IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 25, 2018, accepted March 31, 2018, date of publication April 6, 2018, date of current version April 25, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2823723

Full-Duplex Cooperative Non-Orthogonal Multiple Access With Beamforming and Energy Harvesting

YAMEN ALSABA, CHEE YEN LEOW, (Member, IEEE), AND SHARUL KAMAL ABDUL RAHIM, (Senior Member, IEEE)
Wireless Communication Centre, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Malaysia

Corresponding author: Chee Yen Leow (bruceleow@fke.utm.my)

This work was supported in part by H2020-MSCA-RISE- 2015 under Grant 690750, in part by the Ministry of Higher Education Malaysia under Grant 4F818, Grant 07085, Grant 4J210, and in part by Universiti Teknologi Malaysia under Grant 19H58.

ABSTRACT In this paper, a novel communication scheme that combines beamforming, energy harvesting, and cooperative non-orthogonal multiple access (NOMA) system is introduced. In the proposed scheme, NOMA is first combined with beamforming to serve more than one user in each beamforming vector. Later, simultaneous wireless information and power transfer (SWIPT) technique is exploited to encourage the strong user to relay the weak user's information messages in full-duplex (FD) manner. However, one major drawback of FD communications is the self-interference (SI) signal due to signal leakage from terminal's output to the input. Three different cases are adopted. In the first case, the SI signal is assumed to be fully cancelled at the strong user using SI cancellation techniques. In the second case, SI is only cancelled at the information decoding circuits, while being harvested in the energy harvester to provide extra energy. The third case investigates the impact of imperfect SI cancellation on system performance is investigated. It is proved that introducing SWIPT doesn't only motivate users to collaborate, but also mitigates the impact of the SI signal. In addition, the problem of total sum rate maximisation is formulated and solved locally by means of two-step difference of convex functions (DC)-based procedure. Furthermore, the outage probability of both weak and strong user is derived and provided in closed-form expressions. Numerical simulations are presented to illustrate the sum rate gain of the proposed scheme if compared with existing schemes, and to verify the derived formulas.

INDEX TERMS Non-orthogonal multiple access (NOMA), beamforming, energy harvesting, simultaneous wireless information and power transfer, full-duplex, cooperative NOMA, self-interference.

I. INTRODUCTION

It is widely believed that the fifth generation (5G) communication systems will not be an incremental version of the fourth generation (4G) systems, as in addition to higher data rates, future communication systems have many anticipated functionalities, such as internet-of-things (IoT) and cloud-based applications [1]. These envisioned new services pose challenging requirements like higher data rates, low latency, massive connectivity and higher spectral and power efficiency. In order to meet these requirements, a variety of new technologies are needed such as new multiple access techniques, novel spectrum and power utilization methods, multi-antenna techniques (MIMO, Beamforming), FD communications [2].

Non-Orthogonal Multiple Access (NOMA) has been recognised as the potential multiple access scheme for 5G communication system, for its appealing features of spectral efficiency, massive connectivity, user fairness and low latency [3]. NOMA exploits the power domain to serve multiple-users simultaneously at the same time, frequency, or code. NOMA base station differentiates users according to their channel conditions. Users with poor channel conditions (weak users) are assigned with higher power level than users with better channel conditions (strong users). In order to implement NOMA, the base station superimposes the multiple information messages of the intended receivers using superposition coding (SC) technique. Each NOMA user subtracts all weaker users' information messages by means of successive interference cancellation (SIC), while considering stronger users' messages as a noise in order to decode the own message [4]. The knowledge of weaker users' information messages feature can be exploited by encouraging strong users to relay weaker users' messages to enhance the reliability of the system, in what is referred to as cooperative NOMA scheme [5], [6].

Introducing 5G potential technologies such as beamforming, energy harvesting and FD communications to NOMA in order to improve the full system performance has drawn considerable attention of late. In some literature, NOMA is combined with multiple-antenna techniques like beamforming (NOMA-BF) to exploit both power and spatial domains to enhance the signal to noise plus interference ratio (SINR) [7], or to increase the spatial multiplexing gain [8], [9] by serving more than one user per each beamforming vector. On the other hand, NOMA and energy harvesting techniques are merged in a few literature to enhance both energy and spectral efficiency and overcome energy and spectrum scarcity in the system. Sun *et al.* [10], Liu *et al.* [11] introduce simultaneous wireless information and power transfer (SWIPT) to NOMA system to encourage strong users to relay weak users' information messages as this collaboration will not drain their batteries. While wireless powered communication networks (WPCN) technique is merged with NOMA uplink system to increase the individual data rate in [12]. Strong users in [13], use the harvested energy in the first time slot, to relay weak users' messages in the second time slot using beamforming in half-duplex (HD) manner. Xu *et al.* [14] tackle the problem of maximising the data rate of the strong user with guaranteeing the QoS of the weak user in HD cooperative SWIPT NOMA system. The formulated nonconvex problem is solved by optimising both beamforming weights and the SWIPT power splitting ratio jointly. Of course, working in HD scheme isn't optimal as the resources are divided between receiving and transmitting processes. Hence, some literature has introduced FD to the cooperative NOMA systems.

FD communication has gained a lot of attention as it has the potential of increasing the spectral efficiency of wireless networks. In favour of the ability of transmitting and receiving signals simultaneously at the same frequency, FD can double the date rate of the system for a given bandwidth. However, the real implementation of FD has been considered impractical due to the SI signal which can be billions of times greater than the desired receive signal [15]. Recent advances in signal processing allow this SI suppressing to within tolerable limits through a combination of passive and active cancellation in both analogue, and digital domains [16]. Passive cancellation involves antenna-based isolation techniques that depend on the separation distance between antennas, orientation and polarisation [17]. Active cancellation approaches are carried out via digital processing techniques at baseband that require accurate knowledge of the channels after passive cancellation [18], or by superimposed signalling-based schemes where no channel estimation is required [19].

FD in cooperative NOMA systems can be exploited in two different methods. Either by letting the strong users relay the weak users' information messages in what referred to as user-assisted cooperative NOMA [20], [21]. Or by utilizing dedicated relays to convey the information-bearing signals, namely relay-assisted cooperative NOMA [22]–[25]. Zhang *et al.* [20] propose a dynamic multiple access scheme that switches between cooperative NOMA, non-cooperative NOMA, and conventional OMA schemes depending on the residual SI level and the link condition. Comparisons between FD and HD cooperative NOMA systems are provided by [21] in two different scenarios, mainly with or without direct link between the base station and the weak user. The results illustrate that FD NOMA has higher sum rate than that of the HD NOMA scheme in the low SNR region. Furthermore, it is proved that the use of the direct link overcomes the zero diversity for the weak user caused by the SI signal. Zhong and Zhang [22] study a cooperative NOMA system consisting of a base station, two users, and a dedicated FD relay that helps the communication out between the base station and the weak user. The proposed system is proved to achieve higher ergodic sum capacity than the FD system. So and Sung [23] prove that the achievable rate region of relay-assisted cooperative NOMA system is bigger than that of the conventional non-cooperative NOMA system. A multi-antenna relay is utilized in [24] to help the communication out between the NOMA base station and the far user in FD manner. The outage probability of the proposed system is derived, in addition to proposing two relay selection schemes. The work in [24] is extended in [25] to FD cooperative cognitive NOMA system. Where the beamforming vector and the transmit power are optimized to maximise the data rate of the strong user while satisfying the quality of service (QoS) requirement of the far user in the proposed scheme. Sun *et al.* [26] propose a different approach for benefiting from FD operation in NOMA systems. In the proposed scheme, the NOMA base station exploits FD for serving multiple downlink and uplink NOMA users simultaneously. The cooperation in the previous works on FD NOMA schemes is threatened by power scarcity in the system, as users are selfish and prefer to keep their power to decode the own messages. Hence, it is encouraging to introduce wireless power compensating techniques like energy harvesting to motivate users to cooperate.

In this paper, NOMA, beamforming, SWIPT and FD techniques are combined to propose a downlink commutation system with higher sum rate. In the proposed scheme, NOMA is first combined with zero-forcing (ZF) beamforming to serve more than one user in each beamforming vector (cluster). The strong user (with better channel state) in cluster subtracts the weak user's information message using SIC. This enables the strong user to serve as a FD relay for the weak user in the same cluster. As an incentive for the strong user to collaborate, the base station deploys SWIPT technique to transfer information and energy simultaneously to power users. The proposed strategy demonstrates high sum rate gain and outperforms the non-cooperative NOMA-BF proposed in [8]. However, due to working in FD manner strong user suffers from the SI signal, which is assumed to be totally cancelled in the first case, while it is harvested to provide more energy to the strong user terminal in the second case. In addition, imperfect SI cancellation is considered, where the residual SI is modelled, and its impact on the system performance is investigated. Furthermore, the problem of total sum rate maximization is formulated and solved by proposing clustering algorithm and power allocation strategies, in addition to deriving the outage probability of both weak and strong users.

II. SYSTEM MODEL

We consider a downlink cooperative NOMA and ZF beamformer with SWIPT system consisting of a base station equipped with N antenna communicating with M user ($M \geqslant 2N$). The users are provided with two antennas, one for receiving and relaying. Each NOMA-beamforming vector can support more than one user (will be referred to as a cluster). For the sake of simplicity, we will consider that there is only two users in each cluster (this model can be extended to more than two users at the same cluster, by letting each user relays the information message to the next weaker user). User with better (or worse) channel will be referred to as strong (or weak) user. The channel is Rayleigh fading with zero mean and unit variance multiplied by the path loss. The base station deploys superposition coding to build the information message for the user pair in the same cluster, and transfer it via SWIPT technique. In each cluster the strong user receives the base station signal and relays the weak user's information signal in FD manner using the power harvested from the SWIPT technique, while the weak user receives the base station and the strong user signals via the receiving antenna, while its transmitting antenna will be idle and all power is used for information decoding, as illustrated in Fig.1. The information message of the beamforming cluster number k can be written in the following form

$$x_k = \sqrt{P_k}\mathbf{w}_k(\sqrt{\alpha_{k1}}s_{k1} + \sqrt{\alpha_{k2}}s_{k2}), \tag{1}$$

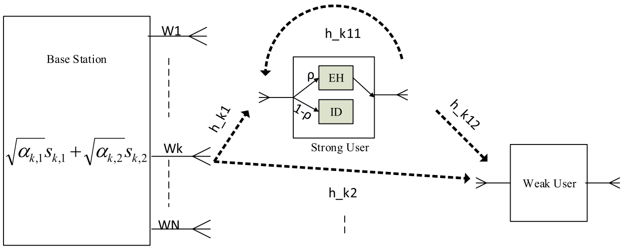

FIGURE 1. **The proposed cooperative NOMA scheme.**

where s_{k1} and s_{k2} are the information symbols for the strong and weak user respectively, with $\| s_{k1} \|^2 = \| s_{k2} \|^2 = 1$. α_{k1}, α_{k2} are the NOMA power allocation coefficients for the strong and the weak user respectively, with $\alpha_{k1} + \alpha_{k2} = 1$ and $\alpha_{k2} > \alpha_{k1}$. P_k and $\mathbf{w}_k$ the power allocated and the beamforming weight for the cluster k respectively.

A. PERFECT SI CANCELLATION

In the first case, we consider that SI signal at the strong user is cancelled using prefect cancellation procedures at the front end of the strong user terminal. In this case, the signal received at the strong user can be written as

$$\begin{aligned} y_{k1} = \underbrace{\mathbf{h}_{k1}\mathbf{w}_k\sqrt{P_k\alpha_{k1}}s_{k1}}_{\text{Signal}} + \underbrace{\mathbf{h}_{k1}\mathbf{w}_k\sqrt{P_k\alpha_{k2}}s_{k2}}_{\text{Intra-cluster Interference}} \\ + \underbrace{\sum_{j=1, j\neq k}^{N} \mathbf{h}_{k1}\mathbf{w}_j x_j}_{\text{Inter-cluster Interference}} + \underbrace{n_{k1}}_{\text{Noise}}, \end{aligned} \tag{2}$$

where $\mathbf{h}_{k1}$ is the channel gain between the base station and the strong user at cluster k. n_{k1} is an additive white complex Gaussian noise (AWGN) with zero mean and variance of ${\sigma_{k1}}^2 = {\sigma_k}^2$. Strong user subtracts the weak user's message from the combined signal by means of the SIC technique, and then decodes his own [27]. In addition, in ZF beamforming the weights are chosen to eliminate the interference coming from other clusters at the strong user in order to perform the SIC process successfully. As the inter-cluster interference reduces the strong user capability of correctly decoding the received signal. Hence, the ZF-based beamforming is designed based on the channel of the strong user in each cluster to satisfy:

$$\frac{\mathbf{h}_{k1}}{\mid \mathbf{h}_{k1} \mid}\mathbf{w}_j = \begin{cases} 1, & \text{if } k = j. \\ 0, & \text{otherwise.} \end{cases} \quad with \mid \mathbf{w}_j \mid^2 = 1.$$

Let $\mathbf{H} = [\mathbf{h}_{11}^T, \ldots, \mathbf{h}_{k1}^T, \ldots, \mathbf{h}_{N1}^T]^T$ be the matrix of strong users channels, where $(.)^T$ denotes the transpose operation. Then, the matrix of beamforming weights equals to the pseudo-inverse of the matrix $\mathbf{H}$, i.e. $\mathbf{W} = [\mathbf{w}_1, \ldots.\mathbf{w}_N] = \mathbf{H}^H(\mathbf{H}\mathbf{H}^H)^{-1}$., where $(.)^H$ is the conjugate transpose operation.

Thus, $\sum_{j=1, j\neq k}^{N} \mathbf{h}_{k1}\mathbf{w}_j x_j = 0$, and the signal received at the strong user is reduced to

$$y_{k1} = \mathbf{h}_{k1}\mathbf{w}_k\sqrt{P_k\alpha_{k1}}s_{k1} + n_{k1}. \tag{3}$$

The total signal power received by the strong user is divided be certain power splitting factor ρ_k, between information decoding and energy harvesting processes, with $0 \leq \rho_k \leq 1$. The value of ρ_k is determined by the target rate of the strong user R_{k1} and it is given by [11]

$$\rho_k = \max\Bigg(0, \frac{(2^{R_{k1}} - 1){\sigma_k}^2}{P_k(\alpha_{k1} - (2^{R_{k1}} - 1)\alpha_{k2}) \mid h_{k1} \mid^2}\Bigg).$$

When $\rho_k = 0$ all energy goes to information decoding process, and no harvested energy, while if $\rho_k = 1$ then all energy is used for harvesting and no information decoding.

The signal to interference and noise ratio (SINR) at the strong user is expressed as

$$SINR_{k1}^{1} = \frac{P_k(1-\rho_k)\alpha_{k1} \mid \mathbf{h}_{k1} \mid^2}{{\sigma_k}^2}, \tag{4}$$

and the rate of the strong user at cluster number k is given by

$$R_{k1} = \log_2(1 + SINR_{k1}^{1}), \tag{5}$$

while the harvested power at the strong user is given by

$$P_h = \eta\rho_k \mid \mathbf{h}_{k1} \mid^2 P_k, \tag{6}$$

where η is the energy harvesting efficiency factor that depends on energy harvesting devices and the rectification process. This harvested power is used by the strong user to transmit the weak user information in FD manner. The strong user harvests the weak user's powers as well, and not only his own. This justifies the potential gain of the scheme, especially that the level of power allocated to the weak user is higher in NOMA. Hence, the signal received by the weak user is the base station and the strong user signals, in addition to the inter-cluster interference signal and can be expressed as

$$y_{k2} = \underbrace{\sqrt{P_k\alpha_{k2}}\mathbf{h}_{k2}\mathbf{w}_k s_{k2} + \sqrt{P_h}\mathbf{h}_{k12}s_{k2}}_{\text{Signal}} + \underbrace{\mathbf{h}_{k2}\mathbf{w}_k\sqrt{P_k\alpha_{k1}}s_{k1}}_{\text{Intra-cluster interference}} + \underbrace{\sum_{j=1,j\neq k}^{N}\mathbf{h}_{k2}\mathbf{w}_j x_j}_{\text{Inter-cluster interference}} + \underbrace{n_{k2}}_{\text{Noise}}, \tag{7}$$

where $\mathbf{h}_{k2}$, $\mathbf{h}_{k12}$, are the channels between the weak user and the base station, and the channel between the weak user and the strong user respectively. n_{k2} is the receiver AWGN. We assume that the two signals from base station and strong user are fully resolvable at the weak user, so they can be merged using maximal ratio combining (MRC) [20]. Therefore, the overall SINR at the weak user after MRC is

$$\begin{aligned} SINR_{k2}^{1} &= \frac{P_k\alpha_{k2} \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2 + P_h \mid \mathbf{h}_{k12} \mid^2}{P_k\alpha_{k1} \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2 + \sum_{j=1,j\neq k}^{N} P_j \mid \mathbf{h}_{k2}\mathbf{w}_j \mid^2 + \sigma_k^2} \\ &= \frac{P_k\alpha_{k2} \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2 + P_k\eta\rho_k \mid \mathbf{h}_{k1} \mid^2 \mid \mathbf{h}_{k12} \mid^2}{P_k\alpha_{k1} \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2 + \sum_{j=1,j\neq k}^{N} P_j \mid \mathbf{h}_{k2}\mathbf{w}_j \mid^2 + \sigma_k^2}. \end{aligned} \tag{8}$$

The rate of the weak user at cluster k is expressed as

$$R_{k2} = \log_2(1 + SINR_{k2}^{1}). \tag{9}$$

B. PERFECT SI CANCELLATION AND SI HARVESTING

In this subsection, the SI signal resulting from FD mode at the strong user is assumed to be perfectly cancelled at information decoding path, while being harvested in the energy harvesting circuits to provide additional energy.

The signal received by the strong user in this case can be expressed as

$$y_{k1} = \sqrt{(1-\rho_k)}\mathbf{h}_{k1}\mathbf{w}_k\sqrt{P_k\alpha_{k1}}s_{k1} + \sqrt{(1-\rho_k)}\sqrt{P_t}\mathbf{h}_{k11}s_{k2} + n_{k1}, \tag{10}$$

where $\mathbf{h}_{k11}$ is the loop-channel gain between transmitting and receiving antennas, P_t is the transmitted power at the strong user. Under perfect cancellation assumption we have $\sqrt{(1-\rho_k)}\sqrt{P_t}\mathbf{h}_{k11}s_{k2} = 0$, and the strong user's information decoding signal can be reduced to

$$y_{k1}^{ID} = \sqrt{(1-\rho_k)}\mathbf{h}_{k1}\mathbf{w}_k\sqrt{P_k\alpha_{k1}}s_{k1} + n_{k1}. \tag{11}$$

The SINR at the strong user

$$SINR_{k1}^{2} = \frac{P_k(1-\rho_k)\alpha_{k1} \mid \mathbf{h}_{k1} \mid^2}{{\sigma_k}^2}. \tag{12}$$

SI signal is harvested at energy harvesting circuits with ratio ρ_k, then the transmitted power is the harvested energy of the sum of base station and SI signals and expressed as

$$\begin{aligned} P_t &= \eta\rho_k P_k \mid \mathbf{h}_{k1} \mid^2 + \eta\rho_k P_t \mid \mathbf{h}_{k11} \mid^2 \\ &= \frac{\eta\rho_k P_k \mid \mathbf{h}_{k1} \mid^2}{1 - \eta\rho_k \mid \mathbf{h}_{k11} \mid^2}. \end{aligned} \tag{13}$$

Using (13) and (8), the SINR at weak user can be expressed as

$$SINR_{k2}^{2} = \frac{P_k\alpha_{k2} \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2 + P_t \mid \mathbf{h}_{k12} \mid^2}{P_k\alpha_{k1} \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2 + \sum_{j=1,j\neq k}^{N} P_j \mid \mathbf{h}_{k2}\mathbf{w}_j \mid^2 + \sigma_k^2}. \tag{14}$$

C. IMPERFECT SI CANCELLATION AND SI HARVESTING

As a matter of fact, active and passive suppression techniques are only capable of introducing significant reduction to SI signal and not total cancellation. Moreover, these SI cancellations techniques suffer from imperfections due to several distortions such as nonlinearity, time-varying channels and carrier offsets [15]. These imperfect cancellation techniques resulting in a residual SI signal. Some literature considers this residual signal as a constant floor, while real experiments have revealed that this residual SI is a random variable and not constant [28]. The channel between transmitting and receiving antennas after imperfect SI cancellation, which represents the residual SI interference is modelled in multiple-antenna case by a Rayleigh fading channel with independent and identically distributed (i.i.d) Gaussian random entries. This model is common in the literature [29], [30], as line-of-sight components are normally efficiently reduced by cancellation procedures and the major effect comes from scattering. Hence, the received signal at information decoding circuits at strong user terminal at single-antenna case is expressed as

$$\begin{aligned} y_{k1}^{ID} = \sqrt{(1-\rho_k)}\mathbf{h}_{k1}\mathbf{w}_k\sqrt{P_k\alpha_{k1}}s_{k1} + \sqrt{(1-\rho_k)}\sqrt{P_t}hr_{k11}s_{k2} \\ + n_{k1}, \end{aligned} \tag{15}$$

where hr_{k11} is the channel between transmitting and receiving antenna after the imperfect SI cancellation process with variance βP_t, P_t is the transmit power and $\beta \geq 0$ is SI cancellation quality parameter that depends on the efficiency of the cancellation techniques, i.e., worse cancellation techniques result higher values of β [30]. Hence, the SINR at the information decoder circuit of the strong user in this case equals to

$$SINR_{k1}^{3} = \frac{(1-\rho_k)P_k\alpha_{k1} \mid \mathbf{h}_{k1} \mid^2}{(1-\rho_k)\beta P_t + {\sigma_k}^2}, \tag{16}$$

while the signal and the SINR of the week user remains the same as (14).

D. BASELINE SCHEME

In the baseline scheme proposed in [8], no cooperation between users at the same cluster is considered. Hence, the SINR at the strong user is given by

$$SINR_{k1}^{4} = \frac{P_k\alpha_{k1} \mid \mathbf{h}_{k1} \mid^2}{{\sigma_k}^2}, \tag{17}$$

while for the weak user

$$SINR_{k2}^{4} = \frac{P_k\alpha_{k2} \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2}{P_k\alpha_{k1} \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2 + \sum_{j=1,j\neq k}^{N} P_j \mid \mathbf{h}_{k2}\mathbf{w}_j \mid^2 + {\sigma_k}^2}. \tag{18}$$

III. NOMA POWER ALLOCATION OPTIMIZATION

In this section, the total sum rate of system is maximized with respect to NOMA power coefficient per cluster α_k and inter-cluster power coefficients P_k, subject to total power constraint. This optimization problem can be formulated as

$$\begin{aligned} \underset{\alpha_k, P_k}{\text{maximize}} \ & \sum_{k=1}^{N} R_{k1} + R_{k2} \\ \text{subject to} \ & \sum_{k=1}^{N} P_k \leq P_T, \\ & 0 \leq \alpha_k \leq 1 \\ & 0 \leq P_k \leq P_T \end{aligned} \tag{19}$$

The optimization problem is NP-Hard, as finding global optimal solution can't be done by polynomial time algorithm. Using a similar approach to that proposed in [31] for OFDM-NOMA systems, the optimization problem is divided into two steps problem, and each step solved by an efficient suboptimal algorithm. In the first step, a clustering algorithm will group the users in each sector, then the intra-cluster NOMA coefficient factor α_k is optimized for the paired user in each cluster. In the second step, the across cluster power portion P_k will be optimized, to allocate power efficiently across different clusters.

A. CLUSTERING ALGORITHM

User pairing has a crucial impact on the NOMA system performance, hence a clustering algorithm that groups users in each cluster is proposed. In order to exploit cooperation between users at the same cluster, users with high difference in gain should be paired together, so the user with high channel will relay the weak user's message. Apart from cooperation, pairing users with high difference in channel gain increases the average throughput of the system, as the two grouped users will be allocated with a higher power level difference. As the strong user does SIC so he does not suffer from the intra-cluster interference i.e., the high power level assigned to the weak user collocated with it. On the other hand, the high power level allocated to the weak user will increase its average throughput and the average sum throughput of the entire system eventually. From the previous discussion, it is reasonable to distribute users with the N highest channel gain into the N available clusters as a first step.

Another issue should be taken into consideration in the proposed system, that users accommodated at the same cluster should not have orthogonal channels so they can be grouped at the same beamforming vector. Therefore, in the proposed algorithm we divide the users into two sets. The first set consists of the N strongest users, and the second set is the remaining $M - N$ weak users. The N strongest users will be distributed in the available N clusters as a first step, then for each strong user from the first set, we search in the weak users set for the weak user that maximizes the product with corresponding beamforming weight of the paired strong user. Using this criterion to pair users decreases the inter-cluster interference at the weak user and guarantee that the channels of the paired users aren't orthogonal and can be grouped in the same beamforming as illustrated in Algorithm 1.

Algorithm 1 The Proposed Clustering Algorithm

```
Sort users in according to channel gain in descending order $| h_1 |^2 \geq | h_2 |^2 \geq .. \geq | h_M |^2$
Set $i := 1$
while $i \leq N$ do
    Define the corresponding beamforming weight $w_i$
    Find $j = argmax(| h_j w_i |^2), j = N + 1, ...M$
    Define $Cluster_i = \{i, j\}$
    $i := i + 1$
end while
```

1) COMPLEXITY

The complexity of the proposed clustering algorithm for a system consisting of M number of users and N number of clusters is $O(M) + O(N(M - N))$ [32]. In order to reduce the complexity of searching all possible weak users, another scenario could be adopted by pairing the strongest user with weakest user, and the second strongest user with the second weakest and so on as the non-orthogonality condition $| h_j w_i |^2 \neq 0$ is verified, to guarantee the implementation of the ZF scheme. If the weak user is paired with the strong user has orthogonal channel, then the next user will be considered.

B. INTRA-CLUSTER POWER ALLOCATION

After grouping the NOMA users in clusters using the clustering algorithm mentioned above, NOMA power coefficient factor between weak and strong user will be optimized. The power coefficients per cluster can be dynamically allocated to each user using the suboptimal fractional transmit power allocation (FTPA) scheme [4], or can be found by solving the following optimization problem.

$$\underset{\alpha_k}{\text{maximize}} \quad R_{k1}(\alpha_k) + R_{k2}(\alpha_k) \tag{20}$$

1) FRACTIONAL TRANSMIT POWER ALLOCATION

In FTPA scheme NOMA power coefficients are dynamical assigned to the paired users according to their channel gain. The power portion for the user number i grouped with the user j in the cluster k is given as follows:

$$P^i{}_k = \frac{P_k \mid h_i \mid^{-\psi}}{\mid h_i \mid^{-\psi} + \mid h_j \mid^{-\psi}}, \tag{21}$$

where $0 \leq \psi \leq 1$ the decay factor. The power portion assigned to a user is inversely proportional to his channel gain, thus the weak user will be assigned with higher power level. Of course this scheme is simple to implement but sub-optimal.

2) CCP POWER ALLOCATION ALGORITHM

The optimization problem in (20) can be rewritten as:

$$\underset{\alpha_k}{\text{minimize}}\ e(\alpha_k) = f(\alpha_k) - g(\alpha_k) \tag{22}$$

where

$$f(\alpha_k) = -\log_2(1 + \frac{P_k(1-\rho_k)\alpha_k \mid \mathbf{h}_{k1} \mid^2}{{\sigma_k}^2}).$$

and the value of $g(\alpha_k)$ is given in the equation shown at the bottom of this page, both functions f and g are convex with respect to α_k.

The aforementioned problem is a difference of two convex functions and referred to as DC programming problems, which is not convex in general. DC problems can be efficiently solved using various of numerical methods like Convex-Concave procedure (CCP) [33]. CCP is a heuristic iterative procedure that transfers the non-convex DC problem into a convex one, by replaces the non-convex part (the function g) with its convex affine approximation to find the local solutions starting from initial feasible point, i.e,

$$\hat{g}(x; x_k) = g(x_k) + \nabla g(x_k)^T (x - x_k). \tag{23}$$

The CCP is expressed in Algorithm 2. It is easy to prove that the CCP will converge as $\hat{e}(x_{k+1}) \leq \hat{e}(x_k)$, so the function $\hat{e}(x_k)$ will decrease with each step until the stopping criterion is satisfied. As for the stopping criterion a reasonable suggestion will be to use the criterion $e(x_0) - e(x_k) \leq \zeta$ where ζ is a certain threshold.

Algorithm 2 Basic CCP Algorithm

```
procedure CCP
    Given an initial feasible point $x_0$
    Set $k := 0$
    while stopping criterion is not satisfied do
        Define $\hat{g}(x; x_k) = g(x_k) + \nabla g(x_k)^T (x - x_k)$
        Define $\hat{e}(x_k) = f(x) - \hat{g}(x; x_k)$
        Find
            $x_{k+1} = argmin(\hat{e}(x_k))$        (24)
        Update $k := k + 1$
    end while
end procedure
```

Choosing the initial value plays crucial role in achieving the optimal solution as CCP is a heuristic algorithm. Therefore the algorithm is initialized with different initial points and the one that leads to the local solution with lowest run times will be adopted.

As α_k is scalar the optimal value can be found from the CCP directly without introducing line search algorithm to solve (24) (unlike most of DC problem algorithms) [33].

3) COMPLEXITY

The overall complexity of the clustering and per-cluster power allocation algorithms is $O(M) + O(N(M - N)) + TO(N)$, where T is the average number of iterations for the iterative CCP algorithm to converge [32].

C. INTER-CLUSTER POWER ALLOCATION

After optimizing the power coefficient between users in the same cluster, the power portions among cluster will be now allocated. Again, this problem can be tackled either by easy but sub-optimal solution like allocating all clusters with equal portions of the total power or by solving the following optimization problem:

$$\begin{aligned} &\underset{P_k}{\text{maximize}}\ R_{tot} = \sum_{k=1}^{N} (R_{k1} + R_{k2}) \\ &\text{subject to} \sum_{k=1}^{N} P_k \leq P_T \end{aligned} \tag{25}$$

1) EQUAL POWER APPROACH

As a suboptimal solution, but less complex total power can be divided equally among clusters, where each cluster will be assigned with total power divided by number of clusters.

$$\begin{aligned} g(\alpha_k) &= \log_2(1 + \frac{P_k(1-\alpha_k) \mid \mathbf{h}_2\mathbf{w}_k \mid^2 + P_k \eta \rho_k \mid \mathbf{h}_{k1} \mid^2 \mid \mathbf{h}_{k12} \mid^2}{P_k \alpha_k \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2 + \sum_{j \neq k} P_j \mid \mathbf{h}_{k2}\mathbf{w}_j \mid^2 + \sigma_k^2}) \\ &= \log_2(\frac{P_k(\mid \mathbf{h}_2\mathbf{w}_k \mid^2 + \eta \rho_k \mid \mathbf{h}_{k1} \mid^2 \mid \mathbf{h}_{k12} \mid^2) + \sum_{j \neq k} P_j \mid \mathbf{h}_{k2}\mathbf{w}_j \mid^2 + \sigma_k^2}{P_k \alpha_k \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2 + \sum_{j \neq k} P_j \mid \mathbf{h}_{k2}\mathbf{w}_j \mid^2 + \sigma_k^2}), \end{aligned}$$

2) CCP POWER ALLOCATION ALGORITHM

In this approach, the optimal value of the power level allocated to each cluster is determined by finding the solution to the following optimization problem.

$$\begin{aligned} &\underset{P_k}{\text{minimize}}\ -R_{tot} \\ &\text{subject to} \sum_{k=1}^{N} P_k \leq P_T \end{aligned} \tag{26}$$

where the value of R_{tot} is given in (27), as shown at the bottom of this page. So the optimization problem can be written as follows

$$\begin{aligned} &\underset{P_k}{\text{minimize}}\ U(P)-H(P) \\ &\text{subject to} \sum_{k=1}^{N} P_k \leq P_T \end{aligned} \tag{28}$$

where

$$H(P)=-\sum_{k=1}^{N}\log_2(P_k\alpha_k\,|\mathbf{h}_{k2}\mathbf{w}_k\,|^2+\sum_{j=1,j\neq k}^{N} P_j\,|\mathbf{h}_{k2}\mathbf{w}_j\,|^2+\sigma_k^2),$$

and

$$\begin{aligned} U(P) = -\sum_{k=1}^{N}\Big(&\log_2(1+\frac{P_k(1-\rho_k)\alpha_k\mid\mathbf{h}_{k1}\mid^2}{{\sigma_k}^2}) \\ &+\log_2(P_k\mid\mathbf{h}_2\mathbf{w}_k\mid^2+P_k\eta\rho_k\mid\mathbf{h}_{k1}\mid^2\mid\mathbf{h}_{k12}\mid^2 \\ &+\sum_{j=1,j\neq k}^{N} P_j\mid\mathbf{h}_{k2}\mathbf{w}_j\mid^2+\sigma_k^2)\Big). \end{aligned}$$

Again both functions $H(P)$, $U(P)$ are convex with respect to the power vector P, as $\nabla^2 H(P)$ and $\nabla^2 U(P)$ are semi-definite positive matrices. As P is a vector, its optimal value is found by solving (25) by any numerical method used to solve convex problems such as the interior point method [34].

IV. OUTAGE BEHAVIOUR

In order to investigate interference's impact on the system throughput, outage probability of both strong and weak user is derived and provided in closed-form expressions in this section. We will start with the strong user, then the outage probability of the weak user will be derived.

A. THE OUTAGE PROBABILITY OF STRONG USER

We say that the strong user is in outage, if he can't decode the information message of the weak user, or he can decode it but he can't decode his own message. Let A_1 and A_2 denote the events that the strong user can't decode the weak user's message and his own message respectively. Then, the outage probability of the strong user is expressed as

$$P_1 = 1-(A_1^c \cap A_2^c), \tag{29}$$

where A^c is the complement of the event A, here represents the success probability. The probability that strong user can decode weak user's information message is

$$\begin{aligned} \mathbb{P}(A_1^c) &= \mathbb{P}(\frac{(1-\rho_k)\delta_k\alpha_{k2}\mid\mathbf{h}_{k1}\mid^2}{(1-\rho_k)\delta_k\alpha_{k1}\mid\mathbf{h}_{k1}\mid^2+1} > \Theta_2) \\ &= \mathbb{P}(\mid\mathbf{h}_{k1}\mid^2 > \frac{\Theta_2}{(1-\rho_k)\delta_k(\alpha_{k2}-\Theta_2\alpha_{k1})}), \end{aligned} \tag{30}$$

where $\delta_k = \frac{P_k}{\sigma_k^2}$ is the transmit SNR at cluster k, $\Theta_2 = 2^{R_{k2}}-1$, and R_{k2} the target rate of the weak user at cluster k.

The probability that strong user can decode his own message is given by

$$\begin{aligned} \mathbb{P}(A_2^c) &= \mathbb{P}(\delta_k(1-\rho_k)\alpha_{k1}\mid\mathbf{h}_{k1}\mid^2 > \Theta_1) \\ &= \mathbb{P}(\mid\mathbf{h}_{k1}\mid^2 > \frac{\Theta_1}{(1-\rho_k)\delta_k\alpha_{k1}}), \end{aligned} \tag{31}$$

where $\Theta_1 = 2^{R_{k1}}-1$, and R_{k1} the target rate of the strong user at cluster k. Hence, the outage probability of the strong user has the following form

$$\mathbb{P}_{k1} = \begin{cases} \mathbb{P}(\mid\mathbf{h}_{k1}\mid^2 < \frac{\Theta_{max}}{(1-\rho_k)\delta_k}), \Theta_2 < \frac{\alpha_{k2}}{\alpha_{k1}} \\ 1, \Theta_2 \geq \frac{\alpha_{k2}}{\alpha_{k1}} \end{cases}$$

Where $\Theta_{max} = Max\Big(\frac{\Theta_1}{\alpha_{k1}}, \frac{\Theta_2}{\alpha_{k2}-\alpha_{k1}\Theta_2}\Big)$. In order to implement NOMA the condition $\Theta_2 < \frac{\alpha_{k2}}{\alpha_{k1}}$ should be satisfied.

$$\begin{aligned} R_{tot} &= \sum_{k=1}^{N}\Big(\log_2(1+\frac{P_k(1-\rho_k)\alpha_k\mid\mathbf{h}_{k1}\mid^2}{{\sigma_k}^2}) \\ &\quad+\log_2(\frac{P_k(\mid\mathbf{h}_2\mathbf{w}_k\mid^2+\eta\rho_k\mid\mathbf{h}_{k1}\mid^2\mid\mathbf{h}_{k12}\mid^2)+\sum_{j\neq k}P_j\mid\mathbf{h}_{k2}\mathbf{w}_j\mid^2+\sigma_k^2}{P_k\alpha_k\mid\mathbf{h}_{k2}\mathbf{w}_k\mid^2+\sum_{j\neq k}P_j\mid\mathbf{h}_{k2}\mathbf{w}_j\mid^2+\sigma_k^2})\Big) \\ &= \sum_{k=1}^{N}\Big(\log_2(1+\frac{P_k(1-\rho_k)\alpha_k\mid\mathbf{h}_{k1}\mid^2}{{\sigma_k}^2}) \\ &\quad+\log_2(P_k(\mid\mathbf{h}_2+\mathbf{w}_k\mid^2\ \eta\rho_k\mid\mathbf{h}_{k1}\mid^2\mid\mathbf{h}_{k12}\mid^2)+\sum_{j\neq k}P_j\mid\mathbf{h}_{k2}\mathbf{w}_j\mid^2+\sigma_k^2) \\ &\quad-\log_2(P_k\alpha_k\mid\mathbf{h}_{k2}\mathbf{w}_k\mid^2+\sum_{j\neq k}P_j\mid\mathbf{h}_{k2}\mathbf{w}_j\mid^2+\sigma_k^2)\Big) \end{aligned} \tag{27}$$

With the aid of order statistics [35] the relationships between both PDF and the CDF of the ordered strong user $X =\mid \mathbf{h}_{k1} \mid^2$ in cluster k and those of the unordered channels are given by

$$f_X(x) = \frac{M!}{(M-k)!(k-1)!} f_{|\mathbf{h}|^2}(x)(F_{|\mathbf{h}|^2}(x))^{M-k}$$
$$\left(1 - F_{|\mathbf{h}|^2}(x)\right)^{k-1}$$
$$= \frac{M!}{(M-k)!(k-1)!} \sum_{i=0}^{k-1} \binom{k-1}{i} (-1)^i f_{|\mathbf{h}|^2}(x)$$
$$\times \left(F_{|\mathbf{h}|^2}(x)\right)^{M-k+i},$$
$$F_X(x) = \frac{M!}{(M-k)!(k-1)!} \sum_{i=0}^{k-1} \binom{k-1}{i} \frac{(-1)^i}{M-k+i+1}$$
$$\times \left(F_{|\mathbf{h}|^2}(x)\right)^{M-k+i+1},$$

where $f_{|\mathbf{h}|^2}(.), F_{|h|^2}(.)$ are the PDF and the CDF of the unsorted channel gain of an arbitrary user. (The users are sorted in descending order, that is why the index $M-k+1$ is used instead of k)

The distribution of the unsorted channel gain for strong users in the proposed scheme obeys Gamma distribution with parameters $(N, 1)$ and hence its PDF and CDF are expressed as

$$f_{|\mathbf{h}|^2}(x) = \frac{1}{\Gamma(N)} x^{N-1} e^{-x}.$$
$$F_{|\mathbf{h}|^2}(x) = 1 - \sum_{j=0}^{N-1} \frac{1}{j!} x^j e^{-x}.$$

Hence, the outage probability of strong user can be characterized as

$$\mathbb{P}_{k1} = \frac{M!}{(k-1)!(M-k)!} \sum_{i=0}^{k-1} \binom{k-1}{i} \frac{(-1)^i}{M-k+i+1}$$
$$\times \left(1 - \sum_{j=0}^{N-1} \frac{1}{j!} \left(\frac{\Theta_{max}}{(1-\rho_k)\delta_k}\right)^j\right.$$
$$\left.\times \exp\left(-\frac{\Theta_{max}}{(1-\rho_k)\delta_k}\right)\right)^{M-k+i+1}. \tag{32}$$

B. OUTAGE PROBABILITY OF THE WEAK USER

The weak user is in outage if the weak and the strong user can't decode weak user's message (event B), or the strong user can decode the weak user's message but the total SINR at the weak user is less than the threshold (event C).

1) CALCULATION OF EVENT B

If the strong user can't decode the weak user's information message, then he can not relay it and the signal received by the weak user terminal is only the base station message. Hence, the SINR at the weak user in this case can be expressed as

$$SINR_{k2} = \frac{\delta_k \alpha_{k2} \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2}{\sum_{j=1, j\neq k}^{N} \delta_j \mid \mathbf{h}_{k2}\mathbf{w}_j \mid^2 + \delta_k \alpha_{k1} \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2 + 1}. \tag{33}$$

We assume that $\sigma_1^2 = \sigma_2^2 = ... = \sigma_N^2$.

The probability of event (B) can be expressed as

$$\mathbb{P}_B = \mathbb{P}\Big(\frac{(1-\rho_k)\delta_k\alpha_{k2} \mid \mathbf{h}_{k1} \mid^2}{(1-\rho_k)\delta_k\alpha_{k1} \mid \mathbf{h}_{k1} \mid^2 + 1} < \Theta_2,$$
$$\frac{\delta_k \alpha_{k2} \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2}{\sum_{j=1, j\neq k}^{N} \delta_j \mid \mathbf{h}_{k2}\mathbf{w}_j \mid^2 + \delta_k \alpha_{k1} \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2 + 1} < \Theta_2\Big)$$
$$= \underbrace{\mathbb{P}\Big(X < \Theta_3\Big)}_{I_1} \times \underbrace{\mathbb{P}\Big(Y < \Theta_4\Big)}_{I_2},$$

where $\Theta_3 = \frac{\Theta_2}{(1-\rho_k)\delta_k(\alpha_{k2}-\alpha_{k1}\Theta_2)}$, and $\Theta_4 = \frac{\Theta_2}{\delta_k\alpha_{k2}-\Theta_2(\delta_k\alpha_{k1}+\sum_{j=1,j\neq k}^{N}\delta_j)}$.

Similarly to (32) the term I_1 can expressed as

$$I_1 = \mathbb{P}\Big(X < \Theta_3\Big)$$
$$= \frac{M!}{(M-k)!(k-1)!} \sum_{i=0}^{k-1} \binom{k-1}{i} \frac{(-1)^i}{M-k+i+1}$$
$$\times \left(1 - \sum_{j=0}^{N-1} \frac{1}{j!} \Theta_3^j \exp(-\Theta_3)\right)^{M-k+i+1}.$$

The unsorted random variable $\hat{Y} =\mid \mathbf{h}\mathbf{w}_j \mid^2$ obeys the exponential distribution, i.e. $Y \sim Exp(1)$. Let l be the index of the weak user to be grouped with the strong user number k according to the proposed clustering algorithm. Then, the CDF of the ordered $Y =\mid \mathbf{h}_l\mathbf{w}_j \mid^2 =\mid \mathbf{h}_{k2}\mathbf{w}_j \mid^2$ random variable can be given as

$$F_Y(x) = \frac{M!}{(M-l)!(l-1)!} \sum_{i=0}^{l-1} \binom{l-1}{i} \frac{(-1)^i}{M-l+i+1}$$
$$(1 - e^{-x})^{M-l+i+1}.$$

Hence, the term I_2 can be expressed as

$$I_2 = \mathbb{P}(Y < \Theta_4) = \frac{M!}{(l-1)!(M-l)!} \sum_{i=0}^{l-1} \binom{l-1}{i} \frac{(-1)^i}{M-l+i+1}$$
$$\times \Big(1 - \exp(-\Theta_4)\Big)^{M-l+i+1}.$$

and the probability of event (B) equals to

$$\mathbb{P}(B) = \begin{cases} I_1 \times I_2, & \Theta_3, \Theta_4 > 0 \\ 1, & \Theta_3, \Theta_4 \leq 0 \end{cases}$$

2) CALCULATION OF EVENT C

Theorem 1: The probability that the strong user can decode the weak user's message but the total SINR at the weak user is less than the threshold, for the weak user in the proposed scheme is given by

$$\begin{aligned}&\mathbb{P}(C)\\&=\frac{(M!)^2}{(M-k)!(k-1)!(M-l)!(l-1)!\Gamma(N)}\\&\quad\sum_{r=0}^{l-1}(-1)^r\binom{l-1}{r}\sum_{i=0}^{k-1}(-1)^i\binom{k-1}{i}\sum_{t=0}^{M-k+i}(-1)^t\Sigma_{t'}B_{t'}M_{t'}\\&\quad\frac{\Gamma(N-1+\bar{t},(t+1)\Theta_3)}{(t+1)^{N-1+\bar{t}}}\sum_{q=0}^{M-l+r}(-1)^q\binom{M-l+r}{q}\frac{1}{\eta\rho_k\delta_k}\\&\quad\left(\Theta_2(1-e^{-(q+1)\Theta_4})-\frac{\Theta_4}{\Theta_2}(\frac{1}{q^2}-\frac{(q\Theta_4+1)e^{-q\Theta_4}}{q^2})\right),\end{aligned}\tag{34}$$

where $\Sigma_{t'}=\sum_{t_1=0}^{t}\sum_{t_2=0}^{t-t_1}\cdots\sum_{t_{N-1}=0}^{t-t_1\cdots-t_{N-2}}$, $B_{t'}=\binom{t}{t1}\binom{t-t1}{t2}\ldots\binom{t-t1-\ldots t_{N-2}}{t_{N-1}}$, $M_{t'}=\left(\prod_{j=0}^{N-2}\frac{x^j}{j!}\right)^{t_j+1}\left(\frac{1}{(N-1)!}\right)^{t-t_1\cdots-t_{N-2}}$, $\bar{t}=(N-1)(t-t_1)-(N2)t_2-(N3)t_3-\ldots t_{N-1}$.

Proof: See Appendix. ■

Now the outage probability of the weak user can be expressed as

$$\mathbb{P}_{k2}=\begin{cases}\mathbb{P}(B)+\mathbb{P}(C), & \Theta_3,\Theta_4>0\\1, & \Theta_3,\Theta_4\leq 0\end{cases}$$

And the outage probability of the cluster k is given by

$$\mathbb{P}(k)=1-(1-\mathbb{P}_{k1})(1-\mathbb{P}_{k2}).\tag{35}$$

V. ASYMPTOTIC BEHAVIOUR OF THE OUTAGE PROBABILITY

In this section we let the transmit SNR (δ) goes to infinity and analyse the diversity order achieved by both strong and weak users. The diversity order is defined as

$$d=-\lim_{\delta\to\infty}\frac{\log(\mathbb{P}(\delta))}{\log\delta}\tag{36}$$

The outage probability of the strong user in (32) can be expressed as

$$\begin{aligned}\mathbb{P}_{k1}&=\frac{M!}{(k-1)!(M-k)!}\sum_{i=0}^{k-1}\binom{k-1}{i}\frac{(-1)^i}{M-k+i+1}\\&\quad\times\exp\left(-\frac{\Theta_{max}}{(1-\rho_k)\delta_k}\right)^{M-k+i+1}\\&\quad\times\left(\exp\left(\frac{\Theta_{max}}{(1-\rho_k)\delta_k}\right)-\sum_{j=0}^{N-1}\frac{1}{j!}\left(\frac{\Theta_{max}}{(1-\rho_k)\delta_k}\right)^j\right)^{M-k+i+1}.\end{aligned}\tag{37}$$

The Maclaurin series of the function $\exp\left(\frac{\Theta_{max}}{(1-\rho_k)\delta_k}\right)$ is

$$\exp\left(\frac{\Theta_{max}}{(1-\rho_k)\delta_k}\right)=\sum_{j=0}^{\infty}\frac{\left(\frac{\Theta_{max}}{(1-\rho_k)\delta_k}\right)^j}{j!}.\tag{38}$$

Using (37) and (38) the outage probability of the strong user derived as

$$\begin{aligned}\mathbb{P}_{k1}&=\frac{M!}{(k-1)!(M-k)!}\sum_{i=0}^{k-1}\binom{k-1}{i}\frac{(-1)^i}{M-k+i+1}\\&\quad\times\exp\left(-\frac{\Theta_{max}}{(1-\rho_k)\delta_k}\right)^{M-k+i+1}\\&\quad\times\left(\sum_{j=N}^{\infty}\frac{1}{j!}\left(\frac{\Theta_{max}}{(1-\rho_k)\delta_k}\right)^j\right)^{M-k+i+1}.\end{aligned}\tag{39}$$

When $\delta\to\infty$, $\exp\left(-\frac{\Theta_{max}}{(1-\rho_k)\delta_k}\right)=1$ and the summation expression in (39) simplifies as $\left(\frac{\Theta_{max}}{(1-\rho_k)\delta_k}\right)^N$. Then the asymptotic outage probability of the strong user can be given by

$$\begin{aligned}\mathbb{P}_{k1}^{\infty}&\approx\frac{M!}{k!(M-k)!}\left(\frac{\Theta_{max}}{(1-\rho_k)}\right)^{N(M-k+1)}\\&\qquad\frac{1}{\delta_k^{N(M-k+1)}}\propto\frac{1}{\delta_k^{N(M-k+1)}},\end{aligned}\tag{40}$$

where $\propto$ means "be proportional to". Hence, the diversity order achieved for the strong user in the proposed model is $N(M-k+1)$, i.e. the diversity order of the strong user is relevant to the antenna number N and the user order among all users k.

Similar to (40), the asymptotic outage probability of the weak user for both events (B) and (C) is found to be

$$\mathbb{P}_{k2}^{\infty}\propto\frac{1}{\delta_k^{N(M-k+1)*(M-l+1)}}.\tag{41}$$

Thus, the diversity achieved by the weak user is $N(M-k+1)*(M-l+1)$, i.e. relevant to the antenna number and both strong and weak user order among all users.

VI. NUMERICAL RESULTS

In this section, numerical results are provided to demonstrate the performance evaluation in terms of the sum rate in the proposed cooperative NOMA scheme. The representative results in the considered network, are drawn according to the values in Table I. The random users' locations follow the uniform distribution.

Figure 2 represents the average sum rate of the conventional beamforming orthogonal multiple access scheme (OMA-BF), the basic non-cooperative NOMA-BF (baseline scheme), the proposed cooperative NOMA-BF with perfect SI cancellation (Case 1), the proposed cooperative

TABLE 1. **Simulation Parameters.**

Parameter	Value
Cell layout	Hexagonal
Cell radius	1000 m
Users locations	uniformly distributed
Total transmission power	46 dBm MHz
Bandwidth	4.32 MHz
Antenna transmission gain	1 dBi
Path Loss model	128.1 + 37.6 log(r) dB
Channel model	Rayleigh slow fading
Receiver noise density	-169 dBm
Power conversion efficiency factor	0.75
SI Cancellation factor	10^{-3}
Number of users per cell	2,4,....,50

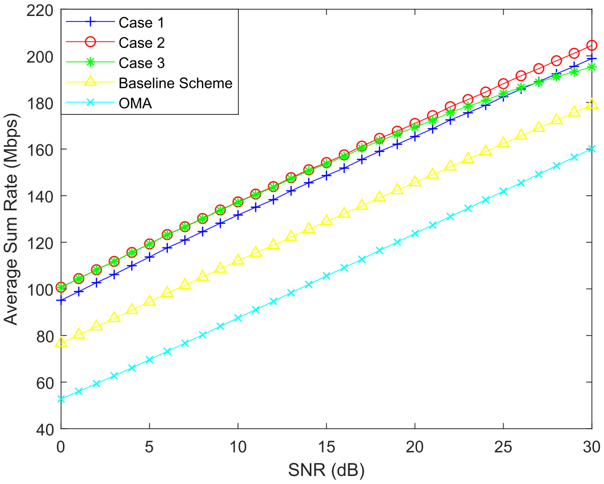

FIGURE 2. **The average sum rate of the proposed schemes.**

TABLE 2. **Legends.**

Case 1	Perfect SI cancellation
Case 2	Perfect SI cancellation + SI harvesting
Case 3	Imperfect SI cancellation + SI harvesting
Baseline scheme	Non-cooperative scheme
OMA	Conventional OMA-BF scheme

NOMA-BF with self-energy harvesting and perfect SI cancellation (Case 2), and the proposed cooperative NOMA-BF with self-energy harvesting and imperfect SI (Case 3), see Table II. The enhancement obtained by the new scheme is quite remarkable in terms of sum rate. This gain increases with SNR, as this extra high level of energy will increase the help of the strong user to the weak user. It is obvious that case 2 has a better sum rate than case 1 and case 3, while the performance degrades in case 3 with high SNR as the residual IS term becomes significant in high SNR regime. Overall, the proposed scheme shows that a higher sum rate can be achieved when the strong user is able to harvest the RF energy to relay information to the weak user. Additional gain can be obtained if the SI is considered in the energy harvester indicating that introducing SWIPT technique to the system not only simulates users to cooperate, but also mitigates the impact of SI. Furthermore, the conventional OMA-BF has the poorest performance in terms of sum rate as only one user can be served per beamforming vector.

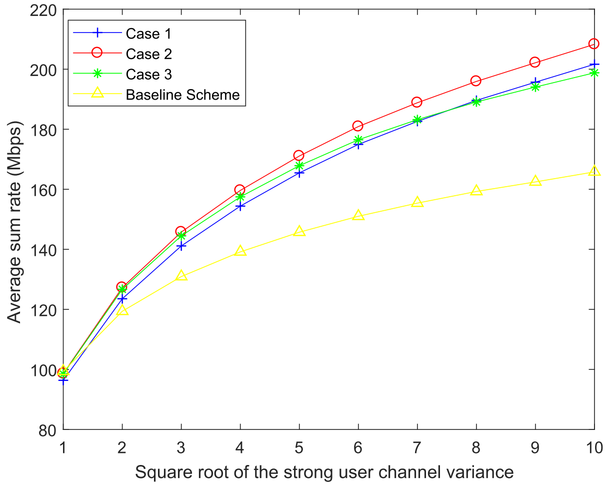

FIGURE 3. **The average sum rate as a function of the square root of the strong user channel gain.**

The curves shown in Figure 3, represent the sum rate of versus the square root of the strong user channel gain. One can notice that when the channel of the strong user is better, the enhancement of the proposed schemes on the system performance increases. The higher the channel gain of the strong user the higher the SNR and the harvested energy, resulting in a higher sum rate. This verifies the principle of distributing the strong users into the different available clusters.

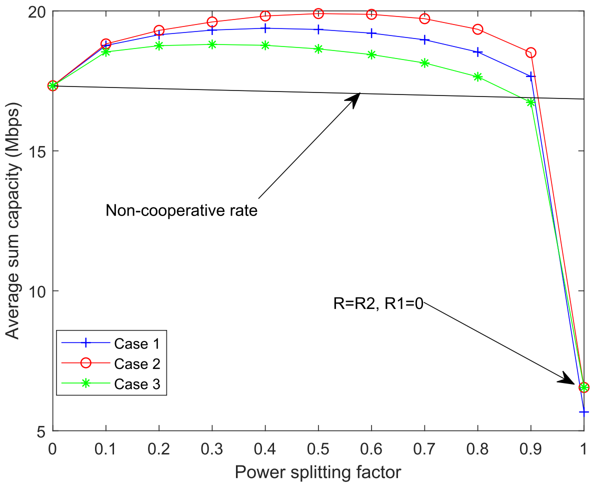

FIGURE 4. **The average sum rate versus power splitting factor.**

Figure 4, illustrates the impact of energy harvesting power splitting factor, on the sum rate of the proposed cooperative NOMA-BF protocols. When $\rho_k = 0$, then no harvested energy and no cooperation (baseline scheme). For $0 < \rho_k < 1$ the strong user harvests energy and starts to cooperate and the sum rate is increased. One can notice that the rates in all cooperative cases are higher than the non-cooperative rate. For $\rho_k = 1$, all energy goes to the energy harvester and the sum rate equals to the rate of the weak user only. Case 2 still has the best performance for different values of ρ_k. However,

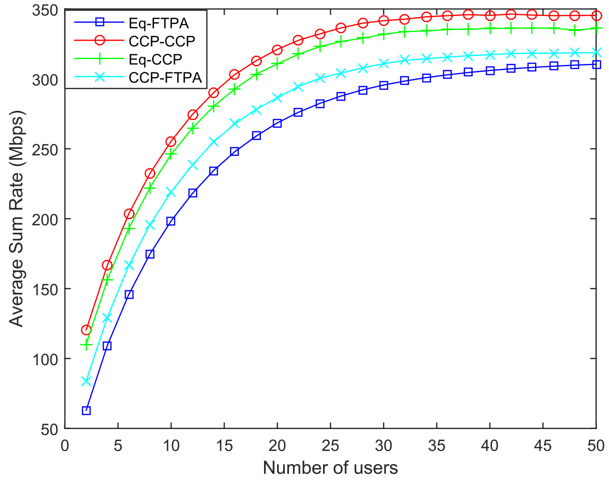

FIGURE 5. Total average sum rate with respect to number of users.

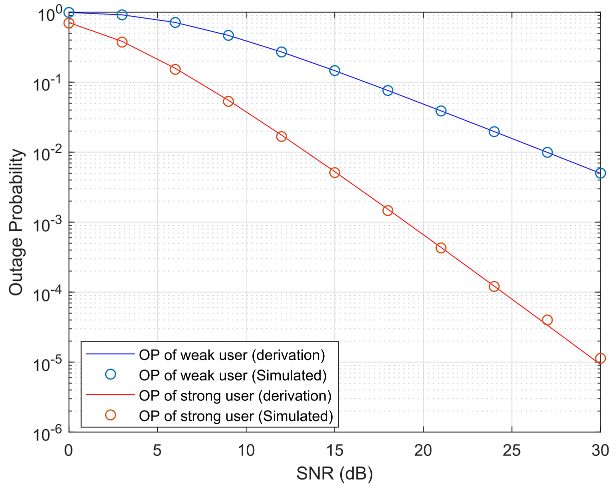

FIGURE 6. Outage Probability of Strong and Weak User Versus SNR.

the value of ρ_k can't be assigned randomly, as it is determined by the strong user's target rate.

Figure 5, represents a comparison among the different combinations of intra-cluster (CCP and fractional transmit power allocation) and inter-cluster (CCP and equal power) power allocation algorithms (Table III). The total sum rate is drawn as a function of the total number of users. It is clear that adopting CCP algorithm as an inter-cluster and intra-cluster power allocation schemes outperforms all other power allocation algorithms combinations. It is shown that using equal power as inter-cluster power allocation and CCP as intra-cluster power allocation (Eq-CCP) has better permanence than using CCP as inter-cluster power allocation and FTPA as intra-cluster power allocation (CCP-FTPA). Hence, intra-cluster power allocating has a higher impact than inter-cluster power allocation on the overall system performance at the cost of increased system complexity.

The curves in Figure 6 represent the outage probability of both strong and weak user versus transmit SNR. In order to verify the derived results, the analytical formulas (solid line) are drawn along with numeral results of Monte Carlo simulation (dotted line). The match between simulated and derived results verify the correctness of the provided closed-form formulas.

TABLE 3. Legends2.

Algorithm	Inter-Cluster Power Allocation	Intra-Cluster Power Allocation
Eq-FTPA	Equal Power Allocation	FTPA
CCP-FTPA	CCP Algorithm	FTPA
Eq-CCP	Equal Power Allocation	CCP Algorithm
CCP-CCP	CCP Algorithm	CCP Algorithm

VII. CONCLUSION

A novel downlink cooperative communication system that combines NOMA, beamforming, SWIPT, and FD techniques is proposed. The proposed scheme achieves higher sum rate than that of the conventional non-cooperative NOMA and the OMA-BF systems. SI resulting from FD relaying mode is harvested to provide extra energy to power the relay node and mitigating the SI negative impact making the FD concept more practical. Perfect and imperfect SI cancellation techniques are investigated, and it is proved that harvesting the SI signal while being perfectly cancelled in the information decoder is the best scenario. Furthermore, a clustering algorithm is proposed and the power allocation coefficients of NOMA per and across cluster are optimized to maximize the total sum rate of the system. In addition, the outage probability of both strong and weak users in the system is derived and verified by numerical simulations.

Appendix

The probability that event (C) occurs can be expressed as

$$\begin{aligned}
&\mathbb{P}(C)\\
&= \mathbb{P}\Big(\frac{(1-\rho_k)\delta_k\alpha_{k2} \mid \mathbf{h}_{k1} \mid^2}{(1-\rho_k)\delta_k\alpha_{k1} \mid \mathbf{h}_{k1} \mid^2 +1} > \Theta_2,\\
&\quad \frac{\delta_k\alpha_{k2} \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2 + \eta\rho_k\delta_k \mid \mathbf{h}_{k1} \mid^2 \mid \mathbf{h}_{k12} \mid^2}{\sum_{j=1, j\neq k}^{N} \delta_j \mid \mathbf{h}_{k,2}\mathbf{w}_j \mid^2 + \delta_k\alpha_{k1} \mid \mathbf{h}_{k2}\mathbf{w}_k \mid^2 +1} < \Theta_2\Big)\\
&= \mathbb{P}\Big(Z < \frac{\Theta_2 - \frac{\Theta_4}{\Theta_2} \mid \mathbf{h}_{k2} \mid^2}{\eta\rho_k\delta_k \mid \mathbf{h}_{k1} \mid^2}, X > \Theta_3, Y < \Theta_4\Big). \qquad (42)
\end{aligned}$$

The distribution of the random variable $Z = \mid \mathbf{h}_{k12} \mid^2$ follows the exponential distribution, as the channel between the two users is single-input single-output (SISO) channel. Hence, after conditioning on X and Y, $\mathbb{P}(C)$ can be expressed as

$$\begin{aligned}
\mathbb{P}(C) &= \int_0^{\Theta_4} \int_{\Theta_3}^{\infty} \int_0^{\frac{\Theta_2 - \frac{\Theta_4}{\Theta_2} y}{\eta\rho_k\delta_k x}} f_Z(z) f_X(x) f_Y(y) dz dx dy\\
&= \int_0^{\Theta_4} \int_{\Theta_3}^{\infty} (1 - e^{-\frac{\Theta_2 - \frac{\Theta_4}{\Theta_2} y}{\eta\rho_k\delta_k x}}) f_X(x) f_Y(y) dx dy, \qquad (43)
\end{aligned}$$

using the approximation $e^{-\psi x} \approx 1 - \psi x$ for small values of x (high SNR regime approximation), we can write

$$\begin{aligned}
\mathbb{P}(C) &\approx \int_0^{\Theta_4} \int_{\Theta_3}^{\infty} \frac{\Theta_2 - \frac{\Theta_4}{\Theta_2} y}{\eta\rho_k\delta_k x} f_X(x) f_Y(y) dx dy\\
&= \frac{M!}{(M-k)!(k-1)!\Gamma(N)} \sum_{i=0}^{k-1} (-1)^i \binom{k-1}{i}
\end{aligned}$$

$$\int_0^{\Theta_4}\int_{\Theta_3}^{\infty}\frac{\Theta_2-\frac{\Theta_4}{\Theta_2}y}{\eta\rho_k\delta_k x}x^{N-1}e^{-x}\underbrace{\left(1-\sum_{j=0}^{N-1}\frac{1}{j!}x^j e^{-x}\right)^{M-k+i}}_{\Psi}dxf_Y(y)dy. \qquad (44)$$

Similarly to [36], the term Ψ can be expressed as

$$\begin{aligned}\Psi &= \left(1-\sum_{j=0}^{N-1}\frac{1}{j!}x^j e^{-x}\right)^{M-k+i}\\ &= \sum_{t=0}^{M-k+i}(-1)^t\binom{M-k+i}{t}e^{-tx}\underbrace{\left(\sum_{j=0}^{N-1}\frac{x^j}{j!}\right)^t}_{\Psi_1}. \end{aligned}\qquad (45)$$

By successive binomial expansion, the term Ψ_1 can be written in the following form

$$\begin{aligned}\Psi_1 &= \left(\sum_{j=0}^{N-1}\frac{x^j}{j!}\right)^t\\ &= \sum_{t_1=0}^{t}\binom{t}{t_1}\left(\sum_{j=1}^{N-1}\frac{x^j}{j!}\right)^{t-t_1}\\ &= \sum_{t_1=0}^{t}\sum_{t_2=0}^{t-t_1}\binom{t}{t_1}\binom{t-t_1}{t_2}x\left(\sum_{j=2}^{N-1}\frac{x^j}{j!}\right)^{t-t_1-t_2}\\ &= \sum_{t_1=0}^{t}\sum_{t_2=0}^{t-t_1}\cdots\sum_{t_{N-1}=0}^{t-t_1\cdots-t_{N-2}}\binom{t}{t1}\binom{t-t1}{t2}\\ &\quad\ldots\binom{t-t1-\ldots t_{N-2}}{t_{N-1}}\left(\frac{x^{N-1}}{(N-1)!}\right)^{t-t_1\cdots-t_{N-1}}\\ &\quad\left(\prod_{j=0}^{N-2}\frac{x^j}{j!}\right)^{t_j+1}. \end{aligned}\qquad (46)$$

By substituting (46) in (45) we can write Ψ on the following form

$$\Psi = \sum_{t=0}^{M-k+i}(-1)^t\Sigma_{t'}B_{t'}M_{t'}x^{\bar{t}}e^{-tx}, \qquad (47)$$

Substitution in (44) yields

$$\begin{aligned}\mathbb{P}(C) &= \frac{M!}{(M-k)!(k-1)!\Gamma(N)}\sum_{i=0}^{k-1}(-1)^i\binom{k-1}{i}\\ &\quad\sum_{t=0}^{M-k+i}(-1)^t\Sigma_{t'}B_{t'}M_{t'}\\ &\quad\int_0^{\Theta_4}\int_{\Theta_3}^{\infty}\frac{\Theta_2-\frac{\Theta_4}{\Theta_2}y}{\eta\rho_k\delta_k}x^{N-2+\bar{t}}e^{-x(t+1)}dxf_Y(y)dy\\ &= \frac{M!}{(M-k)!(k-1)!\Gamma(N)}\sum_{i=0}^{k-1}(-1)^i\binom{k-1}{i}\\ &\quad\sum_{t=0}^{M-k+i}(-1)^t\Sigma_{t'}B_{t'}M_{t'}\frac{\Gamma(N-1+\bar{t},(t+1)\Theta_3)}{(t+1)^{N-1+\bar{t}}}\\ &\quad\int_0^{\Theta_4}\frac{\Theta_2-\frac{\Theta_4}{\Theta_2}y}{\eta\rho_k\delta_k}f_Y(y)dy. \end{aligned}\qquad (48)$$

The PDF of the ordered weak user with index l that is grouped with the strong user k can be expressed according to [35] as

$$\begin{aligned}f_Y(y) &= \frac{M!}{(M-l)!(l-1)!}\sum_{r=0}^{l-1}(-1)^r\binom{l-1}{r}e^{-y}\left(1-e^{-y}\right)^{M-l+r}\\ &= \frac{M!}{(M-l)!(l-1)!}\sum_{r=0}^{l-1}(-1)^r\binom{l-1}{r}\\ &\quad\sum_{q=0}^{M-l+r}(-1)^q\binom{M-l+r}{q}e^{-y(q+1)}. \end{aligned}\qquad (49)$$

By implying (49) in (48), the event $\mathbb{P}(C)$ can be expressed as

$$\begin{aligned}&\mathbb{P}(C)\\ &= \frac{M!}{(M-k)!(k-1)!\Gamma(N)}\frac{M!}{(M-l)!(l-1)!}\\ &\quad\sum_{r=0}^{l-1}(-1)^r\binom{l-1}{r}\sum_{i=0}^{k-1}(-1)^i\binom{k-1}{i}\sum_{t=0}^{M-k+i}(-1)^t\Sigma_{t'}B_{t'}M_{t'}\\ &\quad\frac{\Gamma(N-1+\bar{t},(t+1)\Theta_3)}{(t+1)^{N-1+\bar{t}}}\\ &\quad\sum_{q=0}^{M-l+r}(-1)^q\binom{M-l+r}{q}\int_0^{\Theta_4}\frac{\Theta_2-\frac{\Theta_4}{\Theta_2}y}{\eta\rho_k\delta_k}e^{-(q+1)y}dy.\\ &= \frac{(M!)^2}{(M-k)!(k-1)!(M-l)!(l-1)!\Gamma(N)}\\ &\quad\sum_{r=0}^{l-1}(-1)^r\binom{l-1}{r}\sum_{i=0}^{k-1}(-1)^i\binom{k-1}{i}\sum_{t=0}^{M-k+i}(-1)^t\Sigma_{t'}B_{t'}M_{t'}\\ &\quad\frac{\Gamma(N-1+\bar{t},(t+1)\Theta_3)}{(t+1)^{N-1+\bar{t}}}\sum_{q=0}^{M-l+r}(-1)^q\binom{M-l+r}{q}\frac{1}{\eta\rho_k\delta_k}\\ &\quad\left(\Theta_2(1-e^{-(q+1)\Theta_4})-\frac{\Theta_4}{\Theta_2}(\frac{1}{q^2}-\frac{(q\Theta_4+1)e^{-q\Theta_4}}{q^2})\right). \end{aligned}\qquad (50)$$

The proof is completed.

REFERENCES

[1] G. Wunder *et al.*, "5GNOW: Non-orthogonal, asynchronous waveforms for future mobile applications," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 97–105, Feb. 2014.

[2] J. G. Andrews *et al.*, "What will 5G be?" *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[3] A. Benjebbour, A. Li, Y. Saito, Y. Kishiyama, A. Harada, and T. Nakamura, "System-level performance of downlink NOMA for future LTE enhancements," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2013, pp. 66–70.

[4] Y. Saito, A. Benjebbour, Y. Kishiyama, and T. Nakamura, "System-level performance evaluation of downlink non-orthogonal multiple access (NOMA)," in *Proc. IEEE 24th Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2013, pp. 611–615.

[5] Z. Ding, M. Peng, and H. V. Poor, "Cooperative non-orthogonal multiple access in 5G systems," *IEEE Commun. Lett.*, vol. 19, no. 8, pp. 1462–1465, Aug. 2015.

[6] N. T. Do, D. B. da Costa, T. Q. Duong, and B. An, "A BNBF user selection scheme for NOMA-based cooperative relaying systems with SWIPT," *IEEE Commun. Lett.*, vol. 21, no. 3, pp. 664–667, Mar. 2017.

[7] K. Higuchi and A. Benjebbour, "Non-orthogonal multiple access (NOMA) with successive interference cancellation for future radio access," *IEICE Trans. Commun.*, vol. 98, no. 3, pp. 403–414, 2015.

[8] B. Kim *et al.*, "Non-orthogonal multiple access in a downlink multiuser beamforming system," in *Proc. IEEE Military Commun. Conf. (MILCOM)*, Nov. 2013, pp. 1278–1283.

[9] J. Choi, "Minimum power multicast beamforming with superposition coding for multiresolution broadcast and application to NOMA systems," *IEEE Trans. Commun.*, vol. 63, no. 3, pp. 791–800, Mar. 2015.

[10] R. Sun, Y. Wang, X. Wang, and Y. Zhang, "Transceiver design for cooperative non-orthogonal multiple access systems with wireless energy transfer," *IET Commun.*, vol. 10, no. 15, pp. 1947–1955, Oct. 2016.

[11] Y. Liu, Z. Ding, M. Elkashlan, and H. V. Poor, "Cooperative non-orthogonal multiple access with simultaneous wireless information and power transfer," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 938–953, Apr. 2016.

[12] P. D. Diamantoulakis, K. N. Pappi, Z. Ding, and G. K. Karagiannidis, "Wireless-powered communications with non-orthogonal multiple access," *IEEE Trans. Wireless Commun.*, vol. 15, no. 12, pp. 8422–8436, Dec. 2016.

[13] M. Ashraf, A. Shahid, J. W. Jang, and K.-G. Lee, "Energy harvesting non-orthogonal multiple access system with multi-antenna relay and base station," *IEEE Access*, vol. 5, pp. 17660–17670, 2017.

[14] Y. Xu *et al.*, "Joint beamforming and power-splitting control in downlink cooperative SWIPT NOMA systems," *IEEE Trans. Signal Process.*, vol. 65, no. 18, pp. 4874–4886, Sep. 2017.

[15] S. Hong *et al.*, "Applications of self-interference cancellation in 5G and beyond," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 114–121, Feb. 2014.

[16] A. Sabharwal, P. Schniter, D. Guo, D. W. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 9, pp. 1637–1652, Sep. 2014.

[17] E. Everett, A. Sahai, and A. Sabharwal, "Passive self-interference suppression for full-duplex infrastructure nodes," *IEEE Trans. Wireless Commun.*, vol. 13, no. 2, pp. 680–694, Jan. 2014.

[18] T. Riihonen, S. Werner, and R. Wichman, "Hybrid full-duplex/half-duplex relaying with transmit power adaptation," *IEEE Trans. Wireless Commun.*, vol. 10, no. 9, pp. 3074–3085, Sep. 2011.

[19] A. Koohian, H. Mehrpouyan, A. A. Nasir, S. Durrani, and S. D. Blostein, "Residual self-interference cancellation and data detection in full-duplex communication systems," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2017, pp. 1–6.

[20] Z. Zhang, Z. Ma, M. Xiao, Z. Ding, and P. Fan, "Full-duplex device-to-device-aided cooperative nonorthogonal multiple access," *IEEE Trans. Veh. Technol.*, vol. 66, no. 5, pp. 4467–4471, May 2017.

[21] X. Yue, Y. Liu, S. Kang, A. Nallanathan, and Z. Ding, "Exploiting full/half-duplex user relaying in NOMA systems," *IEEE Trans. Commun.*, vol. 66, no. 2, pp. 560–575, Feb. 2018.

[22] C. Zhong and Z. Zhang, "Non-orthogonal multiple access with cooperative full-duplex relaying," *IEEE Commun. Lett.*, vol. 20, no. 12, pp. 2478–2481, Dec. 2016.

[23] J. So and Y. Sung, "Improving non-orthogonal multiple access by forming relaying broadcast channels," *IEEE Commun. Lett.*, vol. 20, no. 9, pp. 1816–1819, Sep. 2016.

[24] Z. Mobini, M. Mohammadi, H. A. Suraweera, and Z. Ding, "Full-duplex multi-antenna relay assisted cooperative non-orthogonal multiple access," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2017, pp. 1–7.

[25] M. Mohammadi, B. K. Chalise, A. Hakimi, H. A. Suraweera, and Z. Ding, "Joint beamforming design and power allocation for full-duplex NOMA cognitive relay systems," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2017, pp. 1–6.

[26] Y. Sun, D. W. K. Ng, Z. Ding, and R. Schober, "Optimal joint power and subcarrier allocation for full-duplex multicarrier non-orthogonal multiple access systems," *IEEE Trans. Commun.*, vol. 65, no. 3, pp. 1077–1091, Mar. 2017.

[27] T. Cover, "Broadcast channels," *IEEE Trans. Inf. Theory*, vol. 18, no. 1, pp. 2–14, Jan. 1972.

[28] M. Duarte, C. Dick, and A. Sabharwal, "Experiment-driven characterization of full-duplex wireless systems," *IEEE Trans. Wireless Commun.*, vol. 11, no. 12, pp. 4296–4307, Dec. 2012.

[29] T. Riihonen, S. Werner, and R. Wichman, "Mitigation of loopback self-interference in full-duplex MIMO relays," *IEEE Trans. Signal Process.*, vol. 59, no. 12, pp. 5983–5993, Dec. 2011.

[30] H. Q. Ngo, H. A. Suraweera, M. Matthaiou, and E. G. Larsson, "Multipair full-duplex relaying with massive arrays and linear processing," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 9, pp. 1721–1737, Sep. 2014.

[31] P. Parida and S. S. Das, "Power allocation in OFDM based NOMA systems: A DC programming approach," in *Proc. Globecom Workshops (GC Wkshps)*, Dec. 2014, pp. 1026–1031.

[32] T. H. Cormen, *Introduction to Algorithms*. Cambridge, MA, USA: MIT Press, 2009.

[33] T. Lipp and S. Boyd, "Variations and extension of the convex–concave procedure," *Optim. Eng.*, vol. 17, no. 2, pp. 263–287, 2016.

[34] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.

[35] H. A. David and H. N. Nagaraja, *Order Statistics*, 3rd ed. New York, NY, USA: Wiley, 2003.

[36] J. Men, J. Ge, and C. Zhang, "Performance analysis of nonorthogonal multiple access for relaying networks over Nakagami-*m* fading channels," *IEEE Trans. Veh. Technol.*, vol. 66, no. 2, pp. 1200–1208, Feb. 2017.

YAMEN ALSABA received the B.Eng. degree in electrical and telecommunication engineering from the Higher Institute of Applied Science and Technology, Damascus, Syria, and the M.S. degree from Supelec, Paris, France, in 2005 and 2010, respectively. He is currently pursuing the Ph.D. degree with the Wireless Communication Centre, Universiti Teknologi Malaysia, Skudai, Malaysia. His research interests include simultaneous wireless information and power transfer, non-orthogonal multiple access, beamforming, physical layer security, large scale network analysis, and 5G.

CHEE YEN LEOW (S'08–M'12) received the B.Eng. degree in computer engineering from Universiti Teknologi Malaysia (UTM), Skudai, Malaysia, and the Ph.D. degree from Imperial College London, U.K., in 2007 and 2011, respectively. Since 2007, he has been the Academic Staff with the Faculty of Electrical Engineering, UTM. He is currently a Senior Lecturer with the Faculty and a Researcher with the Wireless Communication Centre Higher Institution Centre of Excellence, UTM, and UTM-Ericsson Innovation Centre for 5G. His research interests include cooperative communication, MIMO, UAV communication, physical layer security, convex optimization, communications theory, wireless power transfer and communication, non-orthogonal multiple access, and 5G.

SHARUL KAMAL ABDUL RAHIM received the first degree in electrical engineering from the University of Tennessee, USA, in 1996, the M.Sc. degree in engineering (communication engineering) from Universiti Teknologi Malaysia (UTM), Skudai, in 2001, and the Ph.D. degree in wireless communication system from the University of Birmingham, U.K., in 2007. He is currently an Associate Professor with the Wireless Communication Centre, Faculty of Electrical Engineering, UTM. He has published over 50 journal papers and technical proceedings on rain attenuations, smart antenna system, microwave design and reconfigurable antenna in national and international journals and conferences. His research interests include smart antenna on communication system. He is also a member of the IEEE Malaysia Section, the Member Board of Engineer Malaysia, the Member of Institute of Engineer Malaysia, and the Eta Kappa Nu Chapter (International Electrical Engineering Honour Society, University of Tennessee).

• • •