Limited Rate Feedback Scheme for Resource Allocation in Secure Relay-Assisted OFDMA Networks

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***Abstract*—In this paper, we consider the problem of resource allocation for secure communications in decode-and-forward (DF) relay-assisted orthogonal frequency-division multiple access (OFDMA) networks. In our setting, users want to securely communicate to the base station (BS) with the help of a set of relay stations (RSs) in the presence of multiple eavesdroppers. We assume that all channel state information (CSI) of the legitimate links and only the channel distribution information (CDI) of the eavesdropper links are available. We formulate our problem as an optimization problem whose objective is to maximize the sum secrecy rate of the system subject to individual transmit power constraint for each user and RS. As a first work which considers limited feedback schemes for secure communications in cooperative OFDMA networks, we consider the limited-rate feedback case, where in addition to transmit power and subcarrier assignments, channel quantization should be performed and boundary regions of channels should be computed. We further consider the noisy feedback channel. We solve our problem using the dual Lagrange approach and propose an iterative algorithm whose convergence is analyzed. Using simulations, we evaluate the performance of the proposed scheme in numerous situations.**

***Index Terms*—Physical (PHY) layer security, limited feedback, eavesdropper, decode-and-forward (DF) relay.**

I. Introduction

ORTHOGONAL Frequency-Division Multiple Access (OFDMA) is a promissing technology for the existing and future networks such as the 4G long-term evolution (LTE) as well as the envisioned 5G networks. However, the broadcast nature of the wireless channel makes the transmitted signals available to unauthorized users as well. Physical layer security approaches which are concerned with whether a positive data rate can be supported, independent of the type of the decoding approach the unauthorized users use, have been attracted much interest in the research community [1], [2] which is the scop of this paper.

A. Related Works

The concept of physical layer security was first established by Wyner [1]. In [3], the authors consider the problem of secure communications in OFDMA networks in which two groups of users, namely secure users and ordinary users, exist. Their objective is to maximize the ordinary users' data rate under the individual secrecy rate constraint for secure users and total transmit power of base station (BS). The authors in [4] consider secure communications for Orthogonal Frequency-Division Multiplexing (OFDM) pair in the presence of an eavesdropper which adopts OFDM structure of a more complex one. Since the eavesdropper is a passive attacker, obtaining its channel state information (CSI) is impossible in most cases. Hence, the assumption of the eavesdropper channel availability is not practical. In this context, the authors in [5] consider energy efficiency for secure communications in OFDMA network. They assume that CSI of eavesdropper link is not available. Therefore, the artificial noise generation scheme is considered.

Cooperative communications [6] is a technique for increasing the secrecy rate of the legitimate users by improving the channel condition of those users [7]–[12]. In [7], the authors consider secure transmission from a source to the destination with the help of multiple relay stations (RSs) in the presence of multiple eavesdroppers. In [8], security in ad-hoc networks is considered for both amplify-and-forward relaying (AF) and decode-and-forward (DF) relaying. In [9], a cooperative jamming scheme to enhance the physical layer security in cooperative networks is considered. In [10], RS selection to enhance secure communication is considered for both AF and DF relaying. Secure communications from a source to destination with the help of an RS in multicarrier systems is considered in [11] in which the source can choose between direct communications and communications through the cooperating RS. Secure communications in OFDMA relay networks is considered in [12]. The authors consider the problem of RS selection, subcarrier allocation, and artificial noise generation to maximize the average secrecy outage capacity. In addition to the above mentioned works, there are also some works about secure resource allocation for two way relay networks e.g., [13], [14]. In most of researches done, it is assumed that the perfect CSI of both the legitimate links and the eavesdropper links are

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available. However, since the eavesdropper is a passive attacker, its CSI is hard to obtain. In addition, the CSI of the legitimate links may change fast; perfect CSI of the legitimate links is also hard to obtain. Moreover, these CSIs should be feedbacked to receiver. When the number of system parameters increases, e.g., the number of users and subcarriers, the amount of information which is feedbacked increases as well which, in turn, increases the signalling overhead. In addition, it is important to note that the feedback channel capacity is limited and hence the required signalling overhead should be lower than this limitation. In these situations, it will be of help to quantize the CSI space into a finite number of regions and feedback the index of the region in which the CSI of links lies [15]–[23]. In this way, the amount of feedbacked information decreases. In [18], the authors consider a limited feedback based adaptive power allocation for OFDMA DF relay network. Their objective is to maximize the sum rate under a transmit power constraint. Solving their optimization problem, they obtain power and subcarrier allocations as well as channel quantization. In [19], the authors consider a limited rate feedback scheme for AF and DF relay assisted networks. They divide the CSI ranges into a finite number of regions, formulate their resource allocation problem as an optimization problem whose objective is the ergodic sum rate, and obtain power allocation and boundaries of CSI regions. Quantized ergodic resource allocation for cognitive OFDMA networks with DF relaying is considered in [20] where two iterative algorithms are proposed to solve the developed optimization problem. In [22], the authors consider the adaptive limited feedback for multiple input-single output (MISO) wiretap channel with cooperative jamming. Assuming zero-forcing transmission at the helper and random vector quantization of the channels, an analytic expression for the achievable ergodic secrecy rate due to the resulting quantization errors is derived. In [23], ergodic secret message capacity of the wiretap channel with finite-rate feedback is studied where the upper and lower bounds on the secrecy capacity are derived, and it is shown that as the number of feedback bits increases, these two bounds coincide. With multiple transmit antennas, [24] analyzed the secrecy outage probability in slow fading channels without using artificial noise. For fast fading channels, considering beamforming with artificial noise, [25] provides optimal power allocation that maximizes the ergodic secrecy rate in two asymptotic regions, while in [26], a lower bound on the ergodic secrecy capacity in a integral form is derived and the optimal power allocation is studied numerically. In [27], the authors investigate an optimized secure multi-antenna transmission approach based on artificial-noise-aided beamforming with limited feedback from the desired single-antenna receiver.

In [28] and [29], assuming that the CDI of the eavesdropper is independent and identically distributed (i.i.d.) with Rayleigh distribution, a so-called relay chatting" scheme is proposed. Although the authors in [28] and [29], discussed about friendly jamming by assuming of CDI of the eavesdropper, they did not consider the limited feedback case.

B. Our Contributions

In this paper, we propose a limited rate feedback scheme for OFDMA DF relaying systems using CDI information of channels. In our scheme, a set of distant users want to securely communicate to a BS with the help of some DF RSs in the presence of multiple eavesdroppers. We assume that legitimate transmitters, i.e., network users and RSs, know CDIs of the legitimate channels, i.e., channels from users to RSs and from RSs to the BS. In addition, we assume that the legitimate transmitters have partial information about the legitimate CSIs using limited rate feedback channels. This means that, in our scheme, we divide the CSI space of each channel into a finite number of regions and the index of the region to which the CSI belongs is feedbacked to the transmitter. However, since the eavesdroppers are passive and acquiring their CSIs is hard, we assume that only the CDIs of the channels from users to the eavesdroppers and from RSs to the eavesdroppers are available. CDI can be obtained simply by estimating the path-loss (which includes distance-dependent attenuation and shadowing). In practice, the large-scale channel variations are slow and their estimation is easier than estimating the fast fading fluctuations[1].

In our model, the transmission is performed in two consecutive time slots; in the first time slot, users transmit while RSs, destination, and the eavesdroppers listen. In the second time slot, RSs transmit while the destination and the eavesdroppers listen. We assume that, the destination applies the maximal ratio combining (MRC) approach on the received signals in the first and the second time slots. However, the eavesdroppers listen to both the users' and the RSs' transmission. We assume that the eavesdroppers have no knowledge about the RS selection and subcarrier paring. In this case, the eavesdroppers listen to transmissions from the user to RSs and from RSs to the destination, assumes these information come from different sources, and performs independent decoding. We formulate our proposed scheme into an optimization problem and solve it using dual Lagrange method and find the subcarrier allocation, power allocation, and the boundary regions of each channel. We propose an iterative algorithm to solve the optimization problem and study its convergence. We also consider the case where the CDI information is not perfect and perform CDI quantization as well. Finally, we evaluate our proposed scheme using numerical results. In summary, our contributions are as follows:

1: To our knowledge, this is the first work which investigates limited feedback secure communications in cooperative DF relaying networks. Here, we propose a limited feedback scheme for cooperative OFDMA networks in which users communicate with the BS through a set of DF RSs. The space of each channel, i.e., channels from the users to the RSs and from the RSs to the BS, is divided into a finite number of regions. We consider a more practical case in which the CSIs of the eavesdropper's channels are not available to the legitimate receivers. In other words, we assume that only the CDIs of eavesdropper's channels are available.

2: We incorporate the physical layer security into our scheme where malicious users eavesdrop on the

[1] Indeed, it can be assumed that the CDI for the users over a relatively small geographical area obeys the same distribution as they locate near each others. In this way, channel distributions of legitimate users as well as those of the eavesdropper can be assumed to be independent and identically distributed (i.i.d.). Hence, by knowing the CDIs of legitimate channels, we also know those of the eavesdropper.

information transmission of the users and RSs. Subcarrier pairing, user and relay selection, power control, and channel quantization are performed for secrecy throughput maximization under transmit power constraints. We consider the case where the eavesdroppers can only listen to the information transmitted over links in the first and the second time slots while treating them as coming from independent sources. We also consider the case where the eavesdroppers have complete knowledge which makes it possible to perform the MRC scheme. To the best of our knowledge, few works have considered jointly the channel quantization and security, e.g., [23], and this is the first work which considers limited feedback schemes for secure communications in cooperative OFDMA networks.

3: We propose an iterative algorithm to obtain the solution of the optimization problem and analyze its convergence.

4: We also evaluate our proposed schemes when the feedback channel is noisy and thus the information transmitted over feedback channels could be corrupted. We further study the effect of CDI quantization on the proposed scheme as well as the effect of the error in the feedback links used for CDI information.

This paper is organized as follows. The system model is presented in Section II. Problem formulations for MRC and non-MRC eavesdropper are presented in Section III. Channel quantization and noisy feedback cases are considered in Section IV. In Section V, we provide some other low complexity suboptimal limited feedback schemes. The computational complexity and feedback overhead of our proposed scheme is studied in Section VI. Simulation results are given in Section VII, and the paper is concluded in Section VIII.

II. System Model

We consider the uplink of a cooperative OFDMA network in which a set of U users want to send information to a common destination, i.e., the BS, with the help of K cooperative DF RSs. The total available bandwidth B is divided into N subcarrierswhich can be used by the user stations (USs) and RSs. The set of users is denoted by $\mathcal{U} = \{1, \ldots, U\}$, that of RSs is denoted by $\mathcal{K} = \{1, \ldots, K\}$, and that of subcarriers is denoted by $\mathcal{N} = \{1, \ldots, N\}$. The RSs are assumed to be fixed and evenly distributed on a circle with a radius equal to one half of the cell radius in order to eliminate the effect of RS placements. We assume that, there exist some malicious users in the network which want to eavesdrop on the ongoing information transmission in the network. The set of malicious users is denoted by $\mathcal{E} = \{1, 2, \ldots, E\}$ where E is the number of malicious users in the network. The system model is shown in Fig. 1. We also assume that the transmission frame is divided into two time slots of equal duration. In the first time slot (first hop), the USs transmit while the RSs and the BS receive. The RSs decode the received information in the first time slot, re-encode it, and transmit the re-encoded signals to the BS in the second time slot (second hop). We assume that the transmission and reception at any station do not occur simultaneously on the same frequency band.

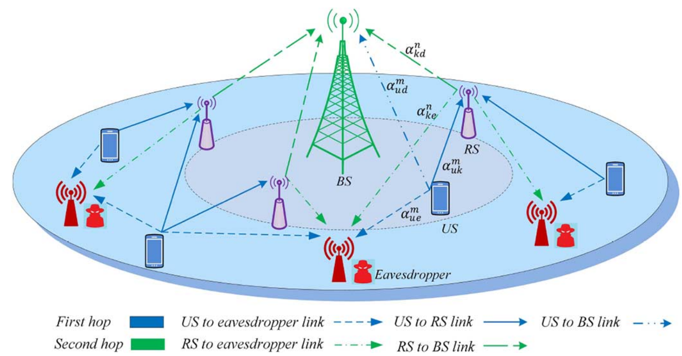


Fig. 1. System Model.

We utilize subcarrier pair (SP) (m, n) to denote that the subcarrier m in the first hop is paired with the subcarrier n in the second hop. Let α_{ud}^m, α_{uk}^m, and α_{kd}^n denote the noise power normalized channel power gains of the channel between user u and destination over subcarrier m, that of channel between user u and RS k over subcarrier m, and that of channel between RS k and the BS overs subcarrier n, respectively. In addition, let α_{ue}^m and α_{ke}^n be the channel power gains of the channel from user u and k^{th} RS to the eavesdropper e over subcarriers m and n, respectively.

III. The Eavesdropper's Strategy

Consider the communication between user u and BS through RS k over SP (m, n). Suppose that BS uses MRC scheme to combine the signals it receives in the first and the second time slots. Therefore, the signal to noise ratio at the BS is given by

$$\gamma_{u,c}^{mn} = p_{uk}^{mn}\alpha_{ud}^m + p_{kd}^{mn}\alpha_{kd}^n, \tag{1}$$

where p_{uk}^{mn} and p_{kd}^{mn} are user u and relay k transmit powers over SP (m, n) to relay k and BS, respectively. Unlike the BS, we assume that the eavesdroppers do not adopt MRC technique. Defining $C(x) = \log_2(1 + x)$, the achievable rate of user u is given by [6]

$$R_{uk}^{mn} = \min\{R_{uk1}^{mn}, R_{uk2}^{mn}\} = \min\{C(p_{uk}^{mn}\alpha_{uk}^m), C(\gamma_{u,c}^{mn})\}. \tag{2}$$

For the eavesdroppers, we adopt the approach in [12] and consider the capacity upper bound for the eavesdroppers. The capacity of eavesdropper e is upper bounded by [12]

$$R_{uk}^{\mathrm{E}mn} = \max\left\{R_{uk3}^{mn}, R_{uk4}^{mn}\right\} = \max\left\{C\left(p_{uk}^{mn}\max_{e\in\mathcal{E}}\left\{\alpha_{ue}^m\right\}\right),\right. \\ \left.C\left(p_{kd}^{mn}\max_{e\in\mathcal{E}}\left\{\alpha_{ke}^n\right\}\right)\right\}. \tag{3}$$

Therefore, the achievable secrecy rate in transmission between user u and the BS through RS k over SP (m, n) is given by [10], [12]

$$R_{uk}^{\mathrm{S}mn} = \left[R_{uk}^{mn} - R_{uk}^{\mathrm{E}mn}\right]^+ = \left[\min\{C(p_{uk}^{mn}\alpha_{uk}^m), C(\gamma_{u,c}^{mn})\}\right. \\ \left.- \max\{C(p_{uk}^{mn}\tilde{\alpha}_{ue}^m), C(p_{kd}^{mn}\tilde{\alpha}_{ke}^n)\}\right]^+, \tag{4}$$

where $[a]^+ = \max\{0, a\}$, $\tilde{\alpha}_{ue}^m = \max_{e\in\mathcal{E}}\{\alpha_{ue}^m\}$ and $\tilde{\alpha}_{ke}^n = \max_{e\in\mathcal{E}}\{\alpha_{ke}^n\}$. Denote $t_{uk}^{mn} \in \{0, 1\}$ as the binary variable for subcarrier pairing and user and relay assignment such that $t_{uk}^{mn} = 1$ indicates that user u and RS k use SP (m, n) for information transmission to BS. Note that, in OFDMA networks, it is required that at each time, each subcarrier is used only once in the network, i.e., only by one user in the first hop or by one RS in the second hop. To include this requirement, we may impose the following constraints:

$$\sum_{u=1}^{U}\sum_{k=1}^{K}\sum_{m=1}^{N} t_{uk}^{mn} = 1, \forall n, \tag{5}$$

$$\sum_{u=1}^{U}\sum_{k=1}^{K}\sum_{n=1}^{N} t_{uk}^{mn} = 1, \forall m. \tag{6}$$

In this paper, our aim is to solve the following optimization problem:

$$\max_{\boldsymbol{p},\boldsymbol{t}} \sum_{u=1}^{U}\sum_{k=1}^{K}\sum_{m,n=1}^{N} \varpi_u t_{uk}^{mn} \frac{1}{2}\mathbb{E}_{\boldsymbol{\alpha}}\left\{R_{uk}^{\mathrm{S}mn}\right\}, \tag{7a}$$

$$\text{s.t.:} \sum_{u=1}^{U}\sum_{m,n=1}^{N} t_{uk}^{mn}\mathbb{E}_{\boldsymbol{\alpha}}\{p_{kd}^{mn}\} \le P_k^T, \forall k, \tag{7b}$$

$$\sum_{k=1}^{K}\sum_{m,n=1}^{N} t_{uk}^{mn}\mathbb{E}_{\boldsymbol{\alpha}}\{p_{uk}^{mn}\} \le P_u^T, \forall u, \tag{7c}$$

$$(5), (6), p_{uk}^{mn}, p_{kd}^{mn} \ge 0, t_{uk}^{mn} \in \{0,1\}, \forall u,k,m,n, \tag{7d}$$

where $\boldsymbol{p} = [\boldsymbol{p}_1, \boldsymbol{p}_2]$, $\boldsymbol{p}_1 = [p_{11}^{11}, \ldots, p_{uk}^{mn}, \ldots, p_{UK}^{NN}]$, $\boldsymbol{p}_2 = [p_{11}^{11}, \ldots, p_{kd}^{mn}, \ldots, p_{Kd}^{NN}]$, $\boldsymbol{\alpha} = [\alpha_{11}^1, \ldots, \alpha_{ud}^m, \ldots, \alpha_{Ud}^N, \ldots, \alpha_{uk}^m, \ldots, \alpha_{UK}^N, \ldots, \alpha_{kd}^n, \ldots, \alpha_{Kd}^N, \ldots, \tilde{\boldsymbol{\alpha}}]$, $\tilde{\boldsymbol{\alpha}} = [\tilde{\alpha}_{ke}^n, \ldots, \tilde{\alpha}_{KE}^N, \ldots, \alpha_{uk}^m, \ldots, \alpha_{UK}^N, \ldots, \tilde{\alpha}_{ue}^m, \ldots, \tilde{\alpha}_{UE}^N]$, $\boldsymbol{t} = [t_{11}^{11}, \ldots, t_{uk}^{mn}, \ldots, t_{UK}^{NN}]$, and $0 \le \varpi_u \le 1$ is a coefficient reflecting fairness consideration based on the notion of proportional fairness which uses a priority coefficient ϖ_u for each user u in equation (7a). In this regard, a larger value of ϖ_u means higher priority is given to user u. We introduce the non-negative variables τ_{uk1}^{mn} and τ_{uk2}^{mn} to transform the max-min problem into a tractable one and write the optimization problem (7) as follows:

Problem $\mathcal{O}^{\text{Non-MRC}}$:

$$\max_{\boldsymbol{p},\boldsymbol{\tau},\boldsymbol{t}} \sum_{u=1}^{U}\sum_{k=1}^{K}\sum_{m,n=1}^{N} \varpi_u \tau_{uk2}^{mn}, \tag{8a}$$

$$\text{s.t.:}\ t_{uk}^{mn}\mathbb{E}_{\boldsymbol{\alpha}}\{R_{uk1}^{mn}\} - (\tau_{uk2}^{mn} + \tau_{uk1}^{mn}) \ge 0, \forall u,k,m,n, \tag{8b}$$

$$t_{uk}^{mn}\mathbb{E}_{\boldsymbol{\alpha}}\{R_{uk2}^{mn}\} - (\tau_{uk2}^{mn} + \tau_{uk1}^{mn}) \ge 0, \forall u,k,m,n, \tag{8c}$$

$$\tau_{uk1}^{mn} - t_{uk}^{mn}\mathbb{E}_{\boldsymbol{\alpha}}\{R_{uk3}^{mn}\} \ge 0, \forall u,k,m,n, \tag{8d}$$

$$\tau_{uk1}^{mn} - t_{uk}^{mn}\mathbb{E}_{\boldsymbol{\alpha}}\{R_{uk4}^{mn}\} \ge 0, \forall u,k,m,n, \tag{8e}$$

$$(7b), (7c), (5), (6), p_{uk}^{mn}, p_{kd}^{mn} \ge 0, t_{uk}^{mn} \in \{0,1\}, \forall u,k,m,n,$$

where $\boldsymbol{\tau} = [\boldsymbol{\tau}_1, \boldsymbol{\tau}_2]$, $\boldsymbol{\tau}_1 = [\tau_{111}^{11}, \ldots, \tau_{uk1}^{mn}, \ldots, \tau_{UK1}^{NN}]$, $\boldsymbol{\tau}_2 = [\tau_{112}^{11}, \ldots, \tau_{uk2}^{mn}, \ldots, \tau_{UK2}^{NN}]$.

IV. Quantized Power Control With Finite Rate Feedback Based On Block Coordinate Descent Algorithm (BCDA)

Here, our main goal is to consider the limited rate feedback scheme for CSIs and studying the effect of noisy feedback channel on the performance of the proposed limited feeedback scheme. We further, for the first time, try to study the effect of limited rate feedback of CDIs' information and the effect of noisy feedback links on the performance of proposed scheme. For the CDI case, we propose a simple, but not optimal, model similar to the case of limited feedback for CSIs. Our proposed iterative resource allocation schemes are based on the BCDA algorithm [30], [31].

A. Quantized CSI With Noisy Feedback Channel (Q-CSI-NF)

Assume that α_{ud}^m is quantized to $J = 2^q$ regions where q is the number of bits required to enumerate the resulting regions. The j^{th} fading region is denoted by $\Omega_{udj}^m = [A_{udj}^m, A_{udj+1}^m)$ with $A_{ud0}^m = 0 < A_{ud1}^m < \cdots < A_{udJ+1}^m = \infty$. In addition, α_{uk}^m is quantized to $I = 2^{\dot{q}}$ where the i^{th} region is denoted by $\dot{\Omega}_{uki}^m = [A_{uki}^m, A_{uki+1}^m)$, and α_{kd}^n is quantized into $L = 2^{\ddot{q}}$ regions where the l^{th} region is denoted by $\ddot{\Omega}_{kdl}^n = [A_{kdl}^n, A_{kdl+1}^n)$. Noisy feedback channel may cause BS to select an incorrect code word. We assume that the noisy feedback channel is memoryless and is distinguished by the index transition probabilities of $\chi_{uki^r i^t}^m, (i^r, i^t = 1, \ldots, I)$ and $\chi_{udj^r j^t}^m, (j^r, j^t = 1, \ldots, J)$ in the first hop and $\chi_{kdl^r l^t}^n, (l^r, l^t = 1, \ldots, L)$ in the second hop. $\chi_{uki^r i^t}^m$ is the probability of receiving index i^r at the US u while index i^t was transmitted by RS k, and $\chi_{udj^r j^t}^m$ and $\chi_{kdl^r l^t}^n$ are similarly defined. The feedback bits used for binary representation of indices j^r and j^t are denoted by $j_{\tau\in\{1,2,\ldots,q\}}^t, j_{\tau\in\{1,2,\ldots,q\}}^r \in \{0,1\}$ where $q = \lceil \log_2 J \rceil$ is the number of feedback bits and $\lceil a \rceil$ denotes the smallest integer which is larger than or equal to a. We assume that there is a binary symmetric channel (BSC) for each feedback bit with the crossover probability ω_{ud}^m. The transition probability $\chi_{udj^r j^t}^m$ can be obtained as follows [20]:

$$\chi_{udj^r j^t}^m = \prod_{\tau=1}^{q} \chi_{udj_\tau^r j_\tau^t}^m = \left(\omega_{ud}^m\right)^{d_{udj^r j^t}^m} \left(1 - \omega_{ud}^m\right)^{q - d_{udj^r j^t}^m}, \tag{9}$$

where $d_{udj^r j^t}^m$ is the Hamming distance between j^t and j^r. Also, the feedback bits used for binary representation of index i^r and i^t are denoted by $i_{\dot{\tau}\in\{1,2,\ldots,\dot{q}\}}^t, i_{\dot{\tau}\in\{1,2,\ldots,\dot{q}\}}^r \in \{0,1\}$ where $\dot{q} = \lceil \log_2 I \rceil$ is the total number of feedback bits. Denoting the crossover probability of the BSC channel with ω_{uk}^m, the transition probability $\chi_{uki^r i^t}^m$ can be obtained as follows:

$$\chi_{uki^r i^t}^m = \prod_{\dot{\tau}=1}^{\dot{q}} \chi_{uki_{\dot{\tau}}^r i_{\dot{\tau}}^t}^m = \left(\omega_{uk}^m\right)^{d_{uki^r i^t}^m} \left(1 - \omega_{uk}^m\right)^{\dot{q} - d_{uki^r i^t}^m}, \tag{10}$$

where $d_{uki^r i^t}^m$ is the Hamming distance between i^t and i^r. the feedback bits used for binary representation of l^r and l^t are denoted by $l_{\ddot{\tau}\in\{1,2,\ldots,\ddot{q}\}}^t, l_{\ddot{\tau}\in\{1,2,\ldots,\ddot{q}\}}^r \in \{0,1\}$ where $\ddot{q} =$

$\lceil \log_2 L \rceil$ is the number of feedback bits. We assume that there is a binary symmetric channel for each feedback bit with crossover probability ω_{kd}^n. Therefore, transition probability $\chi_{kdl^r l^t}^m$ is as follows:

$$\chi_{kdl^r l^t}^n = \prod_{\ddot{\tau}=1}^{\ddot{q}} \chi_{kdl_{\ddot{\tau}}^r l_{\ddot{\tau}}^t}^n = \left(\omega_{kd}^n\right)^{d_{kdl^r l^t}^n} (1-\omega_{kd}^n)^{\ddot{q}-d_{kdl^r l^t}^n}, \quad (11)$$

where $d_{kdl^r l^t}^n$ is the Hamming distance between l^t and l^r. Therefore, the problem $\mathcal{O}^{\text{Non-MRC}}$ will changes to the following one called $\mathcal{O}_{Q-CSI-NF}^{BCDA}$:

$$\max_{\boldsymbol{p},\boldsymbol{t},\boldsymbol{A},\boldsymbol{\tau}} \sum_{u=1}^{U}\sum_{k=1}^{K}\sum_{m,n=1}^{N} \varpi_u \tau_{uk2}^{mn}, \quad (12a)$$

$$\text{s.t.:} \sum_{\substack{j^t=1,\\ j^r=1}}^{J}\sum_{\substack{i^t=1,\\ i^r=1}}^{I}\sum_{\substack{l^t=1,\\ l^r=1}}^{L} t_{uk}^{mn} \chi_{ukj^r i^r l^r}^{mnj^t i^t l^t} \mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\left\{R_{ukj^r i^r l^r 1}^{mnj^t i^t l^t}\right\} \Delta F_{ukj^t i^t l^t}^{mn} - (\tau_{uk2}^{mn}+\tau_{uk1}^{mn}) \geq 0, \quad \forall u,k,m,n, \quad (12b)$$

$$\sum_{j^t,j^r=1}^{J}\sum_{i^t,i^r=1}^{I}\sum_{l^t,l^r=1}^{L} t_{uk}^{mn} \chi_{ukj^r i^r l^r}^{mnj^t i^t l^t} \mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\left\{R_{ukj^r i^r l^r 2}^{mnj^t i^t l^t}\right\} \Delta F_{ukj^t i^t l^t}^{mn} - (\tau_{uk2}^{mn}+\tau_{uk1}^{mn}) \geq 0, \quad \forall u,k,m,n, \quad (12c)$$

$$\tau_{uk1}^{mn} - \sum_{j^t,j^r=1}^{J}\sum_{i^t,i^r=1}^{I}\sum_{l^t,l^r=1}^{L} t_{uk}^{mn} \chi_{ukj^r i^r l^r}^{mnj^t i^t l^t} \mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\left\{R_{ukj^r i^r l^r 3}^{mnj^t i^t l^t}\right\} \Delta F_{ukj^t i^t l^t}^{mn} \geq 0, \quad \forall u,k,m,n, \quad (12d)$$

$$\tau_{uk1}^{mn} - \sum_{j^t,j^r=1}^{J}\sum_{i^t,i^r=1}^{I}\sum_{l^t,l^r=1}^{L} t_{uk}^{mn} \chi_{ukj^r i^r l^r}^{mnj^t i^t l^t} \mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\left\{R_{ukj^r i^r l^r 4}^{mnj^t i^t l^t}\right\} \Delta F_{ukj^t i^t l^t}^{mn} \geq 0, \quad \forall u,k,m,n, \quad (12e)$$

$$\sum_{j^t,j^r=1}^{J}\sum_{i^t,i^r=1}^{I}\sum_{l^t,l^r=1}^{L}\sum_{u=1}^{U}\sum_{m,n=1}^{N} t_{uk}^{mn} \chi_{ukj^r i^r l^r}^{mnj^t i^t l^t} \mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\left\{p_{kdj^r i^r l^r}^{mn}\right\} \Delta F_{ukj^t i^t l^t}^{mn} \leq P_k^T, \forall k, \quad (12f)$$

$$\sum_{j^t,j^r=1}^{J}\sum_{i^t,i^r=1}^{I}\sum_{l^t,l^r=1}^{L}\sum_{k=1}^{K}\sum_{m,n=1}^{N} t_{uk}^{mn} \chi_{ukj^r i^r l^r}^{mnj^t i^t l^t} \mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\left\{p_{ukj^r i^r l^r}^{mn}\right\} \Delta F_{ukj^t i^t l^t}^{mn} \leq P_u^T, \forall u, \quad (12g)$$

$$(5), (6), p_{ukj^r i^r l^r}^{mn}, p_{kdj^r i^r l^r}^{mn} \geq 0, t_{uk}^{mn} \in \{0,1\}, \forall u,k,m,n,$$

where $\chi_{ukj^r i^r l^r}^{mnj^t i^t l^t} = \chi_{udj^r j^t}^m \chi_{uki^r i^t}^m \chi_{kdl^r l^t}^n$, $\Delta F_{ukj^t i^t l^t}^{mn} = \Delta F_{\alpha_{udj^t}^m} \Delta F_{\alpha_{uki^t}^m} \Delta F_{\alpha_{kdl^t}^n}$, $\Delta F_{\alpha_{udj^t}^m} = [F_{\alpha_{udj^t+1}^m} - F_{\alpha_{udj^t}^m}]$, $R_{ukj^r i^r l^r 1}^{mnj^t i^t l^t} = C(p_{ukj^r i^r l^r}^{mn} A_{uki^t}^m)$, $R_{ukj^r i^r l^r 2}^{mnj^t i^t l^t} = C(\gamma_{u,cj^r i^r l^r}^{mnj^t i^t l^t})$, $\gamma_{u,cj^r i^r l^r}^{mnj^t i^t l^t} = p_{ukj^r i^r l^r}^{mn} A_{udj^t}^m + p_{kdj^r i^r l^r}^{mn} A_{kdl^t}^n$, $R_{ukj^r i^r l^r 3}^{mnj^t i^t l^t} = C(p_{ukj^r i^r l^r}^{mn} \tilde{\alpha}_{ue}^m)$, $R_{ukj^r i^r l^r 4}^{mnj^t i^t l^t} = C(p_{kdj^r i^r l^r}^{mn} \tilde{\alpha}_{ke}^n)$, and $F_\alpha(.,\bar{\alpha})$ denotes the cumulative distribution function (CDF) of exponential random variable α with parameter $\bar{\alpha}$, i.e., it's probability density function (PDF) is given by $f_\alpha(\alpha,\bar{\alpha}) = \frac{1}{\bar{\alpha}} e^{-\frac{\alpha}{\bar{\alpha}}}$. We write $F_{\alpha_{kd}^n}(\alpha_{kd}^n, \bar{\alpha}_{kd}^n)$ and $f_{\alpha_{kd}^n}(\alpha_{kd}^n, \bar{\alpha}_{kd}^n)$ to show that these are CDF and PDF functions of exponentially distributed random variable α_{kd}^n with parameter $\bar{\alpha}_{kd}^n$. This notation is useful in the next section where quantized CDI case is considered. The constraints (12b) to (12g) can be obtained from (8) using two facts. First, the random variables in vector $\boldsymbol{\alpha}$ which is divided into legitimate and eavesdropper random variables are independent. Second, from which the summation in the constrains come, the transmission rates of legitimate users and their transmit power are constant over each CSI region, although they are different in different region.

1) Dual Problem Formulation: To write the dual function [32] of the considered problem, we first define $\boldsymbol{\vartheta} = [\vartheta_{11}^{11}, \ldots, \vartheta_{uk}^{mn}, \ldots, \vartheta_{UK}^{NN}]$, $\boldsymbol{\theta} = [\theta_{11}^{11}, \ldots, \theta_{uk}^{mn}, \ldots, \theta_{UK}^{NN}]$, $\boldsymbol{\lambda} = [\lambda_{11}^{11}, \ldots, \lambda_{uk}^{mn}, \ldots, \lambda_{UK}^{NN}]$, $\boldsymbol{\psi} = [\psi_{11}^{11}, \ldots, \psi_{uk}^{mn}, \ldots, \psi_{UK}^{NN}]$, $\boldsymbol{\mu} = [\mu_1, \ldots, \mu_k, \ \ldots, \mu_K]$, and $\boldsymbol{\nu} = [\nu_1, \ldots, \nu_u, \ldots, \ \nu_U]$ as the lagrange multipliers corresponding to constraints (12b), (12c), (12d), (12e), (12f), and (12g), respectively. Next, we write the Lagrangian function as follows:

$$\mathcal{L}(\boldsymbol{p},\boldsymbol{t},\boldsymbol{A},\boldsymbol{\tau},\boldsymbol{\vartheta},\boldsymbol{\theta},\boldsymbol{\lambda},\boldsymbol{\psi},\boldsymbol{\mu},\boldsymbol{\nu}) = \sum_{k=1}^{K} \mathcal{L}_k(\boldsymbol{p},\boldsymbol{t},\boldsymbol{A},\boldsymbol{\tau},\boldsymbol{\vartheta},\boldsymbol{\theta},\boldsymbol{\lambda},\boldsymbol{\psi},\boldsymbol{\mu},\boldsymbol{\nu}), \quad (13)$$

where

$$\begin{aligned}\mathcal{L}_k(\boldsymbol{p},\boldsymbol{t},\boldsymbol{A},\boldsymbol{\tau},\boldsymbol{\vartheta},\boldsymbol{\theta},\boldsymbol{\lambda},\boldsymbol{\psi},\boldsymbol{\mu},\boldsymbol{\nu}) &= \sum_{u=1}^{U}\sum_{m,n=1}^{N}\Big\{\tau_{uk2}^{mn}(\varpi_u - \vartheta_{uk}^{mn} - \theta_{uk}^{mn}) + \tau_{uk1}^{mn}(-\vartheta_{uk}^{mn} - \theta_{uk}^{mn} \\ &+ \lambda_{uk}^{mn} + \psi_{uk}^{mn}) + \sum_{j^t,j^r=1}^{J}\sum_{i^t,i^r=1}^{I}\sum_{l^t,l^r=1}^{L} t_{uk}^{mn}\chi_{ukj^r i^r l^r}^{mnj^t i^t l^t} \\ &\Big(\vartheta_{uk}^{mn}\mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\left\{R_{ukj^r i^r l^r 1}^{mnj^t i^t l^t}\right\} + \theta_{uk}^{mn}\mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\left\{R_{ukj^r i^r l^r 2}^{mnj^t i^t l^t}\right\} \\ &- \lambda_{uk}^{mn}\mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\left\{R_{ukj^r i^r l^r 3}^{mnj^t i^t l^t}\right\} - \psi_{uk}^{mn}\mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\left\{R_{ukj^r i^r l^r 4}^{mnj^t i^t l^t}\right\} \\ &+ \mu_k \mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\left\{p_{kdj^r i^r l^r}^{mn}\right\} + \nu_u \mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\left\{p_{ukj^r i^r l^r}^{mn}\right\}\Big)\Delta F_{uki^t j^t l^t}^{mn}\Big\} \\ &+ \mu_k P_k^T + \sum_{u=1}^{U}\nu_u P_u^T. \end{aligned} \quad (14)$$

Hence, the dual objective function and the dual optimization problem are, respectively, given by

$$\Theta(\boldsymbol{\vartheta},\boldsymbol{\theta},\boldsymbol{\lambda},\boldsymbol{\psi},\boldsymbol{\mu},\boldsymbol{\nu}) = \max_{\boldsymbol{p},\boldsymbol{t},\boldsymbol{A},\boldsymbol{\tau}} \mathcal{L}(\boldsymbol{p},\boldsymbol{t},\boldsymbol{A},\boldsymbol{\tau},\boldsymbol{\vartheta},\boldsymbol{\theta},\boldsymbol{\lambda},\boldsymbol{\psi},\boldsymbol{\mu},\boldsymbol{\nu}), \quad (15)$$

$$\min_{\boldsymbol{\vartheta}\geq 0,\boldsymbol{\theta}\geq 0,\boldsymbol{\lambda}\geq 0,\boldsymbol{\psi}\geq 0,\boldsymbol{\mu}\geq 0,\boldsymbol{\nu}\geq 0} \Theta(\boldsymbol{\vartheta},\boldsymbol{\theta},\boldsymbol{\lambda},\boldsymbol{\psi},\boldsymbol{\mu},\boldsymbol{\nu}). \quad (16)$$

By adopting the dual Lagrange approach, our optimization problem can be decomposed into a master problem which can be solved by the BS and several subproblem which is solved by each RS. Each RS solves one local subproblem with no assistance from other RSs. After solving its subproblem, each RS passes the solution of its corresponding subproblem to BS. Finally, the BS, after receiving all solutions of RSs, solves the master problem.

2) Distributed Solution-Subproblem for Each RS: Since (13) is decomposable in k, to solve (15), each RS k solves the following subproblem:

$$\max_{\boldsymbol{p},\boldsymbol{t},\boldsymbol{A},\boldsymbol{\tau}} \mathcal{L}_k(\boldsymbol{p},\boldsymbol{t},\boldsymbol{A},\boldsymbol{\tau},\boldsymbol{\vartheta},\boldsymbol{\theta},\boldsymbol{\lambda},\boldsymbol{\psi},\boldsymbol{\mu},\boldsymbol{\nu}). \quad (17)$$

Note that, the objective function of (15) is a linear function of τ_{uk1}^{mn} and τ_{uk2}^{mn}. Therefore, the optimal τ_{uk1}^{mn*} and τ_{uk2}^{mn*} that maximize (15) can be obtained, respectively, by

$$\tau_{uk1}^{mn*} = \begin{cases} 0, & \vartheta_{uk}^{mn} + \theta_{uk}^{mn} > \lambda_{uk}^{mn} + \psi_{uk}^{mn}, \\ any, & \vartheta_{uk}^{mn} + \theta_{uk}^{mn} = \lambda_{uk}^{mn} + \psi_{uk}^{mn}, \\ +\infty, & \vartheta_{uk}^{mn} + \theta_{uk}^{mn} < \lambda_{uk}^{mn} + \psi_{uk}^{mn}, \end{cases} \quad (18)$$

$$\tau_{uk2}^{mn*} = \begin{cases} any, & \vartheta_{uk}^{mn} + \theta_{uk}^{mn} = \varpi_u, \\ +\infty, & \vartheta_{uk}^{mn} + \theta_{uk}^{mn} < \varpi_u, \\ 0, & \vartheta_{uk}^{mn} + \theta_{uk}^{mn} > \varpi_u. \end{cases} \quad (19)$$

Here, we develop an iterative algorithm based on the BCDA (see, e.g., [31], [30]) to find the local optimal values for the fading regions boundaries and the transmit powers in the first and the second hops. We first consider the problem (15) and the function (13) for fixed values of $\boldsymbol{\vartheta}$, $\boldsymbol{\theta}$, $\boldsymbol{\lambda}$, $\boldsymbol{\psi}$, $\boldsymbol{\mu}$, $\boldsymbol{\nu}$, and a fixed set of quantizer thresholds, i.e., $\{A_{udj^t}^m\}_{j^t=1}^J$, $\{A_{uki^t}^m\}_{i^t=1}^I$, $\{A_{kdl^t}^n\}_{l^t=1}^L$. Applying Karush-Kuhn-Tucker (K.K.T.) conditions [32], the transmit power assigned to subcarrier m in the first time slot by user u in the region j^r, i^r, l^r can be obtained as:

$$\frac{\partial \mathcal{L}_k(\boldsymbol{p},\boldsymbol{t},\boldsymbol{A},\boldsymbol{\tau},\boldsymbol{\vartheta},\boldsymbol{\theta},\boldsymbol{\lambda},\boldsymbol{\psi},\boldsymbol{\mu},\boldsymbol{\nu})}{\partial p_{ukj^ri^rl^r}^{mn}} = W[p_{ukj^ri^rl^r}^{mn}]^3 + B[p_{ukj^ri^rl^r}^{mn}]^2 + C p_{ukj^ri^rl^r}^{mn} + D = 0, \quad (20)$$

where W, B, C and D are given by

$$\begin{aligned} W &= -\nu_u \ln(2) A_{uki^t}^m \tilde{\alpha}_{ue}^m A_{udj^t}^m, \; B = (\vartheta_{uk}^{mn} + \theta_{uk}^{mn} - \lambda_{uk}^{mn}) \\ & A_{uki^t}^m \tilde{\alpha}_{ue}^m A_{udj^t}^m - \nu_u \ln(2) \left(A_{uki^t}^m \left(\tilde{\alpha}_{ue}^m + A_{udj^t}^m + p_{kdj^ri^rl^r}^{mn} \right.\right. \\ & \left.\left. A_{kdl^t}^n \tilde{\alpha}_{ue}^m \right) + A_{udj^t}^m \; \tilde{\alpha}_{ue}^m \right), C = \left(\tilde{\alpha}_{ue}^m + A_{udj^t}^m + p_{kdj^ri^rl^r}^{mn} A_{kdl^t}^n \right. \\ & \left. \tilde{\alpha}_{ue}^m \right) \left(\vartheta_{uk}^{mn} A_{uki^t}^m - \nu_u \ln(2) \right) - A_{uki^t}^m \left(1 + p_{kdj^ri^rl^r}^{mn} A_{kdl^t}^n \right) \\ & \left(\lambda_{uk}^{mn} \tilde{\alpha}_{ue}^m + \nu_u \ln(2) \right) + \theta_{uk}^{mn} A_{udj^t}^m \left(\tilde{\alpha}_{ue}^m + A_{uki^t}^m \right), \\ D &= \left(1 + p_{kdj^ri^rl^r}^{mn} A_{kdl^t}^n \right) \left(\vartheta_{uk}^{mn} A_{uki^t}^m - \lambda_{uk}^{mn} \tilde{\alpha}_{ue}^m - \nu_u \ln(2) \right) \\ & + \theta_{uk}^{mn} A_{udj^t}^m. \end{aligned}$$

In addition, the transmit power assigned to subcarrier n in the second time slot by RS k in the region j^r, i^r, l^r can be obtained using the following equation:

$$\frac{\partial \mathcal{L}_k(\boldsymbol{p},\boldsymbol{t},\boldsymbol{A},\boldsymbol{\tau},\boldsymbol{\vartheta},\boldsymbol{\theta},\boldsymbol{\lambda},\boldsymbol{\psi},\boldsymbol{\mu},\boldsymbol{\nu})}{\partial p_{kdj^ri^rl^r}^{mn}} = a(p_{kdj^ri^rl^r}^{mn})^2 + b p_{kdj^ri^rl^r}^{mn} + c = 0, \quad (21)$$

where $a = -\mu_k \ln(2) A_{kdl^t}^n \tilde{\alpha}_{ke}^n$, $b = ((\theta_{uk}^{mn} - \psi_{uk}^{mn}) A_{kdl^t}^n \tilde{\alpha}_{ke}^n - \mu_k \ln(2)(A_{kdl^t}^n + \tilde{\alpha}_{ke}^n + p_{ukj^ri^rl^r}^{mn} A_{udj^t}^m \tilde{\alpha}_{ke}^n))$ and $c = \theta_{uk}^{mn} A_{kdl^t}^n - (\psi_{uk}^{mn} \tilde{\alpha}_{ke}^n + \ln(2)\mu_k)(1 + p_{ukj^ri^rl^r}^{mn} A_{udj^t}^m)$. Solution of (21) is given by

$$p_{kdj^ri^rl^r}^{mn*} = \left[\frac{-b \pm \sqrt{\Delta}}{2a} \right]^+. \quad (22)$$

In the next step, we fix the values of $p_{ukj^ri^rl^r}^{mn}$, $p_{kdj^ri^rl^r}^{mn}$, $A_{uki^t}^m$, $A_{kdl^t}^n$, $\tilde{\alpha}_{ue}^m$, $\tilde{\alpha}_{ke}^n$, λ_k, μ_k, and ν_u, and obtain the value of $A_{udj^t}^m$. Taking derivative of Lagrange function (13) with respect to $A_{udj^t}^m$ and equating it to zero, we obtain the following equation for updating the region boundaries:

$$\begin{aligned} F_{\alpha_{udj+1}^m} &= f_{\alpha_{udj}^m} \ln(2) \sum_{\substack{j^t, j^r=1 \\ j^t \neq j}}^{J} \sum_{i^t, i^r=1}^{I} \sum_{l^t, l^r=1}^{L} \sum_{k=1}^{K} \sum_{n=1}^{N} \chi_{ukj^ri^rl^r}^{mnj^ti^tl^t} \\ & \mathbb{E}_{\tilde{\alpha}_{ke}^n} \Bigg\{ \Bigg[-\psi_{uk}^{mn} \log_2 \left(\frac{1 + p_{kdj^ri^rl^r}^{mn} \tilde{\alpha}_{ke}^n}{1 + p_{kdj^r-1i^rl^r}^{mn} \tilde{\alpha}_{ke}^n} \right) + \theta_{uk}^{mn} \\ & \log_2 \left(\frac{1 + p_{ukj^ri^rl^r}^{mn} A_{udj^t}^m + p_{kdj^ri^rl^r}^{mn} A_{kdl^t}^n}{1 + p_{ukj^r-1i^rl^r}^{mn} A_{udj^t-1}^m + p_{kdj^r-1i^rl^r}^{mn} A_{kdl^t}^n} \right) \\ & - \mu_k (p_{kdj^ri^rl^r}^{mn} - p_{kdj^r-1i^rl^r}^{mn}) \\ & + \vartheta_{uk}^{mn} \log_2 \left(\frac{1 + p_{ukj^ri^rl^r}^{mn} A_{uki^t}^m}{1 + p_{ukj^r-1i^rl^r}^{mn} A_{uki^t}^m} \right) \\ & - \lambda_{uk}^{mn} \log_2 \left(\frac{1 + p_{kdj^ri^rl^r}^{mn} \tilde{\alpha}_{ue}^m}{1 + p_{kdj^r-1i^rl^r}^{mn} \tilde{\alpha}_{ue}^m} \right) \\ & - \nu_n (p_{ukj^ri^rl^r}^{mn} - p_{ukj^r-1i^rl^r}^{mn}) \Bigg] \\ & \left(\frac{1 + p_{ukj^ri^rl^r}^{mn} A_{udj^t}^m + p_{kdj^ri^rl^r}^{mn} A_{kdl^t}^n}{\theta_{uk}^{mn} p_{ukj^ri^rl^r}^{mn}} \right) \Bigg\} + F_{\alpha_{udj}^m}. \end{aligned} \quad (23)$$

Next, we fix the values of $p_{ukj^ri^rl^r}^{mn}$, $p_{kdj^ri^rl^r}^{mn}$, $A_{udj^t}^m$, $A_{kdl^t}^n$, $\tilde{\alpha}_{ue}^m$, $\tilde{\alpha}_{ke}^n$, λ_k, μ_k, and ν_u, and obtain the value of $A_{uki^t}^m$. Taking derivative of the Lagrange function (13) with respect to $A_{uki^t}^m$ and setting it to zero, we obtain the following equation for updating the region boundaries:

$$\begin{aligned} F_{\alpha_{uki+1}^m} &= F_{\alpha_{uki}^m} + f_{\alpha_{uki}^m} \ln(2) \sum_{j^t, j^r=1}^{J} \sum_{\substack{i^t, i^r=1 \\ i^t \neq i}}^{I} \sum_{l^t, l^r=1}^{L} \sum_{n=1}^{N} \chi_{ukj^ri^rl^r}^{mnj^ti^tl^t} \\ & \Bigg\{ \left(\frac{1 + p_{ukj^ri^rl^r}^{mn} A_{uki^t}^m}{\vartheta_{uk}^{mn} p_{ukj^ri^rl^r}^{mn}} \right) \Bigg[-\psi_{uk}^{mn} \log_2 \left(\frac{1 + p_{kdj^ri^rl^r}^{mn} \tilde{\alpha}_{ke}^n}{1 + p_{kdj^ri^r-1l^r}^{mn} \tilde{\alpha}_{ke}^n} \right) \\ & + \theta_{uk}^{mn} \log_2 \left(\frac{1 + p_{ukj^ri^rl^r}^{mn} A_{udj^t}^m + p_{kdj^ri^rl^r}^{mn} A_{kdl^t}^n}{1 + p_{ukj^ri^r-1l^r}^{mn} A_{udj^t}^m + p_{kdj^ri^r-1l^r}^{mn} A_{kdl^t}^n} \right) \\ & + \vartheta_{uk}^{mn} \log_2 \left(\frac{1 + p_{ukj^ri^rl^r}^{mn} A_{uki^t}^m}{1 + p_{ukj^ri^r-1l^r}^{mn} A_{uki^t}^m} \right) \\ & - \lambda_{uk}^{mn} \log_2 \left(\frac{1 + p_{kdj^ri^rl^r}^{mn} \tilde{\alpha}_{ue}^m}{1 + p_{kdj^ri^r-1l^r}^{mn} \tilde{\alpha}_{ue}^m} \right) \\ & - \mu_k (p_{kdj^ri^rl^r}^{mn} - p_{kdj^ri^r-1l^r}^{mn}) - \nu_n (p_{ukj^ri^rl^r}^{mn} - p_{ukj^ri^r-1l^r}^{mn}) \Bigg] \Bigg\}. \end{aligned} \quad (24)$$

Finally, we fix the values of $p_{ukj^ri^rl^r}^{mn}$, $p_{kdj^ri^rl^r}^{mn}$, $A_{udj^t}^m$, $A_{uki^t}^m$, $\tilde{\alpha}_{ue}^m$, $\tilde{\alpha}_{ke}^n$, λ_k, μ_k, and ν_u, and set the first derivative of equation (13) with respect to $A_{kdl^t}^n$ to zero to obtain the following equation for updating the region boundaries $A_{kdl^t}^n$:

$$
\begin{aligned}
F_{\alpha^n_{kdl+1}} &= F_{\alpha^n_{kdl}} + f_{\alpha^n_{kdl}} \ln(2) \sum_{j^t, j^r=1}^{J} \sum_{i^t, i^r=1}^{I} \sum_{\substack{l^t, l^r=1 \\ l^t \neq l}}^{L} \sum_{m=1}^{N} \chi^{mnj^t i^t l^t}_{ukj^r i^r l^r} \\
&\Bigg\{ \left(\frac{1 + p^{mn}_{ukj^r i^r l^r} A^m_{udj^t} + p^{mn}_{kdj^r i^r l^r} A^n_{kdl^t}}{\theta^{mn}_{uk}\, p^{mn}_{kdj^r i^r l^r}} \right) \\
&\Bigg[\theta^{mn}_{uk} \log_2 \left(\frac{1 + p^{mn}_{ukj^r i^r l^r} A^m_{udj^t} + p^{mn}_{kdj^r i^r l^r} A^n_{kdl^t}}{1 + p^{mn}_{ukj^r i^r l^r - 1} A^m_{udj^t} + p^{mn}_{kdj^r i^r l^r - 1} A^n_{kdl^t - 1}} \right) \\
&- \psi^{mn}_{uk} \log_2 \left(\frac{1 + p^{mn}_{kdj^r i^r l^r} \tilde{\alpha}^n_{ke}}{1 + p^{mn}_{kdj^r i^r l^r - 1} \tilde{\alpha}^n_{ke}} \right) \\
&- \lambda^{mn}_{uk} \log_2 \left(\frac{1 + p^{mn}_{kdj^r i^r l^r} \tilde{\alpha}^m_{ue}}{1 + p^{mn}_{kdj^r i^r l^r - 1} \tilde{\alpha}^m_{ue}} \right) \\
&+ \vartheta^{mn}_{uk} \log_2 \left(\frac{1 + p^{mn}_{ukj^r i^r l^r} A^m_{uki^t}}{1 + p^{mn}_{ukj^r i^r l^r - 1} A^m_{uki^t}} \right) \mu_k (p^{mn}_{kdj^r i^r l^r} - p^{mn}_{kdj^r i^r l^r - 1}) \\
&- \nu_n (p^{mn}_{ukj^r i^r l^r} - p^{mn}_{ukj^r i^r l^r - 1}) \Bigg] \Bigg\}.
\end{aligned} \tag{25}
$$

3) Subcarrier Assignment Strategy: Given the values of τ^{mn}_{uk1}, τ^{mn}_{uk2}, $p^{mn}_{ukj^r i^r l^r}$, $p^{mn}_{kdj^r i^r l^r}$, $A^m_{udj^t}$, $A^m_{uki^t}$, and $A^n_{kdl^t}$ obtained in previous section, and the values of $\tilde{\alpha}^m_{ue}$, $\tilde{\alpha}^n_{ke}$, and dual variables, we form the following function:

$$
\begin{aligned}
\Lambda_{u,k,m,n} &= \tau^{mn}_{uk2}(1 - \vartheta^{mn}_{uk} - \theta^{mn}_{uk}) + \tau^{mn}_{uk1}(-\vartheta^{mn}_{uk} - \theta^{mn}_{uk} \\
&+ \lambda^{mn}_{uk} + \psi^{mn}_{uk}) + \sum_{j^t, j^r=1}^{J} \sum_{i^t, i^r=1}^{I} \sum_{l^t, l^r=1}^{L} \Bigg[\vartheta^{mn}_{uk} t^{mn}_{uk} \chi^{mnj^t i^t l^t}_{ukj^r i^r l^r} \\
&\mathbb{E}_{\tilde{\boldsymbol{\alpha}}} \left\{ R^{mnj^t i^t l^t}_{ukj^r i^r l^r 1} \right\} + \theta^{mn}_{uk} t^{mn}_{uk} \chi^{mnj^t i^t l^t}_{ukj^r i^r l^r} \mathbb{E}_{\tilde{\boldsymbol{\alpha}}} \left\{ R^{mnj^t i^t l^t}_{ukj^r i^r l^r 2} \right\} \\
&- \lambda^{mn}_{uk} t^{mn}_{uk} \chi^{mnj^t i^t l^t}_{ukj^r i^r l^r} \mathbb{E}_{\tilde{\boldsymbol{\alpha}}} \left\{ R^{mnj^t i^t l^t}_{ukj^r i^r l^r 3} \right\} - \psi^{mn}_{uk} t^{mn}_{uk} \chi^{mnj^t i^t l^t}_{ukj^r i^r l^r} \\
&\mathbb{E}_{\tilde{\boldsymbol{\alpha}}} \left\{ R^{mnj^t i^t l^t}_{ukj^r i^r l^r 4} \right\} + \mu_k \Bigg(P^T_k - \sum_{u=1}^{U} \sum_{m,n=1}^{N} t^{mn}_{uk} \chi^{mnj^t i^t l^t}_{ukj^r i^r l^r} \\
&\mathbb{E}_{\tilde{\boldsymbol{\alpha}}} \left\{ p^{mn}_{kdj^r i^r l^r} \right\} \Bigg) + \nu_u \Bigg(P^T_u - \sum_{m,n=1}^{N} t^{mn}_{uk} \chi^{mnj^t i^t l^t}_{ukj^r i^r l^r} \\
&\mathbb{E}_{\tilde{\boldsymbol{\alpha}}} \left\{ p^{mn}_{ukj^r i^r l^r} \right\} \Bigg) \Bigg] \Delta F^{mn}_{uki^t j^t l^t}.
\end{aligned} \tag{26}
$$

Using (26), we perform the subcarrier pairing and user and RS selection as follows:

$$
(u^*, k^*, m^*, n^*) = \underset{u,k,m,n}{arg\,max}\, \Lambda_{u,k,m,n}. \tag{27}
$$

To solve the master problem at the BS, each RS solves the local problem (17) and transmits the solutions' information to the BS. The BS uses the subgradient method for updating the Lagrange multipliers [32]. The proposed algorithms are shown in Figs. 2 and 3.

When solving an optimization problem using dual approach, one important thing must be taken into consideration: duality gap. The analysis provided here is based on the so called time sharing property which is first introduced in [33]. In [34], the authors provide a more complete interpretation on why time-sharing leads to strong duality via the concept of perturbation function. To show the time sharing property, we may do in the same way as in [33], [35]. Therefore, the duality gaps between the optimization problems (7) and (16) tend to zero as the number of subcarriers goes to infinity. In addition, asymptotic zero duality gap also holds for Q-CDI-NF.

Step 1: Each RS solves its problem.
Step 2: RSs feedback the required information to BS.
Step 3: After receiving the required information from RSs, BS solves its problem.
Step 4: If stopping criterion is fulfilled goto Step 5; otherwise goto Step 1.
Step 5: End.

Fig. 2. The pseudo code of the proposed Algorithm 1.

Iterative algorithm for finding the transmit power and quantizer thresholds in the first and second hop

Step 1: Set iteration number, $\varrho = 0$, for fixed but arbitrary values of $A^{n0}_{kdl^t}$, $A^{m0}_{udj^t}$, $A^{m0}_{uki^t}$, ϑ^{mn0}_{uk}, θ^{mn0}_{uk}, λ^{mn0}_{uk}, ψ^{mn0}_{uk}, μ^0_k, and ν^0_u, obtain the values of $p^{mn0}_{ukj^r i^r l^r}$ and $p^{mn0}_{kdj^r i^r l^r}$ by solving (20) and (22), respectively.
Step 2.1: Fix $p^{mn\varrho-1}_{ukj^r i^r l^r}$, $p^{mn\varrho-1}_{kdj^r i^r l^r}$, $A^{n\varrho-1}_{kdl^t}$, $A^{m\varrho-1}_{uki^t}$, $\vartheta^{mn\varrho-1}_{uk}$, $\theta^{mn\varrho-1}_{uk}$, $\lambda^{mn\varrho-1}_{uk}$, $\psi^{mn\varrho-1}_{uk}$, $\mu^{\varrho-1}_k$, and $\nu^{\varrho-1}_u$; find $A^{m\varrho}_{udj^t}$ using (23).
Step 2.2: Fix $p^{mn\varrho-1}_{ukj^r i^r l^r}$, $p^{mn\varrho-1}_{kdj^r i^r l^r}$, $A^{n\varrho-1}_{kdl^t}$, $A^{m\varrho-1}_{udj^t}$, $\vartheta^{mn\varrho-1}_{uk}$, $\theta^{mn\varrho-1}_{uk}$, $\lambda^{mn\varrho-1}_{uk}$, $\psi^{mn\varrho-1}_{uk}$, $\mu^{\varrho-1}_k$, and $\nu^{\varrho-1}_u$; find $A^{m\varrho}_{uki^t}$ using (24).
Step 2.3: Fix $p^{mn\varrho-1}_{ukj^r i^r l^r}$, $p^{mn\varrho-1}_{kdj^r i^r l^r}$, $A^{n\varrho-1}_{udj^t}$, $A^{m\varrho-1}_{uki^t}$, $\vartheta^{mn\varrho-1}_{uk}$, $\theta^{mn\varrho-1}_{uk}$, $\lambda^{mn\varrho-1}_{uk}$, $\psi^{mn\varrho-1}_{uk}$, $\mu^{\varrho-1}_k$, and $\nu^{\varrho-1}_u$; find $A^{m\varrho}_{kdl^t}$ using (25).
Step 2.4: Fix $A^{n\varrho-1}_{udj^t}$, $A^{m\varrho-1}_{uki^t}$, $A^{m\varrho-1}_{kdl^t}$, $p^{mn\varrho-1}_{kdj^r i^r l^r}$, $\vartheta^{mn\varrho-1}_{uk}$, $\theta^{mn\varrho-1}_{uk}$, $\lambda^{mn\varrho-1}_{uk}$, $\psi^{mn\varrho-1}_{uk}$, $\mu^{\varrho-1}_k$, and $\nu^{\varrho-1}_u$; find $p^{mn\varrho}_{ukj^r i^r l^r}$ using (23).
Step 2.5: Fix $A^{n\varrho-1}_{udj^t}$, $A^{m\varrho-1}_{uki^t}$, $A^{m\varrho-1}_{kdl^t}$, $p^{mn\varrho-1}_{ukj^r i^r l^r}$, $\vartheta^{mn\varrho-1}_{uk}$, $\theta^{mn\varrho-1}_{uk}$, $\lambda^{mn\varrho-1}_{uk}$, $\psi^{mn\varrho-1}_{uk}$, $\mu^{\varrho-1}_k$, and $\nu^{\varrho-1}_u$; find $p^{mn\varrho}_{kdj^r i^r l^r}$ using (24).
Step 2.6: Increment $\varrho = \varrho + 1$.
Step 2.7: Update Lagrange Multipliers, $\vartheta^{mn\varrho}_{uk}$, $\theta^{mn\varrho}_{uk}$, $\lambda^{mn\varrho}_{uk}$, $\psi^{mn\varrho}_{uk}$, μ^{ϱ}_k, ν^{ϱ}_u.
Step 3: If stopping criterion is fulfilled goto Step 4; otherwise goto Step 2.
Step 4: End.

Fig. 3. The pseudo code of the proposed Algorithm 2.

B. Quantized CDI in Noisy Feedback Channel (Q-CDI-NF)

So far, we assumed that the CDI of channels are perfectly known. Actually, the PDF of channels has come parameters which should be estimated by the nodes in the networks and feedbacked to the corresponding entities, i.e., BS and RSs, through the dedicated limited rate feedback channels. This means that, similar to the Q-CSI case, we assume that the space of CDI parameters is divided into a finite number of regions and given the actual values of the CDI's parameters, the index of the region in which the values of parameters lies is feedbacked.

However, note that in this paper, we do not involve ourself in the CDI quantization process and the procedure of choosing the best parameter's value in each region which is used in PDFs of channels. Instead, we adopt a simple, but not optimal, way and assume that the CDI quantization is performed a priori based on some network design objectives and use the boundary values (lower boundary) as the parameters' value in the corresponding PDFs[2]. For the Rayleigh fading channels, the channel power gains, $\alpha_{uk}^m, \alpha_{ud}^m$ and α_{kd}^n, (exponentially distributed) are assumed to have the mean values of $\bar{\alpha}_{uk}^m$, $\bar{\alpha}_{ud}^m$, and $\bar{\alpha}_{kd}^n$, respectively. We assume that the mean value of the channel gain is itself a random variable which follows an arbitrary distribution, i.e., $\bar{\alpha}_{uk}^m \sim f_{\bar{\alpha}_{uk}^m}(\bar{\alpha}_{uk}^m)$, $\bar{\alpha}_{du}^m \sim f_{\bar{\alpha}_{ud}^m}(\bar{\alpha}_{ud}^m)$, and $\bar{\alpha}_{kd}^n \sim f_{\bar{\alpha}_{kd}^n}(\bar{\alpha}_{kd}^n)$. The receivers should send the average channel gains, $\bar{\alpha}_{uk}^m$, $\bar{\alpha}_{ud}^m$ and $\bar{\alpha}_{kd}^n$ to the transmitter by using the feedback channels. However, full CDI at transmitters are rarely possible due to limited feedback resource and feedback delay. The average channel gain of the channel from user u to destination over subcarrier m, i.e., $\bar{\alpha}_{ud}^m$, is quantized to $F = 2^{\eta}$ regions where η is the number of bits required to enumerate the resulting regions and the h^{th} region is denoted by $\Upsilon_{udh}^m = [\bar{A}_{udh}^m, \bar{A}_{udh+1}^m)$ with $\bar{A}_{ud0}^m = \bar{A}_{ud,\min}^m < \bar{A}_{ud1}^m < \cdots < \bar{A}_{udH+1}^m = \bar{A}_{ud,\max}^m$. Moreover, $\bar{\alpha}_{uk}^m$ is quantized to $h = 2^{\dot{\eta}}$ regions where the f^{th} region is denoted by $\dot{\Upsilon}_{ukf}^m = [\bar{A}_{ukf}^m, \bar{A}_{ukf+1}^m)$. In addition, $\bar{\alpha}_{kd}^n$ is quantized to $S = 2^{\ddot{\eta}}$ regions where the s^{th} region is denoted by $\ddot{\Upsilon}_{kds}^n = [\bar{A}_{kds}^n, \bar{A}_{kds+1}^n)$. To consider the noise in the limited feedback channel model, we use the same model as used for noisy Q-CSI in Subsection IV-A. We assume that the noisy feedback channels are memoryless with index transition probabilities of $\kappa_{ukf^r f^t}^m, (f^r, f^t = 1, \ldots, F)$, $\kappa_{udh^r h^t}^m, (h^r, h^t = 1, \ldots, H)$, and $\kappa_{kds^r s^t}^n, (s^r, s^t = 1, \ldots, S)$. The feedback bits for h^r and h^t are denoted by $h_{\zeta\in\{1,2,\ldots,\eta\}}^t, j_{\zeta\in\{1,2,\ldots,\eta\}}^r \in \{0,1\}$ where $\eta = \lceil \log_2 H \rceil$. Denoting by ϕ_{ud}^m the crossover probability of the corresponding BSC channel, the transition probability $\kappa_{udh^r h^t}^m$ can be obtained as follows [20]:

$$\kappa_{udh^r h^t}^m = \prod_{\zeta=1}^{\eta} \kappa_{udh_\zeta^r h_\zeta^t}^m = \left(\phi_{ud}^m\right)^{d_{udh^r h^t}^m} \left(1-\phi_{ud}^m\right)^{\eta - d_{udh^r h^t}^m}, \tag{28}$$

Also, the feedback bits for f^r and f^t are denoted by $f_{\dot{\zeta}\in\{1,2,\ldots,\dot{\eta}\}}^t, f_{\dot{\zeta}\in\{1,2,\ldots,\dot{\eta}\}}^r \in \{0,1\}$ where $\dot{q} = \lceil \log_2 F \rceil$ is the number of feedback bits. Denoting by ϕ_{uk}^m the crossover probability of the corresponding BSC channel, the transition probability $\kappa_{ukf^r f^t}^m$ can be obtained as follows:

$$\kappa_{ukf^r f^t}^m = \prod_{\dot{\zeta}=1}^{\dot{\eta}} \kappa_{ukf_{\dot{\zeta}}^r f_{\dot{\zeta}}^t}^m = \left(\phi_{uk}^m\right)^{d_{ukf^r f^t}^m} \left(1-\phi_{uk}^m\right)^{\dot{\eta} - d_{ukf^r f^t}^m}, \tag{29}$$

The feedback bits used for s^r and s^t are denoted by $s_{\ddot{\zeta}\in\{1,2,\ldots,\ddot{\eta}\}}^t, s_{\ddot{\zeta}\in\{1,2,\ldots,\ddot{\eta}\}}^r \in \{0,1\}$ where $\ddot{\eta} = \lceil \log_2 S \rceil$ is the number of feedback bits. Denoting by ϕ_{kd}^n the crossover probability of the corresponding BSC channel, the transition probability $\kappa_{kds^r s^t}^m$ can be obtained as follows:

$$\kappa_{kds^r s^t}^n = \prod_{\ddot{\zeta}=1}^{\ddot{\eta}} \kappa_{kds_{\ddot{\zeta}}^r s_{\ddot{\zeta}}^t}^n = \left(\phi_{kd}^n\right)^{d_{kds^r s^t}^n} \left(1-\phi_{kd}^n\right)^{\ddot{\eta} - d_{kds^r s^t}^n}, \tag{30}$$

The noisy quantized CDI optimization problem, i.e., $\mathcal{O}_{Q-CDI-NF}^{BCDA}$, is formulated as follows:

$$\max_{\boldsymbol{p},\boldsymbol{t},\boldsymbol{A},\boldsymbol{\tau}} \sum_{u=1}^{U}\sum_{k=1}^{K}\sum_{m,n=1}^{N} \varpi_u \tau_{uk2}^{mn},$$

$$\text{s.t.} \sum_{\substack{j^t=1,\\ j^r=1}}^{J} \sum_{\substack{i^t=1,\\ i^r=1}}^{I} \sum_{\substack{l^t=1,\\ l^r=1}}^{L} \sum_{\substack{h^t=1,\\ h^r=1}}^{H} \sum_{\substack{f^t=1,\\ f^r=1}}^{F} \sum_{\substack{s^t=1,\\ s^r=1}}^{S} t_{uk}^{mn} \varphi_{uki^r i^t j^r j^t l^r l^t}^{mnf^r f^t h^r h^t s^r s^t} \tag{31}$$

$$\mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\{R_{ukj^r i^r l^r 1}^{mnh^r f^r s^r}\}\Delta F_{ukf^t h^t s^t}^{mni^t j^t l^t} - (\tau_{uk2}^{mn} + \tau_{uk1}^{mn}) \geq 0, \forall u,k,m,n,$$

$$\sum_{\substack{j^t=1,\\ j^r=1}}^{J} \sum_{\substack{i^t=1,\\ i^r=1}}^{I} \sum_{\substack{l^t=1,\\ l^r=1}}^{L} \sum_{\substack{h^t=1,\\ h^r=1}}^{H} \sum_{\substack{f^t=1,\\ f^r=1}}^{F} \sum_{\substack{s^t=1,\\ s^r=1}}^{S} t_{uk}^{mn} \varphi_{uki^r i^t j^r j^t l^r l^t}^{mnf^r f^t h^r h^t s^r s^t} \tag{32}$$

$$\mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\{R_{ukj^r i^r l^r 2}^{mnh^r f^r s^r}\}\Delta F_{uki^t j^t l^t}^{mnf^t h^t s^t} - (\tau_{uk2}^{mn} + \tau_{uk1}^{mn}) \geq 0, \forall u,k,m,n,$$

$$\tau_{uk1}^{mn} - \sum_{\substack{j^t=1,\\ j^r=1}}^{J} \sum_{\substack{i^t=1,\\ i^r=1}}^{I} \sum_{\substack{l^t=1,\\ l^r=1}}^{L} \sum_{\substack{h^t=1,\\ h^r=1}}^{H} \sum_{\substack{f^t=1,\\ f^r=1}}^{F} \sum_{\substack{s^t=1,\\ s^r=1}}^{S} t_{uk}^{mn} \varphi_{uki^r i^t j^r j^t l^r l^t}^{mnf^r f^t h^r h^t s^r s^t} \tag{33}$$

$$\mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\{R_{ukj^r i^r l^r 3}^{mnh^r f^r s^r}\}\Delta F_{uki^t j^t l^t}^{mnf^t h^t s^t} \geq 0, \forall u,k,m,n,$$

$$\tau_{uk1}^{mn} - \sum_{\substack{j^t=1,\\ j^r=1}}^{J} \sum_{\substack{i^t=1,\\ i^r=1}}^{I} \sum_{\substack{l^t=1,\\ l^r=1}}^{L} \sum_{\substack{h^t=1,\\ h^r=1}}^{H} \sum_{\substack{f^t=1,\\ f^r=1}}^{F} \sum_{\substack{s^t=1,\\ s^r=1}}^{S} t_{uk}^{mn} \varphi_{ukf^r f^t h^r h^t s^r s^t}^{mni^r i^t j^r j^t l^r l^t} \tag{34}$$

$$\mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\{R_{ukj^r i^r l^r 4}^{mnh^r f^r s^r}\}\Delta F_{uki^t j^t l^t}^{mnf^t h^t s^t} \geq 0, \forall u,k,m,n,$$

$$\sum_{\substack{j^t=1,\\ j^r=1}}^{J} \sum_{\substack{i^t=1,\\ i^r=1}}^{I} \sum_{\substack{l^t=1,\\ l^r=1}}^{L} \sum_{\substack{h^t=1,\\ h^r=1}}^{H} \sum_{\substack{f^t=1,\\ f^r=1}}^{F} \sum_{\substack{s^t=1,\\ s^r=1}}^{S} \sum_{u=1}^{U} \sum_{\substack{m=1,\\ n=1}}^{N} t_{uk}^{mn} \varphi_{uki^r i^t j^r j^t l^r l^t}^{mnf^r f^t h^r h^t s^r s^t} \tag{35}$$

$$\mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\left\{p_{kdj^r i^r l^r}^{mnh^r f^r s^r}\right\}\Delta F_{uki^t j^t l^t}^{mnf^t h^t s^t} \leq P_k^T, \forall k,$$

$$\sum_{\substack{j^t=1,\\ j^r=1}}^{J} \sum_{\substack{i^t=1,\\ i^r=1}}^{I} \sum_{\substack{l^t=1,\\ l^r=1}}^{L} \sum_{\substack{h^t=1,\\ h^r=1}}^{H} \sum_{\substack{f^t=1,\\ f^r=1}}^{F} \sum_{\substack{s^t=1,\\ s^r=1}}^{S} \sum_{k=1}^{K} \sum_{\substack{m=1,\\ n=1}}^{N} t_{uk}^{mn} \varphi_{uki^r i^t j^r j^t l^r l^t}^{mnf^r f^t h^r h^t s^r s^t} \tag{36}$$

$$\mathbb{E}_{\tilde{\boldsymbol{\alpha}}}\left\{p_{ukj^r i^r l^r}^{mnh^r f^r s^r}\right\}\Delta F_{uki^t j^t l^t}^{mnf^t h^t s^t} \leq P_u^T, \forall u,$$

$$(5), (6), p_{ukj^r i^r l^r}^{mnh^r f^r s^r}, p_{kdj^r i^r l^r}^{mnh^r f^r s^r} \geq 0, t_{uk}^{mn} \in \{0,1\}, \forall u,k,m,n, \tag{37}$$

where $\varphi_{uki^r i^t j^r j^t l^r l^t}^{mnf^r f^t h^r h^t s^r s^t} = \kappa_{ukf^r h^r s^r}^{mnf^t h^t s^t} \chi_{uki^r j^r l^r}^{mni^t j^t l^t}$, $\kappa_{ukf^r h^r s^r}^{mnf^t h^t s^t} = \kappa_{udh^r h^t}^m \kappa_{ukf^r f^t}^m \kappa_{kds^r s^t}^n$, $\Delta F_{uki^t j^t l^t}^{mnf^t h^t s^t} = \Delta F_{\alpha_{udj^t h^t}^m} \Delta F_{\bar{\alpha}_{udh^t}^m} \Delta F_{\alpha_{uki^t f^t}^m} \Delta F_{\bar{\alpha}_{ukf^t}^m} \Delta F_{\alpha_{kdl^t s^t}^n} \Delta F_{\bar{\alpha}_{kds^t}^n}$, $\Delta F_{\alpha_{udj^t h^t}^m} = [F_{\alpha_{udj^t+1h^t}^m}$

[2] Optimally, CDI quantization should be performed jointly with CSI quantization, relay and user selection, subcarrier paring, and transmit power allocation. In addition, for each region, it is important to identify which value should be chosen to be used as the corresponding PDF functions' parameter. However, this process is out of the scop of this paper and has been left for future researches.

$- F_{\alpha^m_{udj^t h^t}}]$, $\Delta F_{\bar{\alpha}^m_{udh^t}} = [F_{\bar{\alpha}^m_{udh^t+1}} - F_{\bar{\alpha}^m_{udh^t}}]$, $R^{mnh^r f^r s^r}_{ukj^r i^r l^r 1} = C(p^{mnh^r f^r s^r}_{ukj^r i^r l^r} A^m_{uki^t})$, $R^{mnh^r f^r s^r}_{ukj^r i^r l^r 2} = C(\gamma^{mnh^r f^r s^r}_{u,cj^r j^t i^r l^r l^t})$, $\gamma^{mnh^r f^r s^r}_{u,cj^r j^t i^r l^r l^t} = p^{mnh^r f^r s^r}_{ukj^r i^r l^r} A^m_{udj^t} + p^{mnh^r f^r s^r}_{kdj^r i^r l^r} A^n_{kdl^t}$, $R^{mnh^r f^r s^r}_{ukj^r i^r l^r 3} = C(p^{mnh^r f^r s^r}_{ukj^r i^r l^r} \tilde{\alpha}^m_{ue})$, and $R^{mnh^r f^r s^r}_{ukj^r i^r l^r 4} = C(p^{mnh^r f^r s^r}_{kdj^r i^r l^r} \tilde{\alpha}^n_{ke})$. Problem $\mathcal{O}^{BCDA}_{Q-CDI-NF}$ can be solved in a similar way as that of $\mathcal{O}^{BCDA}_{Q-CSI-NF}$.

C. Iterative Algorithm Convergence

The proposed iterative algorithm converges to a suboptimal solution of the optimization problem. This convergence does not depends on the initial values at which the algorithm starts. Since our proposed algorithm is based on the BCDA algorithm, we must determine if the convergence conditions of the BCDA algorithm is satisfied in our case or not. To do this, we should prove that the function defined in $\mathcal{O}^{BCDA}$ is concave for each variable while the other variables are fixed [30], [36]. The details of the iterative algorithm convergence are given in Appendix A.

V. Other Allocation Schemes

In this section, we provide a number of suboptimal subcarrier and power allocation strategies for the proposed secure limited rate feedback scheme that have low-complexity. These strategies are based on treating some optimization variables separately. For example, we may not find the value of all optimization variables jointly. But, we find the value of some of optimization variables, i.e., transmit powers, subcarrier allocation, or region boundaries, according to some design strategies, insert these values into the optimization problem, and solve the optimization problem to find the other variables.

A. Equally Probable Region Quantizer (EPRQ) Scheme

Here, we consider a quantization scenario where the probability of the occurrence of each region is the same and equal to other regions. This quantizer determines $\{A^m_{uki}\}_{i=1}^I$, $\{A^m_{udj}\}_{j=1}^J$ and $\{A^m_{kdl}\}_{l=1}^L$, so that the probability of α^m_{uk}, α^m_{ud} and α^m_{kd} falling in any of the regions are $1/I$, $1/J$ and $1/L$, respectively. Note that, this quantization does not depend on the transmit powers and subcarrier allocations strategies. To design the equally probable region quantizer, we should calculate A^m_{uki}, A^m_{udj} and A^m_{kdl} to satisfy, respectively, the followings:

$$Pr(\alpha^m_{ud} \in \Omega^m_{udj}) = \int_{A^m_{udj}}^{A^m_{udj+1}} f_{\alpha^m_{ud}}(\alpha^m_{ud}) d\alpha^m_{ud} = 1/J, \forall u, m, \tag{38a}$$

$$Pr(\alpha^m_{uk} \in \dot{\Omega}^m_{uki}) = \int_{A^m_{uki}}^{A^m_{uki+1}} f_{\alpha^m_{uk}}(\alpha^m_{uk}) d\alpha^m_{uk} = 1/I, \forall u, k, m, \tag{38b}$$

$$Pr(\alpha^n_{kd} \in \ddot{\Omega}^n_{kdl}) = \int_{A^n_{kdl}}^{A^n_{kdl+1}} f_{\alpha^n_{kd}}(\alpha^n_{kd}) d\alpha^n_{kd} = 1/L, \forall k, n. \tag{38c}$$

For Rayleigh channels (where subcarrier gains adhere to exponential PDF's), (38) yields to the closed-form solutions for thresholds $\{A^m_{uki}\}_{i=1}^I$, $\{A^m_{udj}\}_{j=1}^J$ and $\{A^n_{kdl}\}_{l=1}^L$ as given in the following:

$$A^m_{udj} = \bar{\alpha}^m_{ud} \ln(J/(J-j)), \forall u, m, j, \tag{39a}$$

$$A^m_{uki} = \bar{\alpha}^m_{uk} \ln(I/(I-i)), \forall u, k, m, i, \tag{39b}$$

$$A^n_{kdl} = \bar{\alpha}^n_{kd} \ln(L/(L-l)), \forall k, n, l. \tag{39c}$$

B. Equal Boundary Regions Quantizer (EBRQ) Scheme

Now, we assume that the values of regions' boundary are the same for all subcarreirs, user, and RSs, i.e., the values of A^m_{udj}, A^m_{uki}, and A^n_{kdl} do not depend on u, k, m, and n. In other word, we have $A^m_{udj} = A^{\mathrm{UD}}_j$, $A^m_{uki} = A^{\mathrm{UR}}_i$, and $A^n_{kdl} = A^{\mathrm{RD}}_l$ where the superscripts UD, UR, and RD, respectively, mean user to destinations, user to relay, and relay to destination. Note that, in contrast to EPRQ Scheme in Subsection V-A where the regions' boundaries are obtained separately, in EBR scheme, the regions' boundaries should be jointly obtained with other optimization variables. The only difference is that in EBR, the number of optimization variables, i.e., regions' boundaries, is reduced to $I + J + L$. This is a suboptimal scheme but the complexity is reduced due to reduction of the number of optimization variables. Further reduction can be obtained by letting the regions' boundaries over all links be equal, i.e., $I = J = L$ and $A^{\mathrm{UD}}_i = A^{\mathrm{UR}}_i = A^{\mathrm{RD}}_i$ for all $i \in \{1, \ldots, L\}$.

C. Greedy Subcarrier Allocation (GSA) Scheme

In this subsection, we propose a suboptimal algorithm with low complexity for subcarrier allocation. In first hop, for each subcarrier m and each link, i.e., from u^{th} user to destination and from u^{th} user to k^{th} RS, we calculate $\varsigma^m_{ud} = \sum_{j=1}^J A^m_{udj} \Delta F_{\alpha^m_{udj}}, \forall u \in \mathcal{U}, m \in \mathcal{N}$, $\varsigma^m_{uk} = \sum_{i=1}^I A^m_{uki} \Delta F_{\alpha^m_{uki}}, \forall u \in \mathcal{U}, k \in \mathcal{K}, m \in \mathcal{N}$ and we follow a greedy scheme [37]. In other word, the subcarrier m is assigned to the link which has the maximum value of ς^m_{ud} or ς^m_{uk}. More precisely, the allocation is performed by $(u^*, k^*) = \arg\max_{u,k} \min(\varsigma^m_{ud}, \varsigma^m_{uk})$.

In second hop, for each subcarrier n and each link, i.e., from k^{th} RS to destination, we calculate $\varsigma^n_{kd} = \sum_{l=1}^L A^n_{kdl} \Delta F_{\alpha^n_{udl}}, \forall k \in \mathcal{K}, n \in \mathcal{N}$. Then, the subcarrier n is assigned to the link which has the maximum value ς^n_{ud}, i.e., $k^* = \arg\max_k \varsigma^n_{kd}$.

VI. Numerical Complexity

In this paper, the proposed schemes operate in two phases:

- An off-line phase in which several parameters that are later used to allocate resources are computed. This phase is run before communication starts. In this phase, the optimum boundary regions and codebooks are designed based on the CDIs of the network's links.
- An on-line phase that takes place during communication. In this phase, the transmitters use the parameters computed during the off-line phase. In other words, in the

on-line phase, the BS and RSs measure the CSIs between their users to their receivers on the up-link. Then, according to the set of all CSIs, the BS finds the related channel partition and boundary region and sends the index to the RSs and its users. Subsequently, BS announces the boundary region index to RSs and its users in order to select the corresponding codeword from the obtained code-book. The codebooks, which are a finite set of codewords, are designed off-line and are known by each node. The destination node selects the optimal power and subcarrier from the codebooks for each user and relay and transmit back the index of the optimal codeword to the user and relay nodes. Since our formulation involves average variables, the computational burden takes place during the initialization (off-line) phase and requires a negligible burden during the transmission (online) phase, which is certainly welcome from an implementation perspective [38].

Now, we discuss the computational complexity of our proposed limited feedback resource allocation algorithm in which the main part of computational complexity comes from the off-line algorithms. This is because, after designing the optimal boundary regions in this phase, the appropriate boundary region index can be selected based on the instantaneous CSI between all users and RSs and BS. Therefore, we focus on the computational complexity of the off-line algorithms. In the proposed algorithm, we have two steps: 1) finding the transmission power and boundary region via iterative BCDA approach. 2) determining the sub-carrier allocation and relay selection by linear search. It is obvious that the subcarrier allocation and relay selection takes $UKMN$ and $UKMN$ comparison operations, respectively. The computational complexity of the proposed optimal scheme is mainly determined by the complexity of solving the dual problem. The complexity of the ellipsoid method is polynomial in the number of dual variables and optimization variables.

Since the number of the optimization variables and dual variables for Q-CSI scheme are $KN^2(IJL(U+1)+2U)+N(UKI+UJ+KL)$ and $4UKN^2+U+K$, respectively, the computational complexity of the ellipsoid method is $O((KN^2(IJL(U+1)+2U)+N(UKI+UJ+KL))^2(4UKN^2+U+K))$ [32]. Moreover, the number of iterations required to achieve δ-optimality, i.e., $g-g^*<\delta$, is on the order of $O(1/\delta^2)$. Hence, the required iteration number does not depend on the number of variables. Therefore, the computational complexity related to convergence is $O\left(\frac{(KN^2(IJL(U+1)+2U)+N(UKI+UJ+KL))^2(4UKN^2+U+K)}{\delta^2}\right)$ [32]. The order of the subcarrier allocation and relay selection complexity is $O(UK(2N+1))$. Following the same line of argument as in Q-CSI, for Q-CDI, the computational complexity of it can be easily obtained as listed in table I.

In online phase, the required feedback information is the most important issue. In our proposed schemes, the required feedback information is $N(UK\lceil I\rceil+U\lceil J\rceil+K\lceil L\rceil)$. Note that in the non-limited feedback (continues case), the value of CSI and allocated power on each subcarrier must be feedbacked to transmitters. Thus, the required feedback information is $N(z^p+z^{ch})$ where z^p and z^{ch} are the required bit for the allocated power and CSI of each subcarrier, respectively.

VII. Simulation Results

We now present some simulations to demonstrate the performance of the proposed scheme. Totally, 10000 randomly generated channel power gain vectors, i.e., $\boldsymbol{\alpha}=[\alpha_{11}^1,\ldots,\alpha_{ud}^m,\ldots,\alpha_{Ud}^N,\ldots,\alpha_{kd}^n,\ldots,\alpha_{Kd}^N,\ldots,\tilde{\alpha}_{ke}^n,\ldots,\tilde{\alpha}_{KE}^N,\ldots,\alpha_{uk}^m,\ldots,\alpha_{UK}^N,\ldots,\tilde{\alpha}_{ue}^m,\ldots,\tilde{\alpha}_{UE}^N]$, are used to approximate the actual average sum secrecy rate of the network in each simulation result. For simplicity, we consider a simple one-dimensional system model which is used in [39]. The relays distance to users are always assumed to be smaller than the BS or the eavesdroppers distance. Channels between any two nodes are simply modeled through distance-dependent attenuation. For example, for the channel between a and b, the channel power gain is obtained by $\alpha_{ab}=\frac{d_{ab}^{-c}}{\sigma_b^2}$ where d_{ab} is the distance between the a and b, c is the path-loss exponent, and σ_b^2 is the variance of noise at b. We set $c=3.5$ which is a typical value in the literature, nevertheless, other values for c also lead to similar results. The users and BS distance is considered to be constant, in particular, we assume users is located at the origin, i.e., coordinates (0,0) and the BS stays at coordinates (100,0) (all the distance units are in meters.). We also assume independent identically distributed (i.i.d.) fading with Rayleigh distribution. We assume equal noise power at RS, destination, and eavesdropper nodes[3], i.e., $\sigma_k^2=\sigma_d^2=\sigma_e^2=-60$ dBm.

A. Convergence Behavior

Now, we study the convergence behavior of our proposed algorithm. Fig. 4(a) shows the behavior of the algorithm for the average sum secrecy rate of networks for different values of the maximum transmit power of users, $P_u^T=P^T,\forall u\in\mathcal{U}$. The coordinates for relays and eavesdropper are (50,0) and (60,0), respectively. It could be seen that the average sum secrecy rate of the network requires nearly 13 iterations for convergence and this number does not dependent on the value of maximum transmitted power of users. Such a number of iterations is low and hence make the computational burden of the proposed scheme very low.

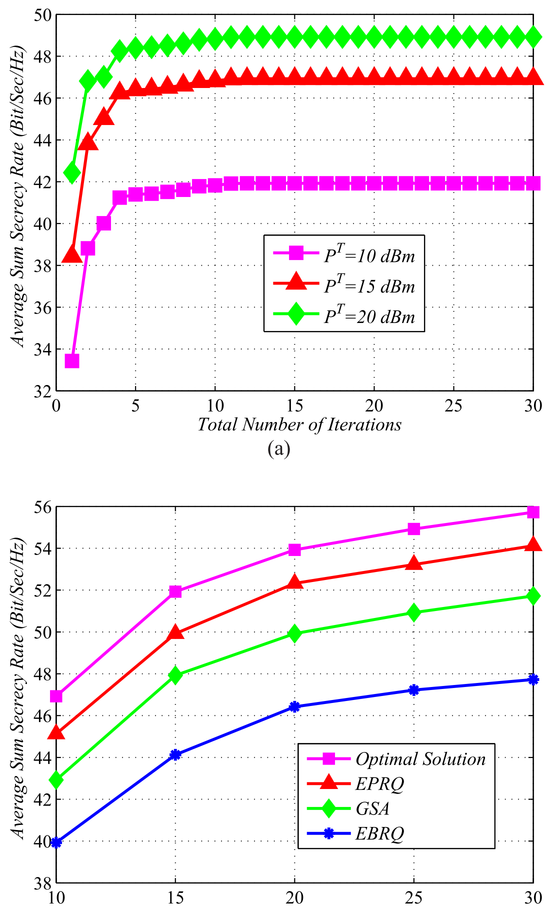
B. Effect of the Number of Threshold Regions

Here, we study the effect of the number of quantization regions on the achievable secrecy rate. Fig. 5(a) depicts the average sum secrecy rate of the network versus the number of users, u, for different number of threshold regions, $J=I=L$ and perfect CSI. It is seen that, the average sum secrecy rate increases as the number of regions increases. Moreover, the average sum secrecy rate of the network is comparable to the capacity of the system when assuming that full knowledge of CSI is available at the transmitters. The figure shows that the $I=J=L=16$ suffice to achieve an average sum secrecy rate for the network almost close to the average sum secrecy rate of the full CSI case. We also compare the average sum secrecy rate of the network for both Non-MRC and MRC schemes at the eavesdroppers. It could be seen in Fig. 5(a) that the average

[3] Since the devices of the same type are placed in the same location, therefore noise power can be considered to be equal

TABLE I
COMPUTATIONAL COMPLEXITY

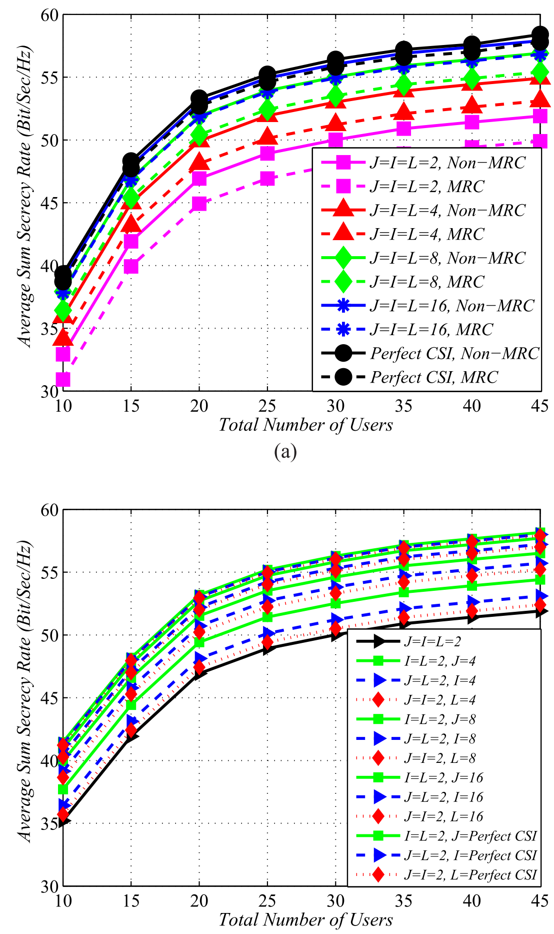
Proposed scheme	Dual problem	Subcarrier allocation	Power allocation	Quantizer thresholds updating
Q-CSI	$O\left(\frac{(KN^2(IJL(U+1)+2U)+N(UKI+UJ+KL))^2(4UKN^2+U+K)}{\delta^2}\right)$	$O(UK(2N+1))$	$O((U+1)KN^2JIL)$	$O(N(UJ+UKI+KL))$
Q-CDI	$O\left(\frac{(KN^2(IJLHFS(U+1)+2U)+N(U(J+F)+UK(I+H)+K(L+S)))^2}{\delta^2} + \frac{(4UKN^2+U+K)}{\delta^2}\right)$	$O(UK(2N+1))$	$O(KN^2 \quad (U+1)$ $JILHFS)$	$O(N(U(J+F)+UK(I+H)$ $+K(L+S)))$



(a)

(b)

Fig. 4. (a) Convergence behavior of the average sum secrecy rate of the network for different values of maximum transmitted power of users, $P_u^T = P^T$, $\forall u \in \mathcal{U}$, for Non-MRC scheme and noiseless feedback channel. The positions of relays and eavesdroppers are at fixed at (50,0) and (60,0), respectively. System parameters: $U = 25$, $K = 10$, $J = I = L = 2$, $P_k^T = 30$ dBm, $\forall k \in \mathcal{K}$, $\varpi_u = 1$, $\forall u \in \mathcal{U}$, $E = 3$. (b) Comparison of the average sum secrecy rate of the network for different allocation schemes, Optimal Solution, EPRQ, GSA, EBRQ, for different values of maximum transmitted power of users, $P_u^T = P^T$, $\forall u \in \mathcal{U}$, for Non-MRC scheme and noiseless feedback channel. The positions of relays and eavesdroppers are at fixed at (50,0) and (60,0), respectively. System parameters: $U = 25$, $K = 10$, $J = I = L = 2$, $P_k^T = 30$ dBm, $\forall k \in \mathcal{K}$, $\varpi_u = 1$, $\forall u \in \mathcal{U}$, $E = 3$.

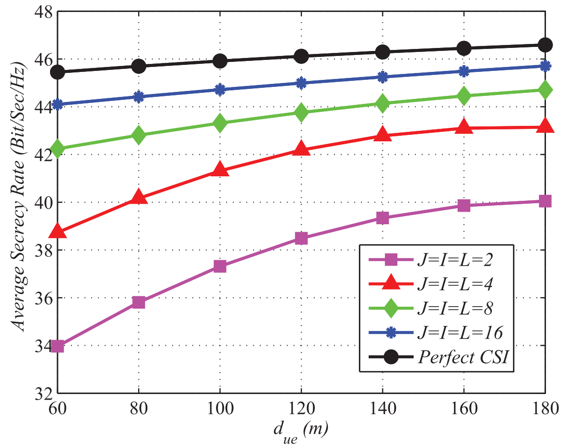


(a)

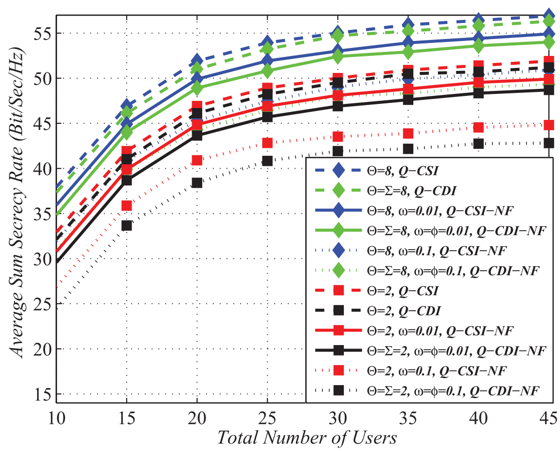
(b)

Fig. 5. (a) Average sum secrecy rate of the network versus the number of users, U, for different number of threshold regions, $J = I = L$, and perfect CSI for Non-MRC and MRC schemes and for noiseless feedback channel. The positions of relays and eavesdroppers are at fixed at (50,0) and (60,0), respectively. System parameters: $K = 10$, $P_u^T = 20$ dBm, $\forall u \in \mathcal{U}$, $P_k^T = 30$ dBm, $\forall k \in \mathcal{K}$, $\varpi_u = 1$, $\forall u \in \mathcal{U}$, $E = 3$. (b) Average sum secrecy rate of the network versus the number of users, U, for different and non-equal number of threshold regions, J, I, L, and perfect CSI for Non-MRC schemes and noiseless feedback channel. The positions of relays and eavesdroppers are at fixed at (50,0) and (60,0), respectively. System parameters: $K = 10$, $P_u^T = 20$ dBm, $\forall u \in \mathcal{U}$, $P_k^T = 30$ dBm, $\forall k \in \mathcal{K}$, $\varpi_u = 1$, $\forall u \in \mathcal{U}$, $E = 3$.

secrecy rate when the eavesdroppers use MRC is less than the case where MRC is not used. This is because, adopting MRC, the eavesdroppers can gather more information from legitimate users compared to the case when MRC is not used. We can, in other word, say that to achieve the same average secrecy rate, MRC case needs more feedback bits than non-MRC case. The effect of imperfect knowledge of CSIs is more when MRC is used.

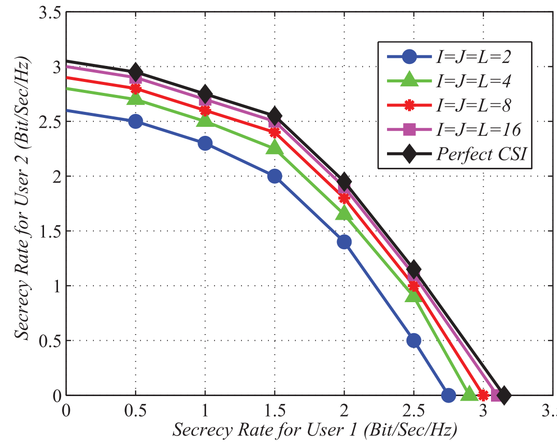


(a)

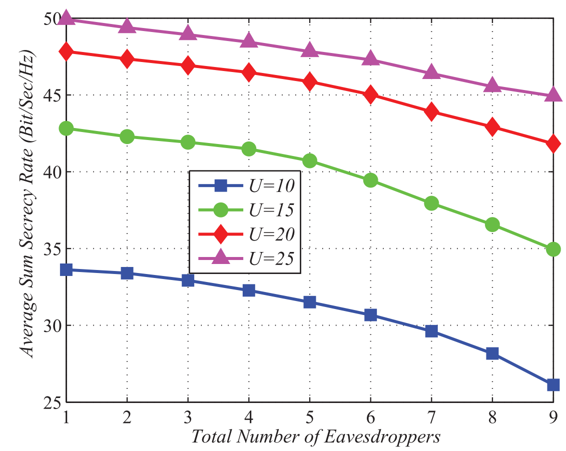


(b)

Fig. 6. (a) Average secrecy rate of the network versus the distance between the users and the eavesdropper, d_{ue}, for different number of threshold regions, $J = I = L$, and perfect CSI for Non-MRC schemes and for noiseless feedback channel. The position of eavesdroppers varies from (60,0) to (180,0). The relays location is fixed at (50,0). System parameters: $K = 10$, $P_u^T = 20$ dBm, $\forall u \in \mathcal{U}$, $P_k^T = 30$ dBm, $\forall k \in \mathcal{K}$, $\varpi_u = 1$, $\forall u \in \mathcal{U}$, $E = 3$. (b) Average sum secrecy rate of the network versus the number of users, U, for different values of cross over probability, $\omega_{ud}^m = \phi_{ud}^m = \omega_{uk}^m = \phi_{uk}^m = \omega_{kd}^n = \phi_{kd}^n = \omega = \phi$, $\forall u, k, m, n$, for different number of threshold regions, $J = I = L = \Theta$, $F = H = S = \Sigma$, for Non-MRC scheme and for noisy and noiseless feedback channel for Q-CDI and Q-CDI schemes. The positions of relays and eavesdroppers are at fixed at (50,0) and (60,0), respectively. System parameters: $K = 10$, $P_u^T = 20$ dBm, $\forall u \in \mathcal{U}$, $P_k^T = 30$ dBm, $\forall k \in \mathcal{K}$, $\varpi_u = 1$, $\forall u \in \mathcal{U}$, $E = 3$.



(a)



(b)

Fig. 7. (a) Secrecy rate for user 2 versus Secrecy rate for user 2, for different number of threshold regions, J, I, L, and perfect CSI, for Non-MRC scheme and noiseless feedback channel. The positions of relays and eavesdroppers are at fixed at (50,0) and (60,0), respectively. System parameters: $P_u^T = 20$ dBm, $\forall u \in \mathcal{U}$, $P_k^T = 30$ dBm, $\forall k \in \mathcal{K}$, $E = 1$, $K = 1$, $U = 2$. (b) Average sum secrecy rate of the network versus the number of Eavesdroppers, E, for different number of users, U, for Non-MRC scheme and noiseless feedback channel. The positions of relays and eavesdroppers are at fixed at (50,0) and (60,0), respectively. System parameters: $J = I = L = 2$, $P_u^T = 20$ dBm, $\forall u \in \mathcal{U}$, $P_k^T = 30$ dBm, $\forall k \in \mathcal{K}$, $\varpi_u = 1$, $\forall u \in \mathcal{U}$.

We next study the importance of each link, i.e., users to RSs, users to destination, and RSs to destination, on the average secrecy sum rate. More precisely, we evaluate the effect of changing the number of quantization regions of each channel alone on the average secrecy sum rate. Here, we start with the number of regions $J = I = L = 2$, and change the number of regions of only one channel while keeping those of other channels unchanged. We assume that the channel conditions of the user to BS links are worse than those of user to RS links and the channel conditions of user to RS links are worse than those of RS to BS links. The results is shown in Fig. 5(b). It is seen that as the number of regions increases, the average secrecy achievable rate increases as well which is due to providing more opportunity for better use of available transmit power budget over channel fading states. However, this effect is more for the links with worse channel conditions. This is because, for exponential distribution of the form $f(x) = \frac{1}{\bar{x}} e^{-\frac{x}{\bar{x}}}$, better channel condition means larger $\bar{x}$ which in turn means that the probabilities are distributed over fading space more evenly. In contrast, worse channel conditions means that more probability mass is assigned to a small portion of the whole fading space. In the latter case, increasing number of regions provides more opportunity for better usage of transmit power and hence, changing the number of regions have more effect on the changes in average achievable secrecy rate.

The next simulation studies the effect of the distance between the eavesdroppers and the users on the average secrecy rate. We fix the relays location at (50,0), and move the position of the eavesdroppers from (60,0) to (180,0). We change the distance between users and eavesdroppers and perform our proposed resource allocation scheme for different number of fading regions. The results are shown in Fig. 6(a). As expected, increasing the distance between users and eavesdroppers make the channel conditions of eavesdroppers worse and hence the eavesdroppers can achieve lower data rate. This means that the secrecy rate increases which is seen in the figure.

Now, we study the effect of the error in the feedback link for both the Q-CSI and Q-CDI schemes. Fig. 6(b) shows the average sum secrecy rate versus the number of user for different values of crossover probabilities, i.e., ω and ϕ, for Non-MRC scheme. It can be observed that as the feedback becomes less reliable, i.e., the crossover probabilities increase, significant performance degradation occurs. In addition, it can be observed that the Q-CDI and Q-CDI-NF schemes always have less performance than the Q-CSI and Q-CSI-NF, respectively.

C. Effect of Priority Coefficient on Fairness

In the previous simulations, we set $\varpi_u = 1$ for all u to obtain the achievable network average sum secrecy rate with all equal-priority users. Here, we study the impact of ϖ_u on the performance of the proposed scheme. We consider the case where two users exist in the network with $\varpi_1 = 1 - \varpi_2$. Fig. 7(a) demonstrates that when $\varpi_1 = 1$, user 1 has a higher priority and user 2 cannot obtain any average secrecy rate and vice versa. For $\varpi_1 = 0.5$, both users have the same priority. By adjusting $\varpi_1 = 1 - \varpi_2$, the priority and fairness between these users changes.

D. Effect of the Numbers of Eavesdroppers

Fig. 7(b) shows the average secrecy rate of the network versus the number of eavesdroppers for different number of users. As expected, the secrecy rate becomes smaller as the number of eavesdroppers increases. It can be observed from Fig. 7(b) that increasing number of eavesdroppers results in a significant reduction in the average sum secrecy rate, especially when the number of users in the network is small.

VIII. Conclusions

In this paper, we proposed a limited rate feedback resource allocation scheme for secure OFDMA DF relay assisted networks where a set of users want to transmit information securely to the BS with the help of some cooperative DF RSs in the presence of multiple eavesdroppers. We assumed that the legitimate transmitters have only the CDI of the main channels and the eavesdropper's links as well as partial information about the legitimate channels' CSIs. We solved our proposed optimization problem using dual method in which we found the power and subcarrier allocations as well as the boundary regions of quantized channels. We evaluated our proposed scheme using simulations. Numerical results showed the efficiency of our proposed quantized feedback schemes. A general observation for these schemes is that, with only few bits of feedback, the average sum secrecy rate with quantized channel information closely approximates that with full CSI information. It is important to note that, when all eavesdroppers adopt MRC, the average secrecy rate is less than when MRC is not used. In addition, to obtain the average secrecy rate which is equal to that of the perfect CSI case, more bits are needed for the MRC case than the Non-MRC case. As a future work, we can consider artificial noise or friendly jammer to improve legitimate link and to degrade the channel of eavesdroppers. Also the use of multiple input-multiple output (MIMO) techniques to improve secrecy rate can be an interesting future work direction. Potential extensions of this work can be to investigate the max-min fairness among users, to study the effects of imperfect CSI in both on-line and off-line phases and to consider users' quality-of-service.

In Fig. 4(b), we compare the performance of the proposed (optimal) Q-CSI solution with other schemes studied in the paper, i.e., schemes in Section V. We observe that the optimal proposed solution gives a significantly higher average sum secrecy rate (better performance) than that of the other schemes. In addition, it can be also seen that increasing the total transmit power will increases the average sum secrecy rate. However, the EPRQ, GSA, and ERQ schemes always have a performance worse than that of the optimal proposed solution.

Appendix A
Convergence of the Iterative Algorithm

For investigating the iterative algorithm convergence, we first focus on the case where the users-to-relays BS CNR quantizer thresholds, $A^m_{uki^t}$ as well as the values of $p^{mn}_{ukj^r i^r l^r}$, $p^{mn}_{kdj^r i^r l^r}$, $A^m_{udj^t}$, $A^n_{kdl^t}$, $\boldsymbol{\vartheta}$, $\boldsymbol{\theta}$, $\boldsymbol{\lambda}$, $\boldsymbol{\psi}$, $\boldsymbol{\mu}$, and $\boldsymbol{\nu}$ are fixed. We show that there exists a single maximum for the $A^m_{uki^t}$ that maximize the (13). In particular by setting the first derivative of the (13) with respect to $A^m_{uki^t}$ to zero, we showed in the previous section that the there exists a single solution. In order to show that this solution maximizes the (13), we need to determine whether the second derivation is negative. By substituting (24) in second derivative of (13) respect to $A^m_{uki^t}$, we obtain as follow:

$$\Xi_{\alpha^m_{uk}} = \sum_{\substack{j^t=1,\\ j^r=1}}^{J} \sum_{\substack{i^t,i^r=1\\ i^t\neq i}}^{I} \sum_{\substack{l^t=1,\\ l^r=1}}^{L} \sum_{n=1}^{N} \chi^{mni^t j^t l^t}_{uki^r j^r l^r} \left[\frac{-\vartheta^{mn}_{uk}[p^{mn}_{ukj^r i^r l^r}]^2 \Delta F_{\alpha^m_{uki^t}}}{(1+p^{mn}_{ukj^r i^r l^r} A^m_{udj^t})^2} - \frac{\vartheta^{mn}_{uk} p^{mn}_{ukj^r i^r l^r} \Delta F_{\alpha^m_{uki^t}}}{\ln(2)(1+p^{mn}_{ukj^r i^r l^r} A^m_{udj^t})} \left(\frac{\frac{\partial f_{\alpha^m_{uki^t}}}{\partial A^m_{uki^t}} \Delta F_{\alpha^m_{uki^t}}}{f_{\alpha^m_{uki^t}}} + 2 f_{\alpha^m_{uki^t}} \right) \right], \tag{A.1}$$

where $\frac{\partial f_{\alpha^m_{uki^t}}}{\partial A^m_{uki^t}}$ is the first derivative of the PDF of $A^m_{uki^t}$. Examining the above equation and knowing that the CDF function is monotonically increasing, we deduce that (A.1) is negative, specially for the solution obtained by (24), i.e., there exists a single $A^m_{uki^t}$ that maximizes (13). Similarly, we can derive convergency of other variables, $A^m_{udj^t}$ and $A^n_{kdl^t}$.

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