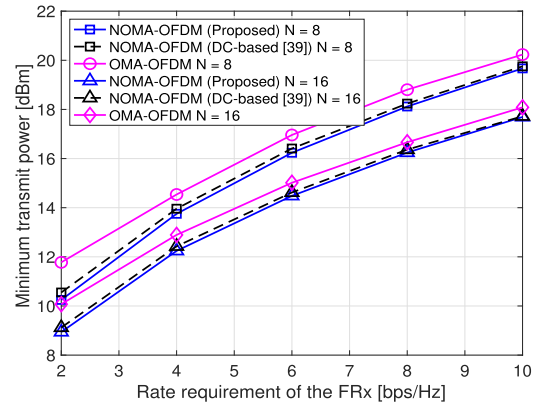

Fig. 2. Minimum transmit power of the Tx versus the requested data rate of the FRx, where the secrecy rate requirement is $R_{\mathrm{NRx}} = 5$ bps/Hz for the NRx.

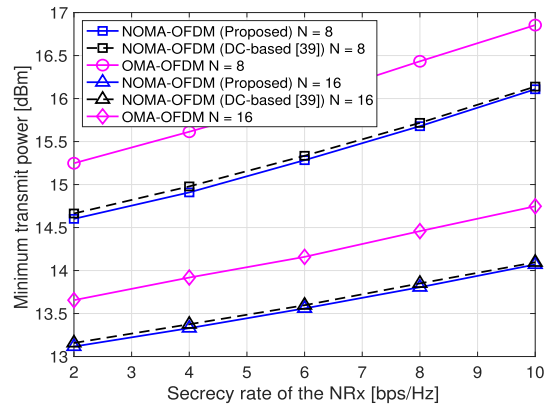

Fig. 3. The minimum transmit power of the Tx versus the secrecy rate of the NRx, where the data rate request is $R_{\mathrm{FRx}} = 5$ bps/Hz for the FRx.

Fig. 3 shows the minimum transmit power of Algorithm 1 in comparison to its DC-based alternative and OMA-based counterpart, with the growing secrecy rate requirement of the NRx, where the data rate requirement of the FRx is $R_{\mathrm{FRx}} = 5$ bps/Hz. We see that Algorithm 1 and its DC-based alternative perform increasingly indistinguishably with the growing secrecy rate requirement. We also observe that the NOMA-based techniques

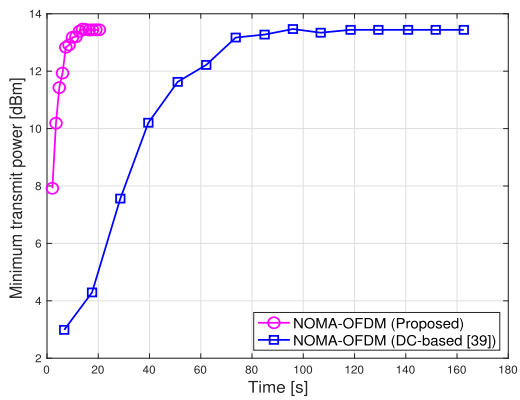

Fig. 4. The minimum transmit power of the Tx versus the iteration convergence time for Algorithm 1 and its DC-based alternative, where $N = 16$, the secrecy rate requirement of the NRx is $R_{\mathrm{NRx}} = 5$ bps/Hz, and the data rate request of the FRx is $R_{\mathrm{FRx}} = 5$ bps/Hz.

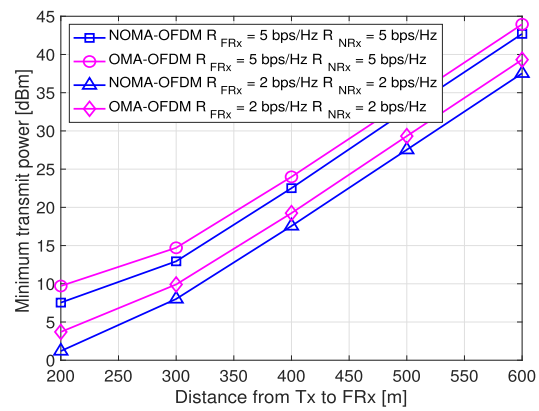

Fig. 5. The minimum transmit power of the Tx versus the distance between the Tx and the FRx, where the number of subcarriers is $N = 16$.

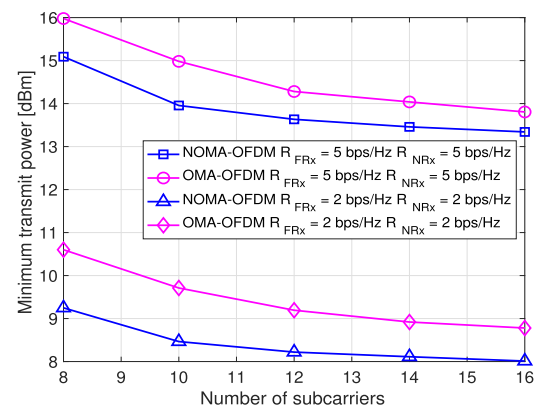

Fig. 6. The minimum transmit power of the Tx versus the number of subcarriers for Algorithm 1.

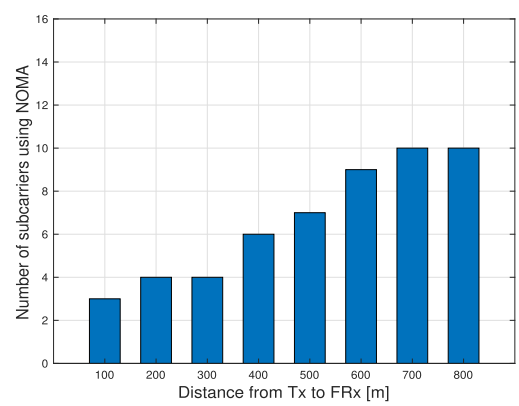

Fig. 7. The number of subcarriers using NOMA versus the distance between the Tx and the FRx, where the number of subcarriers is $N = 16$, the secrecy rate requirement of the NRx is $R_{\mathrm{NRx}} = 5$ bps/Hz, and the data rate request of the FRx is $R_{\mathrm{FRx}} = 5$ bps/Hz.

(i.e., both Algorithm 1 and its DC-based alternative) require a lower transmit power than the OMA-based scheme. The reason is that Algorithm 1 and its DC-based alternative can minimize the transmit power subject to both the secrecy rate of the NRx and the data rate requirement of the FRx, such that the radio resources can be efficiently utilized. Moreover, both the transmit powers of the NOMA-based Algorithm 1 and the OMA-based method increase as the secrecy rate of the NRx grows, under different numbers of subcarriers. Additionally, we notice that the transmit power of Algorithm 1 is higher for $N = 8$ than it is for $N = 16$.

Despite performing (increasingly) indistinguishably close to their respective DC-based alternatives in terms of power consumption and secrecy rate (see Figs. 2 and 3), Algorithms 1 and 2 are substantially more efficient and converge significantly faster (by about 5 times) than the DC-based alternatives, as shown in Fig. 4. Fig. 4 plots the changes of the minimized transmit power of the Tx with the increasing iteration time of Algorithm 1 and its DC-based alternative until convergence. The complexity of Algorithm 1 is $\mathcal{O}(N \log \frac{1}{\epsilon_3}(\log \frac{1}{\epsilon_1} + \log \frac{1}{\epsilon_2}))$. In contrast, the DC-based alternative to Algorithm 1 has a total of $2N$ variables and $(2N + 1)$ convex and linear constraints. With the same convergence accuracy of the outer loop ϵ_3, the complexity of the DC-based approach is $\mathcal{O}(\log \frac{1}{\epsilon_3}(2N)^3(2N + 1))$ according to [40].

Fig. 5 illustrates the minimum transmit power of different schemes against d_{FRx}. It can be seen that the NOMA-based scheme, i.e., Algorithm 1, attains the lower transmit power than the OMA-based scheme. Moreover, both NOMA and OMA require more transmit power, as the distance d_{FRx} increases. The reason lies in the fact that the transmit power required increases to meet the requirements of the FRx, as d_{FRx} increases.

Fig. 6 plots the minimum transmit power of different schemes against the number of subcarriers. It can be observed that the minimum transmit powers of the proposed algorithm, Algorithm 1, and its OMA-based alternative decrease, as the number of subcarriers grows. It can also be seen that, with the increasing number of subcarriers, the performance gap between Algorithm 1 and its OMA-based alternative quickly decreases, which implies that NOMA is particularly efficient when the resource (i.e., subcarriers) is limited.

Fig. 7 shows the percentage of OFDM subcarriers running NOMA against d_{FRx}, where $N = 16$, $R_{\mathrm{FRx}} = 5$ bps/Hz and $R_{\mathrm{NRx}} = 5$ bps/Hz. We find that, as d_{FRx} increases, more subcarriers operate in the NOMA mode The performance of Algorithm 1 is substantially better than its OMA-based alternative

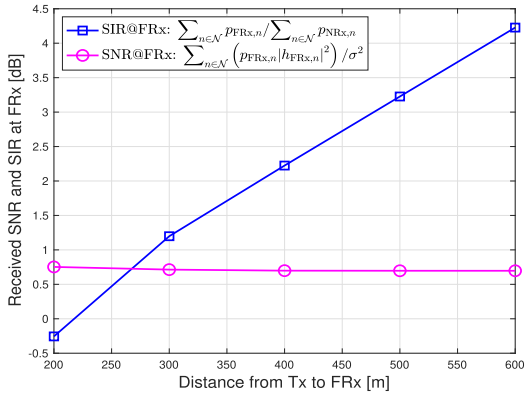

Fig. 8. The received SNR and SIR at the FRx versus the distance between the Tx and the FRx, where $d_{\mathrm{NRx}} = 100$ m, the number of subcarriers is $N = 16$, the secrecy rate requirement of the NRx is $R_{\mathrm{NRx}} = 5$ bps/Hz, and the data rate request of the FRx is $R_{\mathrm{FRx}} = 5$ bps/Hz.

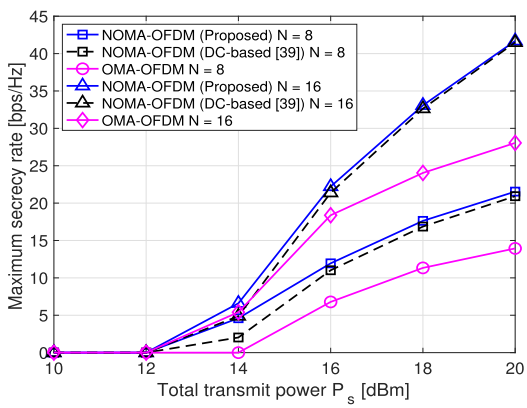

Fig. 9. The maximum secrecy rate of the NRx versus the total transmit power, where the data request is $R_{\mathrm{FRx}} = 5$ bps/Hz for the FRx.

in Fig. 5. This is because, at each subcarrier, both receivers are likely to be active in the proposed algorithm. The OMA scheme is implemented as such that the signals destined for the NRx and FRx are at different subcarriers. As a result, NOMA-OFDM is more effective.

Fig. 8 shows the ration of the signal-to-noise ratio (SNR) and signal-to-interference ratio (SIR) at the FRx, with the increasing distance between the Tx and FRx. The Tx transmits more power to the FRx than its transmits to the NRx, as d_{FRx} increases. In particular, when the FRx is more than 275 m away from the Tx, the received SNR is surpassed by the received SIR at the FRx. In other words, the signal intended to NRx becomes so weak at the FRx the signal that is submerged in the noise of the FRx. To this end, the signal destined for the NRx can be delivered to NRx unnoticed by using the radio resources assigned to the FRx.

Fig. 9 plots the maximum secrecy rate of different schemes against P_s, where Algorithm 2 (developed in Section V), its DC-based alternative (solving the same problem (24) in Section V), and its OMA-based counterpart are tested. As observed, the secrecy rate of the NRx increases with P_s for all the three schemes under different numbers of subcarriers. Algorithm 2 and its DC-based alternative perform increasingly indistinguishably with the growing transmit power. Algorithm 2 is better than its OMA-based alternative in terms of secrecy performance.

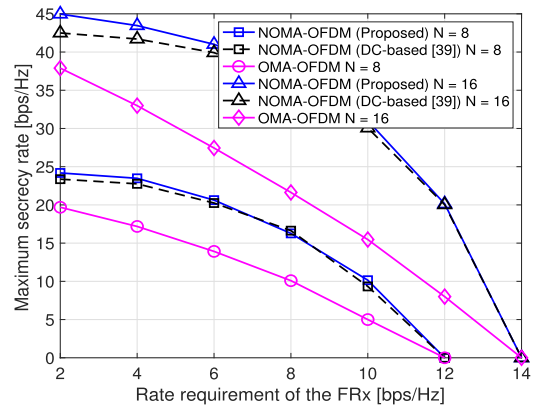

Fig. 10. The maximum secrecy rate of the NRx versus the data rate request of the FRx, where $P_s = 20$ dBm.

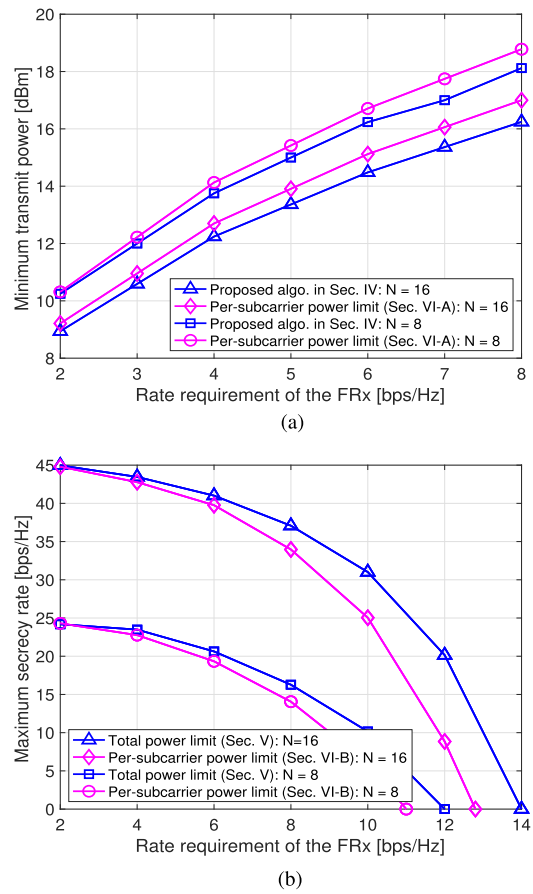

Fig. 11. The minimum transmit power of the Tx and the maximum secrecy rate of the NRx of the proposed algorithms versus the data rate request of the FRx under the per-subcarrier power limit and the total power limit. (a) The minimum transmit power versus the data rate request of the FRx, where $R_{\mathrm{NRx}} = 5$ bps/Hz and $P_{\max} = 20$ dBm. (b) The maximum secrecy rate of the NRx versus the data rate request of the FRx, where $P_{\max} = 20$ dBm.

Fig. 10 plots the maximum secrecy rates against R_{FRx}. We see that the secrecy rate of the NRx drops with the data rate requirement of the FRx under the three schemes. Obviously,

the Tx needs to transmit more power to the FRx to support more stringent data rate requirement of the FRx. Besides, Algorithm 2 provides a higher secrecy rate than the OMA-based scheme. The secrecy rate grows with an increasing number of subcarriers; in other words, more subcarriers leads to a higher secrecy rate. Fig. 11 evaluates the extension of the proposed algorithm under the per-subcarrier power limit. Fig. 11(a) plots the minimum transmit powers under the per-subcarrier power limit, with the growing data rate request of the FRx, where the secrecy rate requirement is $R_{\mathrm{NRx}} = 5$ bps/Hz for the NRx and the maximum total transmit power is 20 dBm. In the case of per-subcarrier power limit, the maximum total transmit power is evenly divided to be the maximum per-subcarrier transmit power. In Fig. 11(a), we see that the optimized transmit power is higher under the per-subcarrier power limit, as the result of more stringent constraints. Fig. 11(b) plots the maximized secrecy rates of the NRx with the increase of R_{FRx}, under the per-subcarrier power limit and the total power limit. We see that the maximized secrecy rate of the NRx drops faster under the per-subcarrier power limit than it does under the total power limit. This is also expected as the result of more stringent per-subcarrier transmit power constraints.

VIII. Conclusion

In this paper, we developed new iterative techniques for stealthy and secure transmissions of secret messages with the NOMA-OFDM waveforms, where the power allocation was optimized across all OFDM subcarriers to minimize the total power subject to the requested data rate of the FRx and the requested secrecy rate. The power allocation was also optimized so that the secrecy rate to the NRx is maximized while the requested data rate of the FRx is satisfied. The proposed algorithms were extended to the case with stringent per-subcarrier power limit. Simulation results show the proposed NOMA-OFDM based algorithms are better than their OMA-based alternatives in terms of power saving and achievable secrecy rate. As the FRx moves further away, the number of subcarriers carrying superposed signals increases. The secret messages can be delivered unnoticed to the NRx.

Appendix A
Proof of Lemma 1

The Lagrangian of (27) is given by

$$\begin{aligned} &L\left(p_{\mathrm{NRx},n}, p_{\mathrm{FRx},n}, \tau, \upsilon\right) \\ &= \sum_{n\in\mathcal{N}} \left(\log_2\left(1 + p_{\mathrm{NRx},n} a_{\mathrm{FRx},n}\right) - \log_2\left(1 + p_{\mathrm{NRx},n} a_{\mathrm{NRx},n}\right)\right) \\ &\quad + \tau\left(R_{\mathrm{FRx}} - \sum_{n\in\mathcal{N}} \log_2\left(1 + \Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right)\right) \\ &\quad + \upsilon\left(\sum_{n\in\mathcal{N}} \left(p_{\mathrm{NRx},n} + p_{\mathrm{FRx},n}\right) - P_s\right). \end{aligned} \tag{64}$$

The solution to (27) satisfies the following KKT conditions:

$$\frac{\partial L\left(p_{\mathrm{NRx},n}, p_{\mathrm{FRx},n}, \tau, \upsilon\right)}{\partial p_{\mathrm{NRx},n}} = 0, n \in \mathcal{N}, \tag{65a}$$

$$\frac{\partial L\left(p_{\mathrm{NRx},n}, p_{\mathrm{FRx},n}, \tau, \upsilon\right)}{\partial p_{\mathrm{FRx},n}} = 0, n \in \mathcal{N}, \tag{65b}$$

$$\tau\left(R_{\mathrm{FRx}} - \sum_{n\in\mathcal{N}} \log_2\left(1 + \Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right)\right) = 0, \tag{65c}$$

$$\upsilon\left(\sum_{n\in\mathcal{N}} \left(p_{\mathrm{NRx},n} + p_{\mathrm{FRx},n}\right) - P_s\right) = 0, \tag{65d}$$

$$R_{\mathrm{FRx}} - \sum_{n\in\mathcal{N}} \log_2\left(1 + \Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right) \leq 0, \tag{65e}$$

$$\sum_{n\in\mathcal{N}} \left(p_{\mathrm{NRx},n} + p_{\mathrm{FRx},n}\right) - P_s \geq 0, \tag{65f}$$

$$\tau \geq 0, \tag{65g}$$

$$\upsilon \geq 0, \tag{65h}$$

where (65a) and (65b) can be written as

$$\begin{aligned} &\frac{\tau p_{\mathrm{FRx},n} a_{\mathrm{FRx},n}^2}{\left(1 + p_{\mathrm{NRx},n} a_{\mathrm{FRx},n} + p_{\mathrm{FRx},n} a_{\mathrm{FRx},n}\right)\left(1 + p_{\mathrm{NRx},n} a_{\mathrm{FRx},n}\right)} + \upsilon \\ &= \frac{a_{\mathrm{NRx},n} - a_{\mathrm{FRx},n}}{\left(1 + p_{\mathrm{NRx},n} a_{\mathrm{NRx},n}\right)\left(1 + p_{\mathrm{NRx},n} a_{\mathrm{FRx},n}\right)}, \end{aligned} \tag{66}$$

$$\frac{\tau a_{\mathrm{FRx},n}}{1 + p_{\mathrm{NRx},n} a_{\mathrm{FRx},n} + p_{\mathrm{FRx},n} a_{\mathrm{FRx},n}} - \upsilon = 0. \tag{67}$$

Clearly, we have: If $\tau = 0$, then $\upsilon = 0$ based on (67). However, if $\tau = 0$, then $\upsilon = 0$. (66) cannot be satisfied under $a_{\mathrm{NRx},n} > a_{\mathrm{FRx},n}$. Thus, it must hold that $\tau > 0, \upsilon > 0$. This indicates that the optimal solution is taken if and only if the equalities hold in both constraints (24b) and (27c).

Appendix B
Proof of Lemma 2

We take the Lagrange relaxation method to prove this lemma. The Lagrangian of (53) is given by

$$\begin{aligned} &L\left(p_{\mathrm{NRx},n}, p_{\mathrm{FRx},n}, \upsilon_1, \upsilon_{2,n}\right) = \sum_{n\in\mathcal{N}} \left(\log_2 \frac{1 + p_{\mathrm{NRx},n} a_{\mathrm{NRx},n}}{1 + p_{\mathrm{NRx},n} a_{\mathrm{FRx},n}}\right) \\ &+ \upsilon_1\left(\sum_{n\in\mathcal{N}} \log_2\left(1 + \Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right) - R_{\mathrm{FRx}}\right) \\ &+ \sum_{n\in\mathcal{N}} \upsilon_{2,n}\left(P_{\max,n} - p_{\mathrm{NRx},n} - p_{\mathrm{FRx},n}\right). \end{aligned} \tag{68}$$

The solution to (53) satisfies the following KKT conditions:

$$\frac{\partial L\left(p_{\mathrm{NRx},n}, p_{\mathrm{FRx},n}, \upsilon_1, \upsilon_{2,n}\right)}{\partial p_{\mathrm{NRx},n}} = 0, n \in \mathcal{N}, \tag{69a}$$

$$\frac{\partial L\left(p_{\mathrm{NRx},n}, p_{\mathrm{FRx},n}, \upsilon_1, \upsilon_{2,n}\right)}{\partial p_{\mathrm{FRx},n}} = 0, n \in \mathcal{N}, \tag{69b}$$

$$\sum_{n\in\mathcal{N}} \log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right) - R_{\mathrm{FRx}} \geq 0, \tag{69c}$$

$$\upsilon_1\left(\sum_{n\in\mathcal{N}} \log_2\left(1+\Gamma_{\mathrm{FRx},n}^{\mathrm{FRx}}\right) - R_{\mathrm{FRx}}\right) = 0, \tag{69d}$$

$$P_{\max,n} - p_{\mathrm{NRx},n} - p_{\mathrm{FRx},n} \geq 0, \tag{69e}$$

$$\sum_{n\in\mathcal{N}} \upsilon_{2,n}\left(P_{\max,n} - p_{\mathrm{NRx},n} - p_{\mathrm{FRx},n}\right) = 0, \tag{69f}$$

$$\upsilon_1 \geq 0, \upsilon_{2,n} \geq 0, n \in \mathcal{N}. \tag{69g}$$

where (69a) and (69b) can be written as

$$\frac{\upsilon_1 p_{\mathrm{FRx},n} a_{\mathrm{FRx},n}^2}{\left(1+p_{\mathrm{NRx},n}a_{\mathrm{FRx},n}+p_{\mathrm{FRx},n}a_{\mathrm{FRx},n}\right)\left(1+p_{\mathrm{NRx},n}a_{\mathrm{FRx},n}\right)} + \sum_{n\in\mathcal{N}} \upsilon_{2,n} = \frac{a_{\mathrm{NRx},n} - a_{\mathrm{FRx},n}}{\left(1+p_{\mathrm{NRx},n}a_{\mathrm{NRx},n}\right)\left(1+p_{\mathrm{NRx},n}a_{\mathrm{FRx},n}\right)}, \tag{70}$$

$$\frac{\upsilon_1 a_{\mathrm{FRx},n}}{1+p_{\mathrm{NRx},n}a_{\mathrm{FRx},n}+p_{\mathrm{FRx},n}a_{\mathrm{FRx},n}} - \sum_{n\in\mathcal{N}} \upsilon_{2,n} = 0. \tag{71}$$

Clearly, if $\upsilon_1 = 0$, then $\sum_{n\in\mathcal{N}} \upsilon_{2,n} = 0$ based on (71). However, if $\upsilon_1 = 0$ and $\sum_{n\in\mathcal{N}} \upsilon_{2,n} = 0$, (70) would not hold under $a_{\mathrm{NRx},n} > a_{\mathrm{FRx},n}$. Therefore, either $\upsilon_1 > 0$ or $\sum_{n\in\mathcal{N}} \upsilon_{2,n} > 0$ must hold. The optimal solution is taken, if and only if the equality holds constraint (53b).

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