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Resource Optimization Framework for Physical Layer Security of Dual-Hop Multi-Carrier Decode and Forward Relay Networks

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ABSTRACT Physical layer security (PLS) is an emerging area for information security against eavesdroppers (Eve). Information security of any system can also be improved by using friendly jammers that produce interference signals to Eve. Traditional security techniques are limited by the processing power of the wireless nodes, whereas PLS can achieve communication secrecy without requiring computationally expensive cryptographic operations. The relay networks have emerged as a promising technology to enhance the performance of the wireless systems. This paper proposes a joint resource optimization framework for the PLS of dual-hop decode and forward (DF) relay network with and without cooperative jamming. In particular, the proposed framework consists of a base station (BS), multiple users, DF relays, multiple subcarriers, and an Eve. Our objective is to maximize the sum secrecy rate (SR) through optimal power loading over different subcarriers at BS and relay nodes, and efficient subcarrier assignment. We formulate a mixed binary integer programing problem for secrecy optimization and adopt Lagrangian dual method to achieve the efficient solutions. We also provide three benchmark frameworks, i.e., joint power optimization with random subcarrier assignment, equal power allocation with efficient subcarrier assignment and equal power with random subcarrier assignment to guage the performance of our joint resource optimization framework. Simulation results unveil that the proposed joint resource optimization framework under cooperative jamming and without jamming performs significantly better than the benchmark frameworks.

INDEX TERMS Cooperative jamming, decode and forward relay, joint resource optimization, physical layer security.

I. INTRODUCTION

THE WIRELESS technologies are developing with a rapid pace and the main demands is to provide secure connections between billions of communication nodes [1]. The use of wireless devices has recently increased significantly [2]. Moreover, several advance technologies such as backscatter communication, non-orthogonal multiple access, intelligent reflecting surfaces, etc. have emerged as the potential solution to meet the energy and spectrum demands of next-generation wireless networks [3]–[6]. Peoples are now more dependent on sharing their private information using wireless devices which can be more susceptible to security attacks. Conventionally, security issues are handled by cryptographic techniques at the upper layers of protocol stack [7], [8]. For this purpose, computational security mechanisms are used where various encryption techniques are employed to secure the information. Even though computational security has proven itself to be a very efficient mechanism, but the variety of emerging network architectures (ad-hoc networks) require additional security measures. The securing of information through key-sharing requires the channels to be perfect, which is not the case [9]. Hence, in practice if either the key or information is changed, the mechanism would fail to provide the required security.

With the passage of time, the immense growth in the size of networks has made data encryption impractical because of the increased computational complexity. Moreover, these layers are exposed to more security threats as compared to physical transmission medium. Hence, physical layer security (PLS) has come forward as a potential candidate for providing security in communication networks [10]–[13]. The PLS enables to secure information by harnessing the randomness of wireless channel characteristics. Several techniques have recently been discussed for the PLS of communication networks [14]. They have noticed that the level of security depends on the amount of information known by eavesdroppers (Eve). They have also observed that the security of any link is measured by a *secrecy rate* (SR) which can be defined as the rate at which information is transmitted to legitimate receiver without the involvement of Eve. The SR depends on the channel of legitimate user and Eve from the source. The link from source to legitimate user is known as the main link and from source to Eve is called the *wiretap link*. The difference in capacities of the main link and wiretap link is called SR, and its positive value considers as perfect security. While the negative value of SR indicates that Eve can overhear the information of legitimate user and the probability of such event is called intercept probability. The secrecy outage probability (SOP) increases when the instantaneous secrecy capacity of the main channel falls below the minimum required data rate of a given system, it may tell us about the status of relay whether it can be trusted or not.

A. RELATED WORKS

This section offers a systematic overview of the work that has been done in this field. Recently, cooperative relaying has been developed as an efficient technique for extending the wireless network, which assists a source by forwarding its information to destination nodes securely. The authors in [15] studied the problem of improving the interrupt performance of wireless channel by considering a single user and multiple Eve. For this purpose, secrecy maximization oriented relay selection scheme was adopted which surpasses the typical max-min methodology of relay selection. Then, in [16] and [17] multiuser cooperative relaying strategies were proposed to ensure reliable and secure communication from transmitter to the receiver end. Likewise, [18] explored the idea of ensuring legitimacy among relay nodes in the presence of large number of Eve and proposed suboptimal relay selection scheme. Furthermore, receiver grouping based selection scheme was proposed to ensure fairness among user terminals. Later on, the authors investigated the effect of self-interference in full-duplex relay networks to improve secrecy performance of the wireless channel [19]. In [20], a relay selection strategy was proposed for multi-hop wireless communication systems having multiple Eve along with numerous source destination pairs. Considering a relay-aided dual-hop communication network, the authors in [21] showed that the intercept probability can be reduced significantly by introducing in-phase and quadrature-phase imbalance at the transmitter and receiver nodes. In the above literature [15]–[21], the problem of power allocation has not been addressed. Henceforth, authors in [22] proposed the user selection criterion in addition with optimum power distribution approach. They maximized the sum SR and minimize the SOP of the overall network, in which a transmitter interacts with a group of receivers through the help of a decode and forward (DF) relay. Afterwards, instead of using DF relay, another cooperative relay system based on amplify and forward (AF) protocol was considered in [23] which consists of a transmitter, receiver and an Eve. The authors in [24] extended the work of [23] and proposed a power optimization framework for networks containing multiple AF relays. In addition, the authors of [25]–[28] also provided resource allocation frameworks for cooperative jamming in device-to-device communication network.

Besides, the authors in [29]–[32] examined the effect of untrusted relay on secrecy performance of wireless network. In [29], AF-relaying system was considered in the presence of point to point links. Multiple transmitters were involved, the best transmitter was chosen to transfer the message signal to the relays and the receiver. An untrusted relay may invade the integrity of the signal. Two suboptimal selection strategies were proposed based on the direct link and relay connections. The goal of the selection strategy was to avoid the leakage of transmitted data by the untrusted relay and to enhance the secrecy capacity of the main channel. An AF relay based system was considered in [30] where transmitter and receiver communicate with each other through an untrusted relay node. Source based jamming strategy was proposed which allows the transmitter to transmit the high frequency signal to confound the Eve, thereby achieving the maximum diversity gain and increased SR in untrusted relay systems. Later, considering power allocation in systems having untrusted relaying node, the authors of [31] proposed a framework to enhance the average SR in the presence of an untrusted AF relay. For multiple untrusted AF relays system, a power allocation to enhance the PLS was considered by [32]. The system model contained a transmitter and receiver node along with multiple untrusted AF relays and a passive multiantenna-aided Eve. Han *et al.* [33] designed artificial noise-aided beamformer for secrecy rate of multiple input single output wiretap channel under the transmit power and secrecy outage constraints.

Recently, cooperative jamming has emerged as an efficient technique to enhance the SR by effectively sending the interference signals from source or relay nodes towards Eve. Orthogonal jamming can be combined with artificial noise to provide better SR performance [34]. In this technique, noise is deliberately added to the signal in a controlled manner such that Eve considers this artificial noise as the legitimate signal. However, when Eve is equipped with multiple antennas, cooperative jamming may not work efficiently. In a recent work [35], Waqar *et al.*, proposed a new beamforming scheme for an AF relay networks with wireless powered jammer and also derived new closed-form expression for ergodic SR. With the help of joint DF cooperative jamming technique, significant performance can be achieved in such a way that total consumption of power is reduced as well as security issue is also resolved. Authors in [36] suggested the collaborative privacy protecting technique, where only one legitimate receiver is selected from a group of receivers for accepting the incoming signal, while remaining receivers are considered as Eve. In this scheme, the cooperative receiver is scheduled in addition with legitimate receiver which sends artificial noise signal to Eve during the phase of data transmission, such that artificial noise can be nullified at the desired receiver. In [37], the power allocation was optimized to enhance the SR of a wireless communication system containing a DF node for relaying the data to the receiver, and a dedicated jamming node that transmits the jamming signals to make decoding hard for the Eve in the system. Considering a system containing multiple Eve and relaying nodes, the authors in [38] proposed a framework to select a relay to forward data to the receiver, and a relay to generate the jamming signal. In addition, the authors in [39] proposed a system that employs an auxiliary node to provide the required level of security in a single transmitter-receiver based orthogonal frequency division multiple access (OFDMA) system. The auxiliary node generates artificial noise, hence, making it difficult for the Eve to correctly decode the signal. Later, the problem of optimizing power allocation to maximize the sum SR of an OFDMA based wireless communication network was considered by [40].

B. MOTIVATION AND CONTRIBUTIONS

Although substantial works have been done to maximize the PLS of communication networks, most of the works have considered simple systems containing a single receiver and transmitter pair. Some works that have considered multiuser scenarios have ignored the problem of optimizing channel allocation. Other works have optimized power at source while considering fixed power allocation at relay node. The joint optimization of channel assignment and power loading at source and relays in multiuser multirelay networks can bring additional benefits to the performance, however, it has not been explored well, to the best of our knowledge. Thus, we aim to provide a joint optimization framework for channel assignment and power loading at source and relays to improve the PLS of the network. In particular, we employ Lagrangian dual method for efficient channel allocation and water filling technique for power loading, respectively. Our provided simulation results show the superiority of the proposed joint optimization framework over the other benchmark schemes. The main contributions of this paper can be summarized as:

- Firstly, we consider a multiuser multirelay based OFDMA system and employ a joint optimization framework for efficient channel assignment and optimal power loading at source and rely nodes to maximize the sum SR of the system. Secondly, we optimize the system parameters for a jamming-enabled system where a relay is not only assigned to a specific user for the data transmission but also acts as cooperative jamming by sending the noise signal towards passive Eve.
- For both systems, we adopt Lagrangian dual method for efficient channel assignment and water filling technique for optimal power loading. In addition, we propose simplified solutions with random channel assignment and fix power allocation, and these solutions serve as the benchmark to evaluate the performance of the joint optimization frameworks.
- We provide detailed simulation results for both cases (with and without cooperative jamming) to compare the performance of the proposed joint optimization and other benchmark schemes. The results unveil that the proposed joint optimization framework significantly improves the PLS compared to the other benchmark schemes.

The rest of this paper is organized as follows: Section II explains the system model, problem formulation, and proposed joint optimization solution for resource allocation under orthogonal channel allocation. Likewise, Section III explains the resource allocation under cooperative jamming. Section IV presents the simulation results, and finally the conclusion of this work and future research directions are provided in Section V. All the notations used in this paper are defined in Table 1.

II. RESOURCE OPTIMIZATION UNDER ORTHOGONAL CHANNEL ALLOCATION

In this section, the system model without jamming is described first, which is then followed by the discussion of problem formulation and proposed optimal solution.

A. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a downlink transmission where the base station (BS) as a source communicates with multiple users through multiple DF relay nodes using OFDMA protocol. We also consider one passive Eve which target the transmitted signals of relay nodes, as shown in Fig. 1. The direct links of users and Eve from BS are missing due to a large distance and shadow fading.

In this work, we assume that: i) All nodes in the network are transmitted information using a single antenna scenario;[1]

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[1] In this work, we consider that all the devices in the network are equipped with single antenna scenario. Considering multi-antenna scenario can further improve the system performance and reliability, however, it is left for our future work to focus here on the joint optimization of subcarrier assignment and power loading at BS and relay nodes.

TABLE 1. List of notations used in this paper.

Not.	Definition
K	Number of users.
M	Number of relay nodes.
N	Number of subcarriers.
$h_{i,m}$	Channel gain from BS to m^{th} relay on i^{th} subcarrier.
$g_{i,m,k}$	Channel gain from m^{th} relay to k^{th} user.
$f_{i,m}$	Channel gain from m^{th} relay to Eve.
y_m	Received signal at m^{th} relay node.
$P_{s,i}$	Transmit power of BS on i^{th} subcarrier.
n	Additive white Gaussian noise.
$P_{i,m,k}$	Transmit power of relay node for k^{th} user.
$C_{m,k}$	Data rate of k^{th} from m^{th} relay.
δ^2_{ni}	Variance of additive white Gaussian noise.
$C_{i,k}$	Data rate of k^{th} user from BS on i^{th} subcarrier.
$C_{e,k,i}$	Data rate of k^{th} user at Eve on i^{th} subcarrier.
$SR_{i,k}$	Secrecy rate of k^{th} user on i^{th} subcarrier.
$\alpha_{i,k}$	Binary variable for user subcarrier assignment.
$\beta_{m,k}$	Binary variable for user relay assignment.
$L(.)$	Lagrangian function.
η	Lagrangian multiplier.
ϕ	Lagrangian multiplier.

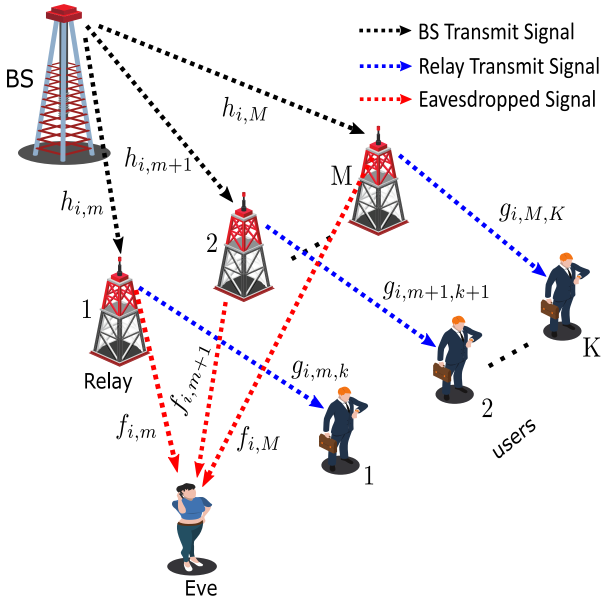

FIGURE 1. System model for PLS.

ii) The channel information is perfectly available at BS [41]; iii) Same noise variance is considered at BS and relay nodes; iv) The wireless channels between different nodes are independent and undergo Rayleigh fading [42]; v) The Eve is passive which intercepts the information of users intending to read not modifying it. Let K, M and N denote the total number of users, DF relays and subcarriers, respectively, where $k = \{1, 2, 3, \ldots, K\}$, $m = \{1, 2, 3, \ldots, M\}$ and $i = \{1, 2, 3, \ldots, N\}$. The channel coefficient from source to m^{th} relay node and from the m^{th} relay to k^{th} user on the i^{th} subcarrier is denoted as $h_{i,m}$ and $g_{i,m,k}$, respectively. Similarly, the corresponding channel coefficient on the i^{th} subcarrier from m^{th} relay to the Eve can be represented as $f_{i,m}$. The channel of each user operates on different frequency band in order to avoid interference. Total power available at the BS is divided among all relay nodes. The power budget of m^{th} relay node is distributed among different subcarriers which is allocated to the k^{th} user. The focus of this work is to maximize the sum SR through joint optimization of subcarrier assignment and power loading at BS and relay nodes. Let the BS sends a symbol 'x' on i^{th} subcarrier to the m^{th} relay node. Then, the signal received at m^{th} relay node is given as

$$Y_m = \sqrt{P_{s,i}} h_{i,m} x + n_1, \tag{1}$$

where, $P_{s,i}$ is the allocated power at BS over the i^{th} subcarrier, and n_1 is additive white Gaussian noise (AWGN) at first hop. The m^{th} relay node decode the received signal of BS and then forward it to the k^{th} user. The signal at the k^{th} user can be expressed as

$$Y_k = \sqrt{P_{i,m,k}}\, g_{i,m,k}\, x + n_2, \tag{2}$$

where, $P_{i,m,k}$ is the power transmitted from m^{th} relay node to k^{th} user over i^{th} subcarrier and n_2 is the AWGN at second hop. Similarly, the signal received at Eve can be written as

$$Y_{e,k} = \sqrt{P_{i,m,k}} f_{i,m} x + n_3, \tag{3}$$

where, n_3 is the AWGN between m^{th} relay and Eve channel. The data rate of k^{th} user on the i^{th} subcarrier is derived as

$$C_{i,k} = \min\big(C_{s,m}, C_{m,k}\big), \tag{4}$$

where, $C_{s,m}$ is the data rate from BS to m^{th} relay node, it can be written as

$$C_{s,m} = \frac{1}{2}\log_2\left(1 + \frac{|h_{i,m}|^2 P_{s,i}}{\delta^2_{ni}}\right), \tag{5}$$

where δ^2_{ni} is the variance of AWGN and $\frac{1}{2}$ appears due the half-duplex transmission of DF relay node, i.e, the transmission takes place in two time slots from source to destination. Similarly, $C_{m,k}$ is the data rate from m^{th} relay node to k^{th} user which can be stated as

$$C_{m,k} = \frac{1}{2}\log_2\left(1 + \frac{|g_{i,m,k}|^2 P_{i,m,k}}{\delta^2_{ni}}\right). \tag{6}$$

Therefore, the data rate of the link from BS to k^{th} user over the i^{th} subcarrier is given by

$$C_{i,k} = \frac{1}{2}\log_2\left[1 + \min\left(\frac{|h_{i,m}|^2 P_{s,i}}{\delta^2_{ni}}, \frac{|g_{i,m,k}|^2 P_{i,m,k}}{\delta^2_{ni}}\right)\right]. \tag{7}$$

Accordingly, the data rate of k^{th} user on i^{th} subcarrier at Eve can be given as

$$C_{e,k,i} = \frac{1}{2}\log_2\left[1 + \min\left(\frac{|h_{i,m}|^2 P_{s,i}}{\delta^2_{ni}}, \frac{|f_{i,m}|^2 P_{i,m,k}}{\delta^2_{ni}}\right)\right]. \tag{8}$$

Next we use $C_{i,k}$ and $C_{e,k,i}$ to calculate the SR of k^{th} user on the i^{th} subcarrier, which can be obtained as

$$SR^{*}_{i,k} = \left(C_{i,k} - C_{e,k,i}\right). \tag{9}$$

Now we formulate the optimization problem for the proposed system model without jamming. The objective of this work is to maximize the sum SR by jointly considering the dynamic channel assignment and power allocation at both BS and relay nodes in an OFDM-based transmission. The sum SR of the system can be expressed as

$$SR_{sum} = \sum_{i=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K}\alpha_{i,k}\beta_{m,k}SR^{*}_{i,k}, \tag{10}$$

where, $\alpha_{i,k}$ and $\beta_{m,k}$ are binary variables and represent the allocation of i^{th} subcarrier and m^{th} relay node to k^{th} user. The joint optimization problem can be then formulated as

$$\begin{aligned}
\max_{(\alpha_{i,k}),(\beta_{m,k}),(P_{s,i}),(P_{i,m,k})} \quad & SR_{sum} \\
s.t. \quad C_1 :\ & \sum_{m=1}^{M}\beta_{m,k} = 1,\ \forall k \in K, \\
C_2 :\ & \sum_{i=1}^{N}\alpha_{i,k} = 1, \forall k \in K, \\
C_3 :\ & \sum_{i=1}^{N}\sum_{k=1}^{K}\sum_{m=1}^{M}\alpha_{i,k}\beta_{m,k}P_{s,i} \le P_T^s, \\
C_4 :\ & \sum_{i=1}^{N}\sum_{k=1}^{K}\sum_{m=1}^{M}\alpha_{i,k}\beta_{m,k}P_{i,m,k} \\
& \le P_T^m,
\end{aligned} \tag{11}$$

where P_T^s and P_T^m denote the power budget available at BS and m^{th} relay node. Constraints C_1 and C_2 are the binary variables for relay selection and subcarrier assignment. More specifically, $\beta_{m,k} = \alpha_{i,k} = 1$ if m^{th} relay node[2] is assigned to k^{th} user over i^{th} subcarrier. Constraints C_3 and C_4 limit the transmit power of BS and each relay node. It is important to note that a subcarrier is assigned to the same user over both hops of transmission to reduce the complexity of the problem.

B. LAGRANGIAN DUAL METHOD-BASED JOINT OPTIMAL SOLUTION

Here we provide a joint optimal solution. It can be observed that the formulated problem in (11) is mixed binary integer programming problem due to assignment variables $\alpha_{i,k}$ and $\beta_{m,k}$ which makes it difficult to solve directly [43]. Therefore, we first need to find the efficient subcarrier assignment $\alpha_{i,k}$ before calculating the power allocation. Let us assign the i^{th} subcarrier to k^{th} user such that maximizes the SR_{sum}. It can be written, mathematically, as

$$\max_{k}\Big(\min\Big(\left|h_{i,m}\right|^2, \left|g_{i,m,k}\right|^2\Big) - \min\Big(\left|h_{i,m}\right|^2, \left|f_{i,m}\right|^2\Big)\Big), \forall i \tag{12}$$

Now we are left with the problem of power loading at BS and relay nodes. To efficiently optimize the power allocation variables, the original problem (11) can be decomposed into two subproblems, i.e., (P_1) and (P_2). Then, we adopt Lagrangian dual method to obtain the efficient solutions [44], [45]. In first step, the power is allocated at the relay nodes, followed by the power allocation at BS in step two. For a given transmit power at BS, the problem of efficient power loading at relay nodes can be simplified as

$$\begin{aligned}
(\mathrm{P}_1)\ \max_{P_{i,m,k}}\ & \sum_{i=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K}\Bigg[\log_2\left(1 + \frac{P_{i,m,k}|g_{i,m,k}|^2}{\delta_{ni}^2}\right) \\
& \qquad - \log_2\left(1 + \frac{P_{i,m,k}|f_{i,m}|^2}{\delta_{ni}^2}\right)\Bigg] \\
s.t.\ \ & C_8\colon \sum_{i=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K}P_{i,m,k} \le P_T^m,
\end{aligned} \tag{13}$$

Following the KKT condition, it ca be stated as

$$\frac{\partial L\left(P_{i,m,k}, \lambda\right)}{\partial P_{i,m,k}}|_{P_{i,m,k}=P^{*}_{i,m,k}} = 0, \tag{14}$$

where the Lagrangian function of (13) is written as

$$\begin{aligned}
L(P_{i,m,k}, \eta) = & \sum_{i=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K}\Bigg[\log_2\left(1 + \frac{P_{i,m,k}|g_{i,m,k}|^2}{\delta_{ni}^2}\right) \\
& \qquad - \log_2\left(1 + \frac{P_{i,m,k}|f_{i,m}|^2}{\delta_{ni}^2}\right)\Bigg] \\
& + \eta\left(P_T^m - \sum_{i=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K}P_{i,m,k}\right),
\end{aligned} \tag{15}$$

where η denotes the Lagrangian multiplier. Taking the partial derivative of (15) with respect to P_{imk}, it can be stated as

$$\begin{aligned}
& \frac{\partial}{\partial P_{i,m,k}}\Bigg(\log_2\left(1 + \frac{P_{i,m,k}\left|g_{i,m,k}\right|^2}{\delta_{ni}^2}\right) \\
& \qquad - \log_2\left(1 + \frac{P_{i,m,k}|f_{i,m}|^2}{\delta_{ni}^2}\right) \\
& \qquad + \eta\left(P_T^m - \sum_{i=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K}P_{i,m,k}\right)\Bigg) = 0,
\end{aligned} \tag{16}$$

$$\begin{aligned}
& \frac{1}{\left(1 + \frac{P_{i,m,k}|g_{i,m,k}|^2}{\delta_{ni}^2} - \frac{P_{i,m,k}|f_{i,m}|^2}{\delta_{ni}^2}\ln 2\right)} \\
& \quad \times \frac{\partial}{\partial P_{i,m,k}}\left(\frac{P_{i,m,k}\left|g_{i,m,k}\right|^2}{\delta_{ni}^2} - \frac{P_{i,m,k}\left|f_{i,m}\right|^2}{\delta_{ni}^2}\right) = \eta,
\end{aligned} \tag{17}$$

$$\frac{\left(\left|g_{i,m,k}\right|^2 - \left|f_{i,m}\right|^2\right)}{\delta_{ni}^2 + P_{i,m,k}\left|g_{i,m,k}\right|^2 - P_{i,m,k}\left|f_{i,m}\right|^2} = \eta. \tag{18}$$

After some straightforward calculations, the expression for

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[2] The optimal relay selection can further enhance the system performance, however, is beyond the scope of this work.

power allocation at m^{th} relay node for k^{th} user over i^{th} subcarrier can be expressed as

$$P^*_{i,m,k} = \left(\frac{1}{\eta} - \frac{\delta^2_{ni}}{\left(\left|g_{i,m,k}\right|^2 - \left|f_{i,m}\right|^2\right)}\right)^+, \quad \forall i \in N, \forall m \in M, \forall k \in K. \tag{19}$$

Likewise, the efficient power allocation at BS can also be derived using the similar steps as described previously for finding the power allocation at relay nodes. To do so, the problem (11) can be reformulated as

$$(\mathrm{P}_2) \ \max_{P_{s,i}} \sum_{i=1}^{N}\sum_{m=1}^{M}\left[\log_2\left(1 + \frac{P_{s,i}\left|h_{i,m}\right|^2}{\delta^2_{ni}}\right)\right]$$
$$\text{s.t.} \ \sum_{i=1}^{N} P_{s,i} \le P^s_T. \tag{20}$$

Accordingly, the Lagrangian function associated with the above sub-problem (P$_1$) can be defined as

$$L(P_{s,i}, \phi) = \sum_{i=1}^{N}\sum_{m=1}^{M}\left[\log_2\left(1 + \frac{P_{s,i}\left|h_{i,m}\right|^2}{\delta^2_{ni}}\right)\right] + \phi\left(P^s_T - \sum_{i=1}^{N} P_{s,i}\right). \tag{21}$$

where ϕ is a Lagrangian multiplier. Next we employ KKT conditions such that

$$\frac{\partial L(P_{s,i}, \eta)}{\partial P_{s,i}}|_{P_{s,i}=P^*_{s,i}} = 0. \tag{22}$$

After calculating the partial derivations, the expression for power allocation at BS can be derived as

$$P^*_{s,i} = \left(\frac{1}{\phi} - \frac{\delta^2_{ni}}{\left|h_{i,m}\right|^2}\right)^+, \quad \forall i \in N. \tag{23}$$

Finally, the value of η and ϕ can be found by standard water-filling algorithm. The algorithm allocates more amount of power to those subcarriers which have good channel conditions, whereas, lesser amount of power will be allocated to those subcarriers with weak channel conditions. Once, the values of η and ϕ are obtained, it is substituted in (19) and (23) to get the optimal values of power at source and relay nodes. Thus, substituting $P^*_{i,m,k}$, $P^*_{s,i}$, $\alpha_{i,k}$ and $\beta_{m,k}$ in (10), sum SR is obtained. In addition, it is important to mention the computational complexity of the proposed joint optimization framework which depends on the number of subcarriers, users and relay nodes. The complexity of the proposed iterative framework can be computed as $\mathcal{O}(KNM)$.

III. RESOURCE OPTIMIZATION UNDER COOPERATIVE JAMMING

In this section, the system model with jamming is described first, which is then followed by problem formulation, and proposed optimization scheme.

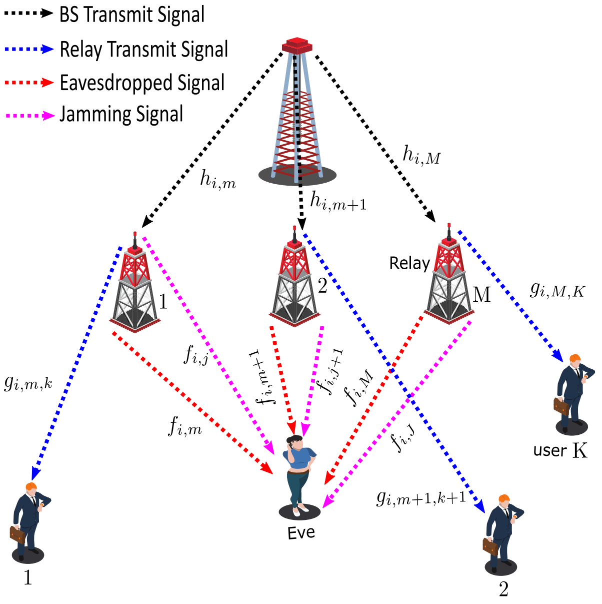

FIGURE 2. System model for resource allocation under cooperative jamming.

A. SYSTEM MODEL AND PROBLEM FORMULATION

In cooperative jamming, m^{th} relay node is responsible for relaying data to the k^{th} user. Meanwhile, the remaining M-1 relay nodes are sending artificial noise towards the Eve, which is basically generating interference to the Eve. Cooperative jamming as shown in Fig. 2, makes the transmission more secure, in such a way that relay nodes are not only relaying the data of their own user but also cooperate to enhance the SR of other users. Subcarrier allocation changes in case of cooperative jamming, which leads to change in optimum power allocation at relay nodes.

Let the BS sends a symbol x' on i^{th} subcarrier to the m^{th} relay node. Then, the signal received at m^{th} relay node can be expressed as

$$Y_{m'} = \sqrt{P'_{s,i}}h_{i,m}x' + n_1. \tag{24}$$

and the signal received by the k^{th} user can be written as

$$Y_{k'} = \sqrt{P'_{i,m,k}}\, g_{i,m,k}\, x' + n_2. \tag{25}$$

Accordingly, the signal received at Eve can be written as

$$Y_{e,k'} = \sqrt{P'_{i,m,k}}f_{i,m}x' + \sum_{i=1}^{N}\sum_{m'=1}^{M}\sum_{k=1}^{K}\sqrt{P'_{i,m',k}}f_{i,m'}z_m + n_3. \tag{26}$$

The data rate of k^{th} user on the i-th carrier can be expressed as

$$\hat{C}_{i,k} = \min\left(\hat{C}_{s,m}, \hat{C}_{m,k}\right), \tag{27}$$

where, $\hat{C}_{s,m}$ is the data rate from source to m^{th} relay, it can be written as

$$\hat{C}_{s,m} = \frac{1}{2}\log_2\left(1 + \frac{|h_{i,m}|^2 P'_{s,i}}{\delta^2_{n,i}}\right). \tag{28}$$

and $\hat{C}_{m,k}$ is the data rate from m^{th} relay to k^{th} user is

$$\hat{C}_{m,k} = \frac{1}{2}\log_2\left(1 + \frac{|g_{i,m,k}|^2 P'_{i,m,k}}{\delta^2_{n,i}}\right). \tag{29}$$

Thus, the data rate of the transmission link from the source to k^{th} user over the i^{th} subcarrier is given by

$$\hat{C}_{i,k} = \frac{1}{2}\log_2\left[1 + \min\left(\frac{|h_{i,m}|^2 P'_{s,i}}{\delta^2_{n,i}}, \frac{|g_{i,m,k}|^2 P'_{i,m,k}}{\delta^2_{n,i}}\right)\right]. \tag{30}$$

The data rate of Eve for k^{th} user on i^{th} subcarrier can be stated as

$$\hat{C}_{e,k,i} = \frac{1}{2}\log_2[1 + \min \left(\frac{|h_{i,m}|^2 P'_{s,i}}{\delta_{n,i}}, \frac{P'_{i,m,k}|f_{i,m}|^2}{\delta_{n,i}\sum_{i=1}^{N}\sum_{m'=1}^{M} P'_{i,m',k}|f_{i,j}|^2}\right)]. \tag{31}$$

The SR of k^{th} user on the i^{th} subcarrier can be obtained as

$$SR^{**}_{i,k} = \left(\hat{C}_{i,k} - \hat{C}_{e,k,i}\right). \tag{32}$$

Here we need to formulate an optimization problem for the proposed system model with cooperative jamming. The objective is to enhance the sum SR by jointly considering the dynamic subcarrier assignment and power loading at both source and relay nodes. The sum SR of the proposed model can be stated as

$$SR'_{sum} = \sum_{i=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K} \alpha'_{i,k}\beta_{m,k} SR^{**}_{i,k}, \tag{33}$$

where, $\alpha'_{i,k}$ and $\beta_{m,k}$ represent the binary variables of assigning i^{th} subcarrier and m^{th} relay node to k^{th} user. The joint optimization problem can be then formulated as

$$\max_{\left(\alpha'_{i,k'}\right),\left(\beta_{m,k}\right),\left(P'_{s,i}\right),\left(P'_{i,m,k}\right)} SR'_{sum} \tag{34}$$

$$\begin{aligned} s.t.\quad & C'_1 : \sum_{m=1}^{M} \beta_{m,k} = 1, \quad \forall k \in K, \\ & C'_2 : \sum_{i=1}^{N} \alpha'_{i,k'} = 1, \forall k \in K, \\ & C'_3 : \sum_{i=1}^{N}\sum_{k=1}^{K}\sum_{m=1}^{M} \alpha'_{i,k'}\beta_{m,k}P'_{s,i} \\ & \leq P^s_T, \\ & C'_4 : \sum_{i=1}^{N}\sum_{k=1}^{K}\sum_{m=1}^{M} \alpha'_{i,k'}\beta_{m,k}P'_{i,m,k} \\ & \leq P^m_T, \end{aligned} \tag{35}$$

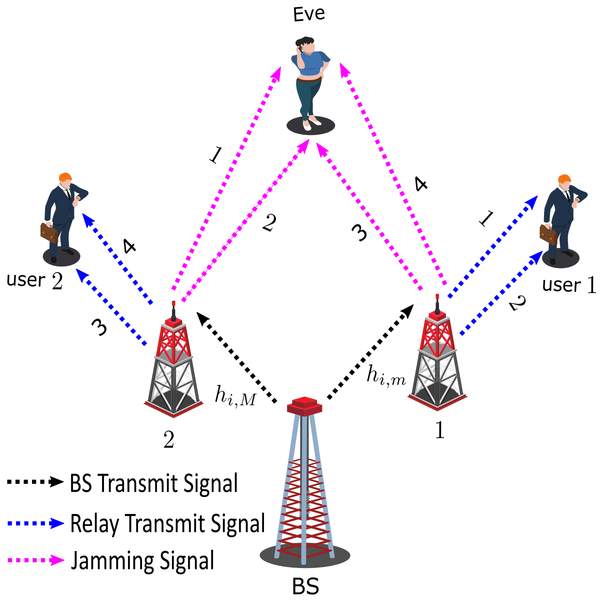

FIGURE 3. Resource allocation under cooperative jamming for $N = 4$, $M = 2$ and $K = 2$.

where the objective in (34) is to maximize the sum SR of the system. Moreover, constraint C'_1 and C'_2 are the binary variables for subcarrier assignment and relay node selection. Furthermore, C'_3 limits the power of the source and C'_4 control the power of each relay node, respectively.

B. LAGRANGIAN DUAL METHOD-BASED JOINT OPTIMAL SOLUTION

Similar to Section II-B, we solve the problem (34) using the same method and steps. In the proposed cooperation model, the available subcarriers can be utilized by each relay node such that some subcarriers are used for data transmission while remaining are used for sending interference towards Eve. More specifically, Fig. 3 is taken as an example where the number of subcarriers, relay nodes, and users are $N = 4$, $M = 2$ and $K = 2$, respectively. We can see that both relay nodes are transmitting over four subcarriers at one time. Particularly, relay node 1 performs data transmission to user one over subcarrier 1 and 2 while transmits interference towards Eve on subcarrier 3 and 4. In contrary, relay 2 transmits data on subcarrier 3 and 4 while sending interference to Eve on subcarrier 1 and 2. The subcarrier allocation variable $\alpha'_{i,k}$ is found by the following expression as

$$\max_{k}\left(\min\left(|h_{i,m}|^2, |g_{i,m,k}|^2\right) - \min\left(\frac{|h_{i,m}|^2, |f_{i,m}|^2}{|f_{i,j}|^2}\right)\right), \ \forall i \tag{36}$$

For any given subcarrier assignment, the optimal power allocation at m^{th} relay node can be calculated as

$$P'_{i,m,k} = \left(\frac{1}{\lambda'} - \frac{\delta^2_{n,i}}{\left(|g_{i,m,k}|^2 - \frac{|f_{i,m}|^2}{|f_{i,j}|^2}\right)}\right)^{+}. \tag{37}$$

Likewise, the optimal power allocation at source node can be obtained as

$$P'_{s,i} = \left(\frac{1}{\lambda''} - \frac{\delta^2_{n,i}}{\left|h_{i,m}\right|^2}\right)^+. \tag{38}$$

The value of λ' and λ'' in (37) and (38) can be obtained from the water-filling algorithm as described in the previous section. Once, the value of λ' and λ'' are obtained, it is substituted in (37) and (38) to get the optimal values of power at source and relay nodes. Similar to the optimization framework studied in Section II-B, the computational complexity of this framework with cooperative jamming can be calculated as $\mathcal{O}(KNM)$.

IV. RESULTS AND DISCUSSION

In this section, we provide the simulation results to evaluate the performance of our proposed schemes. All the channels are obtained from multipath Rayleigh distributed model for all links. Every subcarrier has different value of channel gain due to the multipath effect in which same symbol is coming from different paths. We consider the number of subcarriers as $N = 64$, the number of multipaths for each channel as $tap = 10$, and the same noise variance at all nodes as $\delta = 0.1$. To guage the secrecy performance of the proposed joint optimization framework (denoted as OCOP), we provides three suboptimal frameworks for both jamming and without jamming framework.[3] These frameworks can be summarized as

1) SR-RCOP: It refers to a suboptimal framework that optimizes the sum SR of the system through random subcarrier assignment and optimal power allocation at both source and relay nodes. In particular, the optimal power allocation at source and relay nodes can be obtained by applying the same method as applied in Section II-B.
2) SR-OCEP: This is a suboptimal framework that optimizes the sum SR of the system through efficient channel assignment and equal power allocation at both source and relay nodes. By using the equal power allocation approach, the total transmit power of source and relay nodes are uniformly distributed among all subcarriers.
3) SR-RCEP: This is a non-optimal framework that calculates sum SR without optimization. In this framework, the sum SR of the system is achieved through random subcarrier assignment and equal power allocation at source and relay nodes, respectively.

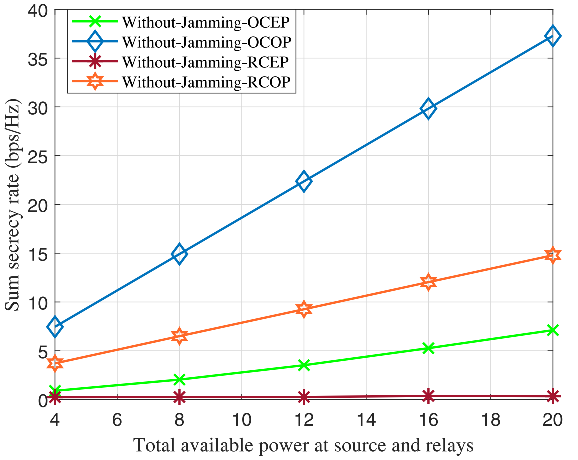

FIGURE 4. **Sum SR versus total available power at source and relays (without jamming) for $N = 64$ subcarriers, $tap = 10$ multi-paths, variance $\delta = 0.1$.**

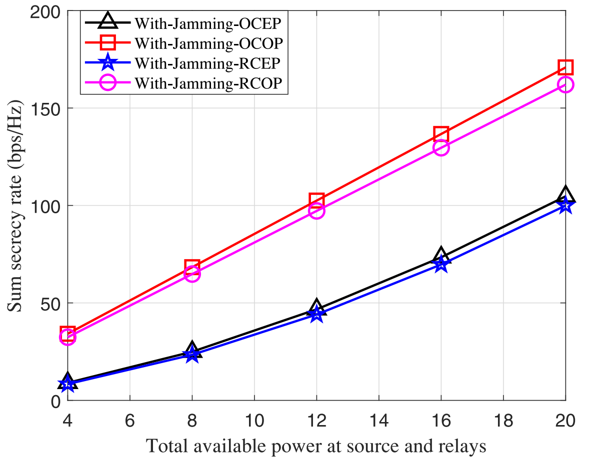

FIGURE 5. **Sum SR versus total available power at source and relays (with jamming) for $N = 64$ subcarriers, $tap = 10$ multi-paths, variance $\delta = 0.1$.**

Fig. 4 depicts the sum SR versus total available power at source and relays without cooperative jamming, where the total available transmit power varies from 4 to 20. For $N = 64$, it is observed that OCOP gives the maximum value of sum SR as compared to other schemes, due to optimal allocation of power and subcarriers. OCEP and RCEP gives the lowest value of sum SR as the power allocation in these schemes is nonoptimal. The figure shows that the benefit of optimizing power allocation is greater than optimizing the channel assignment, as RCOP outperforms OCEP for all values of available power. Further, the gap between OCOP and RCOP increases with the increasing value of available power. This shows that the performance gain from optimizing the power allocation is also dependent on the channel assignment. For optimally assigned channels, the power allocation framework would provide better performance as compared to the random allocation of channels.

Fig. 5 represents the effect of cooperative jamming on sum SR. It can be clearly observed that considerable gains are achieved by all schemes in comparison to the results plotted in Fig. 4. OCOP scheme outperforms the RCOP, OCEP and RCEP schemes. The sum SR increases with the increase in total available power at source and relay nodes. For the small values of available power, the performance of RCOP is very close to OCOP. However, as the available power increase, the performance gap also increases. However, when compared to

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[3] It is important to note that all the calculations involved in these frameworks are omitted in this paper for simplicity.

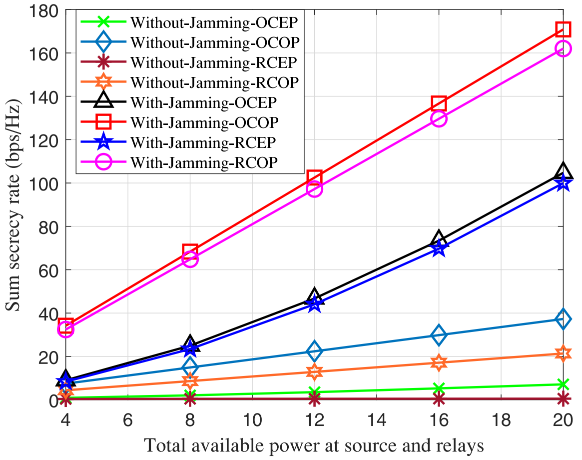

FIGURE 6. **Sum secrecy rate versus total available power at source and relay nodes for $N = 64$ subcarriers, multi-paths $tap = 10$, variance $\delta = 0.1$. Comparison between optimal, suboptimal and non-optimal scheme (without jamming and with jamming).**

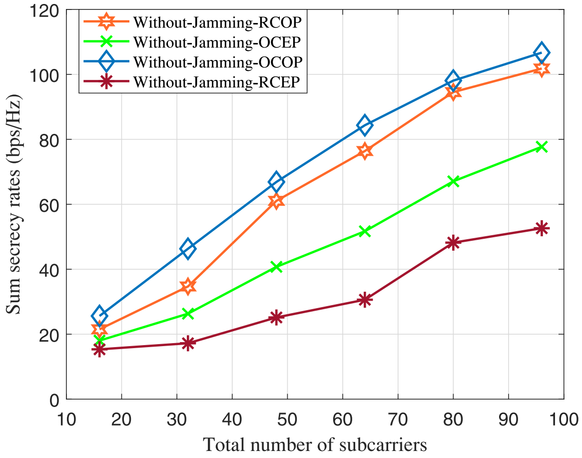

FIGURE 7. **Sum SR versus number of subcarriers (without jamming) for $tap = 10$ multi-paths, variance $\delta = 0.1$, total power budget at source and relays is 20.**

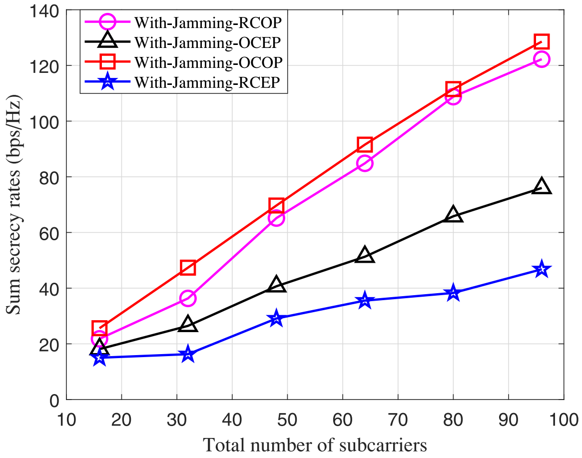

FIGURE 8. **Sum SR versus number of subcarriers (with jamming) for $tap = 10$ multi-paths, variance $\delta = 0.1$, total power budget at source and relays is 20.**

the case without cooperative jamming as depicted in Fig. 4, the difference in performance is very less. This shows that, with cooperative jamming the impact of optimizing channel allocation decreases. This is also evident from the fact that the gap between RCOP and OCEP is much greater in the case of jamming systems, as compared to the difference between RCOP and OCEP schemes of without cooperative jamming systems.

For better comparison, all four schemes are provided collectively for both systems (i.e., with and without jamming) in Fig. 6. It becomes clear from Fig. 6 that cooperative jamming outperforms cooperation without jamming. It is interesting to see that with cooperative jamming even the suboptimal RCEP scheme outperforms the joint optimization framework (OCOP) of the system without cooperative jamming. The cooperative jamming schemes also provide more performance gain with the increase in available power at the source and the relay nodes. This is because, in the case of cooperative jamming the available power at the relay nodes is used for forwarding the data to the users as well as for the jamming signals. Hence, these nodes are more capable of utilizing the available power to maximize the sum SR of the system.

Next, we consider the scenario where the total number of subcarriers is increased and the total available power at source and relays is fixed. When the number of subcarriers is increased the overall performance of each scheme is improved because the optimization frameworks have more options of channels to select from, and also because the bandwidth increases. However, the increase in bandwidth has the similar impact on the rates of users as well as on the rate of the Eve. Hence, the improvement in the SR due to the bandwidth is minimal. When new channels are introduced to the systems, the frameworks can select the channels that have better gains to the users and poor performance for the Eve. Thus, improving the overall SR of the system. Figs. 7 and 8 show the impact of increasing number of subcarriers on the SR offered by each scheme in both cases of cooperative systems (with and without jamming). It can be seen that, similar to previous cases the best performance is provided by OCOP technique. It is interesting to see that with an increase in the number of subcarriers the difference in the SR offered by the schemes with random channel allocation and schemes with optimal channel assignment decreases. This is because with an increase in the number of subcarriers, the probability in the case of random channel assignment, each user will be assigned some subcarriers with good channel gains also increases.

Lastly, we present a comparison of both jamming and without jamming resource management schemes against the increasing number of total subcarriers. From Fig. 9, it can be analyzed that by increasing the number of subcarriers sum SR will also get increased in the case of cooperative jamming systems. For a small number of subcarriers, the performance in the case of cooperative jamming is almost identical to the system without cooperative jamming, for

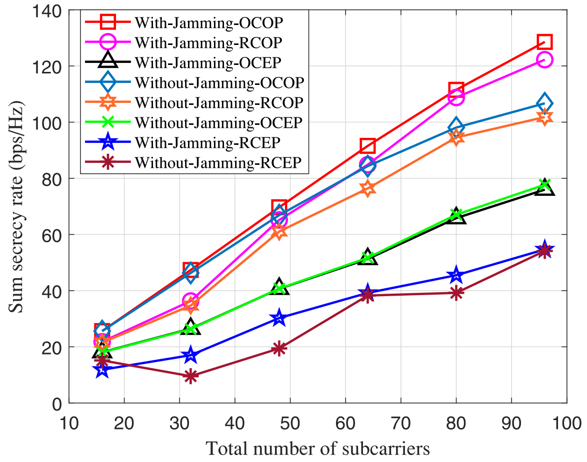

FIGURE 9. **Sum SR versus number of subcarriers (with and without jamming) for *tap* = 10 multi-paths, variance $\delta = 0.1$, total power budget at source and relays is 20.**

all four schemes. However, for a large number of subcarriers, the optimal resource allocation schemes provide better performance in the case of cooperative jamming. This is because, in the case of optimal resource allocation, power is allocated to each subcarrier while keeping into account the gain of the respective channel. Hence, the jamming based systems can take full advantage of the available power to maximize the SR.

V. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

This paper has proposed a joint resource optimization framework for maximizing the PLS of multiuser multirelay networks. Two models have been provided to investigate the SR maximization problems under the constraints of subcarrier allocation and power control. In particular, the joint optimization problem of subcarrier assignment and power allocation at BS and relay nodes has been investigated with and without cooperative jamming. It has been observed that the optimization framework with cooperative jamming can increase the SR significantly compared to the SR achieved without cooperative jamming. Simulation results have also been shown the superiority of the proposed joint optimal frameworks over the other suboptimal frameworks.

The work presented in this paper could be extended in many interesting directions. Better search algorithms could be developed to easily find the appropriate relay and jammer node so that power is saved and the complexity of hardware will be reduced. Multiple Eve with multiple antennas should be assumed rather than considering single Eve to make it more practical and beneficial in terms of SR. Direct links from source to Eve could be considered. Furthermore, subcarrier assignment and relay selection can be performed in such a way that a single relay could be allocated to many users are the extensions to this work, which can further improve the results. Last but not the least, the current work has been mainly concentrated on the optimization techniques and verified the results with a simple channel model. More practical channel models including path loss etc. can be used in future work.

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