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Research paper

A Novel Full-duplex Relay Selection and Resource Management in Cooperative SWIPT NOMA Networks

M. B. Noori Shirazi, M. R. Zahabi*

Faculty of Electrical and Computer Engineering, Babol Noshirvani University of Technology, Babol, Iran.

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*Corresponding Author's Email Address:
zahabi@nit.ac.ir

Abstract

Background and Objectives: Non-orthogonal multiple access (NOMA) is a promising solution to meet a high data rate demand in the new generation of cellular networks. Moreover, simultaneous wireless information and power transfer (SWIPT) was introduced to enhance the performance in terms of energy efficiency. In this paper, a single-cell cooperative NOMA system with energy harvesting full-duplex (FD) relaying is proposed to improve the sum rate and energy efficiency.
Methods: A downlink model consisting of a base station (BS), two cell-center users (nearly located users), and two cell-edge users (far located users) are considered. In each signalling interval, the BS transmits a superposition signal of cell-center and cell-edge users based on the power domain (PD) NOMA strategy. Employing a relay selection criterion, a cell-center user is paired with a cell-edge user and acts as an FD decode and forward (DF) relay to improve the cell-edge user performance. An energy harvesting (EH) model is considered where a power splitting (PS) protocol is adopted at the relay node. The other cell-center user saves the harvested energy from the BS to exploit in the subsequent signalling intervals. Two problems of power allocation for sum rate and energy efficiency maximization in constraints of the minimum required data rate for each user and maximum transmit power at the BS are formulated for the proposed scheme. Due to the non-convexity, the optimization problems are transformed and approximated to the convex optimization problems and solved by iterative algorithms. Difference of convex (DC) programming is employed for solving the sum rate maximization problem where an effective combination of DC programming, bisection method, and Dinkelbach algorithm is utilized for dealing with the energy efficiency maximization problem.
Results: The sum rate and energy efficiency over maximum available power at the BS are presented. Also, the effects of the power splitting factor and the cell radius on the sum rate and energy efficiency are investigated. Moreover, a comparison with the OMA and NOMA schemes is studied for the different minimum required data rates.
Conclusion: Simulation results validate that the proposed scheme outperforms the OMA and NOMA schemes in terms of sum rate in all SNR regimes. Moreover, the energy efficiency of the proposed scheme achieves considerably better performance than OMA for all SNR values and obtains remarkable better performance than NOMA in most SNR values.

Introduction

With the rapid growth of wireless communications and the density of the cellular systems due to the appearance of the Internet of Things (IoT) and machine-type communications, demands for much greater data rates and efficient allocation of communication resources have been the vital subjects. To address these aforementioned challenges, more efficient multiple access (MA) techniques have recently been proposed in 5G and beyond networks to achieve much higher system throughput and massive connectivity. Accordingly, non-orthogonal multiple access (NOMA) was introduced to make highly efficient use of the resources and serve multiple users at the same time, frequency, or code resources. In fact, the NOMA applies the superposition coding where a specific user performs the successive interference cancellation (SIC) to attain its information symbols [1]. It does this by initially decoding the signal(s) of the users with higher power levels, subtracting it from the superposed signal, and then decoding the difference as the user with a lower power level [2]. In contrast to conventional power allocation schemes, the NOMA users with weaker channel conditions are allocated more transmission power for successfully decoding their information symbols. It has been shown in [3] that the downlink NOMA with SIC can improve both the capacity and cell-edge user's throughput. In [4], the ergodic capacity maximization problem and then an optimal power allocation for multiple-input–multiple-output (MIMO) NOMA systems were proposed.

Recently, the user-cooperative relaying has been introduced into the NOMA transmission [5]-[7]. This scenario allows the users with stronger channel conditions to act as a relay for the users with weaker channel conditions. A cooperative NOMA scheme to further boost the performance of the system was proposed in [8]. Also, in [9], a downlink cooperative NOMA scenario is considered, where the base station communicates with multiple mobile users simultaneously with the help of a half-duplex amplify-and-forward (AF) relay.

It is worth noting that a half-duplex cooperative scheme might lead to spectral efficiency loss. As a result, a full-duplex (FD) relaying scheme is a promising solution to deal with this loss. In fact, the combining of cooperative NOMA and FD is a solution that is effective in achieving better spectral efficiency. A cooperative NOMA network with FD relaying was used in [10], in which the system outage probability and ergodic rate were derived. Also, in [11] a NOMA scheme with a near user as an DF relay was proposed where the resource allocation for maximizing the performance in terms of energy efficiency was achieved. In [12], the outage probability, user data rate, and energy efficiency were derived in a cooperative NOMA network with FD relaying. In addition, the performance of a full duplex relay (FDR) assisted cognitive radio (CR) network employing the NOMA scheme was investigated in [13]. In [14], the performance of an FD cooperative NOMA relaying system in the presence of imperfect successive interference cancellation (ISIC) was analysed and evaluated.

On the other hand, the FD relay node consumes more energy for the relay transmission. Hence, reducing the energy consumption of battery-assisted FD relaying users to improve the system performance in terms of energy efficiency has attracted great attention in modern communication systems. Accordingly, we need a solution to consume less energy in an efficient manner. Energy harvesting (EH) is a promising technique that leads to saving energy in a wireless network and permits an improvement in terms of energy efficiency [15]. In this regard, simultaneous wireless information and power transfer (SWIPT) was investigated first in [16]. Accordingly, the authors proposed EH on the basis of time switching (TS) and power splitting (PS) [17].

The efficient combining of SWIPT with the NOMA technique is an effective solution that both improves the system performance and saves energy. Therefore, in [18] SWIPT was applied to a cooperative NOMA system in which power allocation and PS coefficients were optimized by maximizing the energy efficiency. Also, studying a wireless-powered uplink communication system with NOMA and time-allocation method was proposed to maximize individual data rates and to improve the fairness of all users [19]. Moreover, SWIPT was applied to cooperative NOMA networks where the NOMA users near the source acted as EH relays to help far users. The authors in [20] analysed the outage probability and system throughput for a cooperative NOMA network with SWIPT and considered the impact of the PS factor on the performance of the users. The NOMA system's performance with decode-and-forward based multiple EH relays over Nakagami−m fading channels has been investigated in [21]. In [22], the authors presented a two-layered cooperative energy heterogeneous NOMA network, where each base station is powered by both the usual grid and alternative energy resources. Moreover, a joint power optimization, user association, carrier scheduling, and dynamic transmission control in dual-hop/multihop backhaul configurations of reliable NOMA HetNets with EH capability was investigated in [23].

Moreover, some new references employing FDR with SWIPT have been applied in the NOMA transmissions. In [24], the performance of a NOMA network with SWIPT based battery-assisted energy harvesting FDR in terms of outage probability has been investigated. Furthermore, the performance of a wireless powered cooperative spectrum sharing system based on NOMA transmission and a non-linear EH model with the secondary transmitter in the FD mode was analysed in [25]. The effects of beamforming on the energy efficiency in an FD user-assisted cooperative NOMA system were investigated in [26]. An FD TS-SWIPT cooperative NOMA-based IoT relay system with perfect SIC (PSIC) and ISIC was proposed in [27], where one master IoT node acts as an FD DF relay to enhance a cell-edge user's performance.

It should be mentioned that the implementation of machine learning techniques such as multi-agent deep reinforcement learning [28] and deep neural network (DNN) [29]-[31] are suggested for optimal resource management. A novel and effective deep reinforcement learning (DRL)-based approach to addressing joint resource management in a practical multi-carrier NOMA system with ISIC was presented in [32]. Also [33] has investigated a user selection and dynamic power allocation scheme in the SWIPT-NOMA relay system with DNN to optimize the user access and power allocation simultaneously to maximize the sum rate. A machine learning solution to improve harvesting energy based on clustering users was proposed in [34]. However, employing the machine learning based techniques is beyond the scope of our proposed scheme and can be considered as a candidate solution for future works.

Motivation and Contributions

To the best of our knowledge, the NOMA-FD-EH references have focused only on two users' cooperative relaying NOMA, where a cell-center NOMA user act as an FD relay node for a cell-edge NOMA user or an FD relay station after decoding of the BS transmitted symbols; retransmits the information for two users based on NOMA protocol. In contrast to these references, we introduce a model with two cell-center relaying users and two cell-edge users, where all user terminals are served by a BS in a NOMA strategy. In this case, we need to solve an optimization problem with more than two parameters (four parameters) which leads to a more challenging and general problem. Moreover, a novel relaying user selection is employed, while in the previous works there is only one cell-center user, and the relay selection is not required. It is worth noting that the relay selection criterion is not only based on the channel condition but also depends on the harvested energy and hence has a novelty. The existence of more than one cell-center user allows the unselected cell-center user in each signalling interval saves the harvested energy and accordingly improves the energy efficiency. Also, the relay selection follows a user pairing which determines the edge-user that should be paired with the selected relaying user. It should be noted that this scenario can be extended to a model with multiple cell-center users and multiple cell-edge users by employing a new pairing strategy among cell-center and cell-edge users which can exhibit better the superiority of our proposed scheme and can be considered as an attractive scenario for future works.

In this paper, we present a cooperative power domain NOMA for a downlink cellular network that consists of a BS, two cell-center users, and two cell-edge users. The BS sends the information of all users based on the NOMA strategy and a selected cell-center node adopting the energy harvesting model acts as a full-duplex relay user for the cell-edge users. The main contributions of this paper are summarized as follows.

- A cooperative NOMA-FD-EH model is investigated for improving the sum rate and energy efficiency. To the best of our knowledge, it is the first time that multiple users at both cell-center and cell-edge are suggested. The cell-center users detect their own data in addition to the cell-edge users' data and become a candidate as relay nodes for the cell-edge users. As a result, the sum rate formulation and theoretical analysis of this system model are different and more complex than the previous researches that have not been studied yet.
- A novel criterion for relay selection is proposed based on both the channel conditions between the cell-center and cell-edge users and also harvested energy level of each cell-center user. Accordingly, a cell-edge user whose date should be retransmitted is paired with the cell-center relaying user. The other cell-center user saves the energy for subsequent transmissions.
- Due to the non-convexity of the optimization problems, a suboptimal approach is proposed to obtain the power allocation for the sum rate and energy efficiency maximization by iteratively solving the approximated convex problems. We use the difference of convex (DC) programming for solving the sum rate optimization problem while an effective combination of DC programming, bisection method, and Dinkelbach algorithm is employed to efficiently solve the energy efficiency optimization problem.
- The proposed scheme is compared with the OMA and NOMA schemes. The results show the superior performance of the proposed scheme over the OMA and NOMA strategies in terms of both the sum rate and energy efficiency.

The rest of the paper is organized as follows. The system model and problems' formulations are derived. Then, the optimization problems and suboptimal power allocation algorithms for the maximization of the system's sum rate and energy efficiency are developed, respectively. The proposed algorithms' performances are evaluated by simulations and finally, the conclusion of the paper is presented.

Notation: $\mathbb{E}[x]$ is the expectation value of x. Also, $|x|$ denotes the absolute value of the complex scalar x. Moreover, $\nabla f(x_0)$ indicates the gradient of $f(x)$ at point x_0.

System Model and Problem Formulation

Let us consider a wireless network consisting of one BS and four mobile users distributed in a cell. There are two users near the BS and two users at the far locations from the BS. The cell-center users can be candidate as relay nodes for the cell-edge users. The transmission power for the cell-center users is prepared based on employing the PS energy harvesting protocol. Both the BS and users are equipped with single transmit antenna and single receive antenna [14]. We assume that the cell-center users are operating in the FD mode. There is a direct link between BS and all mobile users but the coverage capability of BS for the edge users is potentially weak.

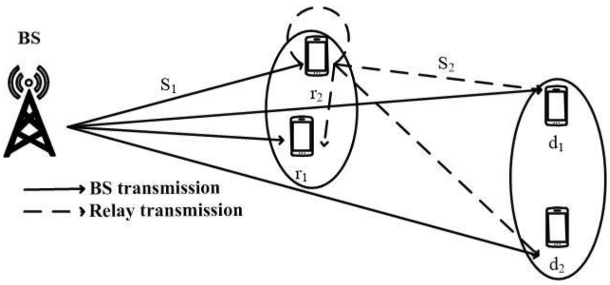

Fig. 1: System model.

The system model is presented in Fig. 1. In our system model, the BS transmits the superposition of all users' signals based on PD NOMA [35]. Since the NOMA users with strong channels can detect the messages of users with weak channels, the cell-center users (r_1 and r_2) are capable of detecting the cell-edge users' signals (d_1 and d_2) and also becoming a relay for retransmission of the cell-edge users' signals. It should be mentioned that the required power for retransmission at the relay is provided by EH in PS mode [17]. In each signalling interval, the selected cell-center user as relay node retransmits only one of the cell-edge users' signals to improve the system's performance. In other words, among the cell-center users, the one that has a maximum product of channel gain (to the cell-edge users) and harvested energy level is selected as a relay. Also, the cell-edge user whose data will be retransmitted is paired with the selected cell-center user based on the relay selection criterion.

Let h_{Bd_i} denote the channel coefficient between the BS and cell-edge user i $(i = 1,2)$ and h_{Br_i} exhibits the channel coefficient between the BS and the cell-center user $i (i = 1,2)$. Also, $h_{r_i d_j} | \, i, j \epsilon \{1,2\}$ denotes the channel coefficient between the cell-center users and the cell-edge users. The channel gains can be viewed as exponentially distributed random variables, providing that the channels are fading with Rayleigh distribution. Furthermore, $h_{r_1 r_2}$ represents the channel coefficient between two cell-center users. We assume the perfect channel state information where is obtained with negligible overhead before each signalling interval. In the proposed model, the superimposed signal transmitted by BS can be expressed as:

$$S_1(t) = \sum_{i=1}^{2} \sqrt{P_s \alpha_i} x_{r_i}(t) + \sum_{j=1}^{2} \sqrt{P_s \gamma_j} x_{d_j}(t) \quad (1)$$

where P_s denotes the BS transmit power and α_i and γ_j are the power allocation coefficients for ith cell-center user and jth cell-edge user, respectively. Also, $x_{r_i}$and x_{d_j} represent the signal of the ith cell-center user and jth cell-edge user, respectively. Without loss of generality, we consider that $|h_{Br_1}| \geq |h_{Br_2}| \geq |h_{Bd_1}| \geq |h_{Bd_2}|$, leading to power allocation coefficients in the descending order as $\gamma_2 \geq \gamma_1 \geq \alpha_2 \geq \alpha_1$ [35]. Moreover, the transmitted signal for users should be such that $\mathbb{E}\left\{\left|x_{r_i}\right|^2\right\} = 1 \, , i \epsilon \{1,2\}$ and also $\mathbb{E}\left\{\left|x_{d_j}\right|^2\right\} = 1 \, , j \epsilon \{1,2\}$.

Now, the criterion for the selection of the relaying user can be shown as follows:

$$r^* = \max_i \left\{ max \left(P_{r_i} \left| h_{r_i d_1} \right|^2, P_{r_i} \left| h_{r_i d_2} \right|^2 \right) \right\}, i \epsilon \{1,2\} \quad (2)$$

where P_{r_i} denotes the harvested power at the ith cell-center user. It should be noted that criterion (2) in addition to the selection of relaying node, jointly determines the cell-edge user whose data will be retransmitted. Then, without loss of generality and assuming that r_2 is selected for relaying the signal of user d_1, the received signal at the relay user for information processing can be represented as:

$$y_{r_2}(t) = \sqrt{\beta_{r_2}} h_{Br_2} \, S_1(t) + \sqrt{\beta_{r_2}} h_{r_2} S_2(t - \tau) + n_{r_2}(t) \quad (3)$$

where $\beta_{r_2}$and $n_{r_2}(t)$ denote power splitting factor and additive white Gaussian noise (AWGN) at the relay node, respectively. Also, τ represents the delays which is caused by the processing and SIC implementation at the relay node [11]. Furthermore, $S_2(t)$ is the retransmitted signal by the relay node after detecting the cell-edge users' signals which is given by:

$$S_2(t) = \sqrt{P_{r_2}} x_{d_1}(t) \quad (4)$$

where P_{r_2} is the harvested power at the relay node before retransmission. Moreover, the total harvested power of r_2 in each signalling interval can be described as [1]:

$$P_{r_2}^{\text{EH}} = \eta(1 - \beta_{r_2}) \mathbb{E} \left\{ \left| \frac{y_{r_2}(t)}{\sqrt{\beta_{r_2}}} \right|^2 \right\} \quad (5)$$

where $0 \leq \eta \leq 1$ is the energy conversion efficiency. After retransmission by the relay node and implementation of SIC and self-interference reduction, the Signal to Interference plus Noise Ratio (SINR) at r_2 is given by:

$$SINR_{r_2} = \frac{\left|h_{Br_2}\right|^2 P_s \alpha_2 \beta_{r_2}}{\frac{\left|h_{r_2}\right|^2}{\zeta} P_{r_2} \beta_{r_2} + \left|h_{Br_2}\right|^2 P_s \alpha_1 \beta_{r_2} + N_0} \quad (6)$$

where α_1 and α_2 denote the power, coefficients allocated to the r_1 and r_2, respectively and N_0 represents the noise power. Furthermore, ζ denotes the self-interference (SI) reduction factor defined as the ratio of the SI powers before and after SI suppression [11]. Also, h_{r_2} represents the SI leakage channel of the relaying user [11] (where the SI cancellation is considered to be perfect).

Moreover, the received signal at the unselected relay (r_1) for information processing is given by:

$$y_{r_1}(t) = \sqrt{\beta_{r_1}} h_{Br_1} S_1(t) + \sqrt{\beta_{r_1}} h_{r_1 r_2} S_2(t-\tau) + n_{r_1}(t) \tag{7}$$

Considering β_{r_1} denotes the power splitting factor, the total harvested power at r_1 in each signalling interval can be expressed as [1]:

$$P_{r_1}^{\mathrm{EH}} = \eta(1-\beta_{r_1})\mathbb{E}\left\{\left|\frac{y_{r_1}(t)}{\sqrt{\beta_{r_1}}}\right|^2\right\} \tag{8}$$

Also, the SINR at the unselected cell-center user (r_1) with the strongest channel gain after SIC implementation and cancellation of the signal from the relaying user (according to the awareness of the cell-edge users' signals) is presented by:

$$SINR_{r_1} = \frac{|h_{Br_1}|^2 P_s \alpha_1 \beta_{r_1}}{N_0} \tag{9}$$

Now, we represent the received signal at two cell-edge users as follows:

$$y_{d_i}(t) = h_{Bd_i} S_1(t) + h_{r_2 d_i} S_2(t-\tau) + n_{d_i}(t), \quad i\epsilon\{1,2\} \tag{10}$$

After SIC implementation and cancellation of the signal of user d_2, the SINR at the cell-edge user d_1 is given by (assuming the phase of the transmitted signal from the relay node is shifted to co-phase the received signals from the relay node and the BS at d_1):

$$SINR_{d_1} = \frac{|h_{Bd_1}|^2 P_s \gamma_1 + |h_{r_2 d_1}|^2 P_{r_2}}{|h_{Bd_1}|^2 P_s (1-\gamma_1-\gamma_2) + N_0} \tag{11}$$

Furthermore, the SINR equation for detection of the other cell-edge user (d_2) signal is exhibited as follows:

$$SINR_{d_2} = \frac{|h_{Bd_2}|^2 P_s \gamma_2}{|h_{Bd_2}|^2 P_s (1-\gamma_2) + N_0} \tag{12}$$

In the following, we present the theoretical analyses for the sum rate and energy efficiency, respectively.

A. Sum Rate Analysis

In this section, we will discuss the performance of the proposed scheme and analyze the sum rate maximization with the constraints on the total consumption power and minimum rate requirement for each user. In the other word, the optimal power allocation will be calculated such that the proposed scheme achieves the best performance in terms of sum rate on the given constraints. Accordingly, the problem formulation in terms of sum rate optimization can be represented as follows:

$$\max_{p_1,\dots,p_4} R_{sum} = \sum_{i=1}^{4} R_i \tag{13}$$

$$s.t.\, C1: \sum_{i=1}^{4} p_i \le P_s^{max} \quad, p_1 \le p_2 \le p_3 \le p_4$$

$$C2 - C5: \quad R_i \ge R_i^{min} \ , i = 1,\dots,4$$

where:

$$\begin{aligned} R_1 &= \log(1+SINR_{r_1}) \\ R_2 &= \log(1+SINR_{r_2}) \\ R_3 &= \log(1+SINR_{d_1}) \\ R_4 &= \log(1+SINR_{d_2}) \\ p_1 &= \alpha_1 P_s \\ p_2 &= \alpha_2 P_s \\ p_3 &= \gamma_1 P_s \\ p_4 &= \gamma_2 P_s \end{aligned} \tag{14}$$

where $\{R_i, p_i, i = 1,2\}$ and $\{R_i, p_i, i = 3,4\}$ represent the achievable rate equations and power assignments to the cell-center ($r_1$and r_2) and cell-edge ($d_1$and d_2) users, respectively. Also, P_s^{max} is the maximum power at the BS and R_i^{min} indicates the minimum required data rate for R_i. Due to the existence of the power allocation parameters at both the numerator and denominator of the achievable rate equations, the cost function is not convex. As a result, the problem (13) in its original form is neither a convex nor quasi-convex problem. Nevertheless, we show that it can be transformed into a convex problem via a linear transformation of the optimization variables [36].

Now we introduce the following variable transformation: $q_i = \sum_{j=1}^{i} p_j$ for $i = 1,2,\dots,4$ or conversely $p_i = q_i - q_{i-1}$ for $i = 2,\dots,4$ and $p_1 = q_1$.

Assuming that $I_1 = N_0$, $I_2 = \frac{|h_{r_2}|^2}{\zeta} P_{r_2}\beta_{r_2} + N_0$, $I_3 = |h_{r_2 d_1}|^2 P_{r_2} + N_0$, $I_4 = N_0$ and $I_5 = N_0$ we will have:

$$\begin{aligned} R_1 &= \log\left(\frac{I_1 + |h_{Br_1}|^2 q_1 \beta_{r_1}}{I_1}\right) \\ R_2 &= \log\left(\frac{I_2 + |h_{Br_2}|^2 q_2 \beta_{r_2}}{I_2 + |h_{Br_2}|^2 q_1 \beta_{r_2}}\right) \\ R_3 &= \log\left(\frac{I_3 + |h_{Bd_1}|^2 q_3}{I_4 + |h_{Bd_1}|^2 q_2}\right) \\ R_4 &= \log\left(\frac{I_5 + |h_{Bd_2}|^2 q_4}{I_5 + |h_{Bd_2}|^2 q_3}\right) \end{aligned} \tag{15}$$

These functions are still non-convex and also non-concave, but with the help of the following presentation and conversion of the maximization problem to a minimization problem, it is possible to define the cost function as a difference of two convex functions and consequently, we will have a DC programming with the convex constraints [37]. In our model, the two convex functions are presented as follows:

$$F(\boldsymbol{q}) = -\Big[\log\Big(I_1 + |h_{Br_1}|^2 q_1\beta_{r_1}\Big) + \log\Big(I_2 + |h_{Br_2}|^2 q_2\beta_{r_2}\Big) + \log\Big(I_3 + |h_{Bd_1}|^2 q_3\Big) + \log\Big(I_5 + |h_{Bd_2}|^2 q_4\Big)\Big]$$
$$G(\boldsymbol{q}) = -\Big[\log\Big(I_2 + |h_{Br_2}|^2 q_1\beta_{r_2}\Big) + \log\Big(I_4 + |h_{Bd_1}|^2 q_2\Big) + \log\Big(I_5 + |h_{Bd_2}|^2 q_3\Big)\Big] \tag{16}$$

It is obvious that both functions are the sum of the several convex functions and as a result, will be convex. Based on variable transformation, the constraint $C1$ in (13) changes from $\sum_{i=1}^{4} p_i \le P_s^{max}$ to $\sum_{i=1}^{4} p_i = q_4 \le P_s^{max}$. In addition, $p_1 \le p_2$, $p_2 \le p_3$, and $p_3 \le p_4$convert to $q_1 \le q_2 - q_1$, $q_2 - q_1 \le q_3 - q_2$, and $q_3 - q_2 \le q_4 - q_3$, respectively. For the constraints $C2 - C5$, the logarithmic functions substitute with their corresponding linear forms. For example, the constraint $R_1 = \log\left(\frac{I_1+|h_{Br_1}|^2 q_1\beta_{r_1}}{I_1}\right) = \log\left(1 + \frac{|h_{Br_1}|^2 q_1\beta_{r_1}}{I_1}\right) \ge R_1^{min}$ easily converts to $q_1 \ge \frac{I_1\left(2^{R_1^{min}}-1\right)}{|h_{Br_1}|^2\beta_{r_1}}$ and so on for the constraints $C3 - C5$. Finally, based on (16) and the aforementioned substitutions, the problem (13) will be transformed to:

$$\begin{aligned}
&\min_{q_1,\dots,q_4}\ Q(\boldsymbol{q}) = F(\boldsymbol{q}) - G(\boldsymbol{q})\\
&s.t.\ C1{:}\ q_4 \le P_s^{max}\quad, q_1 \le q_2 - q_1 \le q_3 - q_2 \le q_4 - q_3\\
&C2{:}\ q_1 \ge \frac{I_1\left(2^{R_1^{min}} - 1\right)}{|h_{Br_1}|^2\beta_{r_1}}\\
&C3{:}\ q_1 \le 2^{-R_2^{min}} q_2 + \frac{\left(2^{-R_2^{min}} - 1\right) I_2}{|h_{Br_2}|^2\beta_{r_2}}\\
&C4{:}\ q_2 \le 2^{-R_3^{min}} q_3 + \frac{\left(2^{-R_3^{min}} I_3 - I_4\right)}{|h_{Bd_1}|^2}\\
&C5{:}\ q_3 \le 2^{-R_4^{min}} q_4 + \frac{\left(2^{-R_4^{min}} - 1\right) I_5}{|h_{Bd_2}|^2}
\end{aligned} \tag{17}$$

For analyzing and solving a DC programming problem, for function $G(\boldsymbol{q})$, we must have an approximation by its linear form as $G^n(\boldsymbol{q}) = G\left(\boldsymbol{q}^{(n)}\right) + \nabla G^T\left(\boldsymbol{q}^{(n)}\right)\left(\boldsymbol{q} - \boldsymbol{q}^{(n)}\right)$ where $G\left(\boldsymbol{q}^{(n)}\right)$ and $\nabla G^T\left(\boldsymbol{q}^{(n)}\right)$ are the value and gradient of the $G(\boldsymbol{q})$ at the point $\boldsymbol{q}^{(n)}$, respectively. Now, with the convexity of $F(\boldsymbol{q})$ and the linearity of $G^n(\boldsymbol{q})$, the cost function is convex. Therefore, due to the linear constraints ($C1 - C5$), the problem (17) is convex and can be efficiently solved via convex optimization methods. Algorithm 1 illustrates the process of sum rate optimization.

Algorithm 1 suboptimal power allocation in sum rate maximization problem

1. Set iteration number $n = 0$
2. **initialize** $\boldsymbol{q}^{(0)} = \boldsymbol{0}$
3. **Repeat** Steps (5) to (7) until $\left|Q\left(\boldsymbol{q}^{(n+1)}\right) - Q\left(\boldsymbol{q}^{(n)}\right)\right| \le \epsilon$
4. Set ${q_4}^{(n)} = P_s^{max}$ for any n
5. Define convex approximation of $Q^n(\boldsymbol{q})$ at $\boldsymbol{q}^{(n)}$ as $Q^n(\boldsymbol{q}) = F(\boldsymbol{q}) - G^n(\boldsymbol{q}) = F(\boldsymbol{q}) - G(\boldsymbol{q}^{(n)}) - \nabla G^T(\boldsymbol{q}^{(n)})(\boldsymbol{q} - \boldsymbol{q}^{(n)})$
6. Solve the convex problem
$$\boldsymbol{q}^{(n+1)} = \underset{\boldsymbol{q}}{argmin}\, Q^n(\boldsymbol{q})$$
$s.t.$ $C1 - C5$ of (17)
7. $n \leftarrow n + 1$

It should be mentioned that the value for q_4 will always be P_s^{max} in the minimization problem of (17), because the cost function is a decreasing function based on q_4. So, we assume in algorithm 1 that $q_4 = P_s^{max}$.

B. *Energy Efficiency Analysis*

In the following, the energy efficiency maximization can be defined and then solved. First, it is worth noting that we define energy efficiency as the achievable sum rate over total power consumption. The energy efficiency optimization problem is derived in (18) in which P_c indicates the circuit power consumption.

$$\begin{aligned}
&\max_{p_1,\dots,p_4} \sum_{i=1}^{4} R_i \Big/ \left(\sum_{i=1}^{4} p_i + P_c\right)\\
&s.t.\ \sum_{i=1}^{4} p_i \le P_s^{max}\quad, p_1 \le p_2 \le p_3 \le p_4\\
&R_i \ge R_i^{min}\ , i = 1,\dots,4 \qquad (R_i\ \text{based on (14)})
\end{aligned} \tag{18}$$

The energy efficiency problem is neither a convex nor quasi-convex problem. But, with the help of transformation similar to the sum rate analysis, it can be transformed into a problem such as the following form:

$$\begin{aligned}
&\min_{q_1,\dots,q_4}\ \left(M(\boldsymbol{q}) - N(\boldsymbol{q})\right)/(q_4 + P_c)\\
&s.t.\ C1{:}\ q_4 \le P_s^{max}\quad, q_1 \le q_2 - q_1 \le q_3 - q_2 \le q_4 - q_3\\
&C2{:}\ q_1 \ge \frac{I_1\left(2^{R_1^{min}} - 1\right)}{|h_{Br_1}|^2\beta_{r_1}}\\
&C3{:}\ q_1 \le 2^{-R_2^{min}} q_2 + \frac{\left(2^{-R_2^{min}} - 1\right) I_2}{|h_{Br_2}|^2\beta_{r_2}}\\
&C4{:}\ q_2 \le 2^{-R_3^{min}} q_3 + \frac{\left(2^{-R_3^{min}} I_3 - I_4\right)}{|h_{Bd_1}|^2}\\
&C5{:}\ q_3 \le 2^{-R_4^{min}} q_4 + \frac{\left(2^{-R_4^{min}} - 1\right) I_5}{|h_{Bd_2}|^2}
\end{aligned} \tag{19}$$

where,

$$M(\boldsymbol{q}) = -\Big[\log\Big(I_1 + |h_{Br_1}|^2 q_1\beta_{r_1}\Big) + \log\Big(I_2 + |h_{Br_2}|^2 q_2\beta_{r_2}\Big) + \log\Big(I_3 + |h_{Bd_1}|^2 q_3\Big) + \log\Big(I_5 + |h_{Bd_2}|^2 q_4\Big)\Big] \quad (20)$$

$$N(\boldsymbol{q}) = -\Big[\log\Big(I_2 + |h_{Br_2}|^2 q_1\beta_{r_2}\Big) + \log\Big(I_4 + |h_{Bd_1}|^2 q_2\Big) + \log\Big(I_5 + |h_{Bd_2}|^2 q_3\Big)\Big]$$

As can be observed, both functions $M(\boldsymbol{q})$ and $N(\boldsymbol{q})$ are convex functions resulting in a difference of the two convex functions at the numerator of the fractional cost function.

Similar to the sum rate optimization problem, we exploit the linear approximation of $N(\boldsymbol{q})$ such that $N^k(\boldsymbol{q}) = N\big(\boldsymbol{q}^{(k)}\big) + \nabla N^T\big(\boldsymbol{q}^{(k)}\big)\big(\boldsymbol{q} - \boldsymbol{q}^{(k)}\big)$ to achieve a convex function at the numerator. For exploiting the Dinkelbach [38], it is necessary to have a concave function at the numerator and a convex function at the denominator of the fractional cost function. The denominator is a linear function of the problem parameters and hence is a convex function. On the other hand, with the conversion of minimization problem to a maximization one, the numerator will be concave. Now, it is possible to solve the problem by using the Dinkelbach algorithm. On the basis of the Dinkelbach algorithm, the following objective function should be introduced:

$$H(\boldsymbol{q},\lambda) = \big(M(\boldsymbol{q}) - N(\boldsymbol{q})\big) - \lambda(q_4 + P_c) \quad (21)$$

where λ is a positive parameter. The optimal solution can be found by solving the problem parameterized by λ such that $H(\boldsymbol{q},\lambda) = 0$ [36]. Consequently, the optimization problem is transformed and given by:

$$\max_{q_1,\dots,q_4} H(\boldsymbol{q},\lambda) = \big(N(\boldsymbol{q}) - M(\boldsymbol{q})\big) - \lambda(q_4 + P_c) \quad (22)$$
$$s.t. \quad C1, - C5 \text{ of } (19)$$

Algorithm 2 illustrates the optimal power allocation in the energy efficiency maximization problem based on Dinkelbach approach. It should be noticed that considering $q_4 = P_s^{max}$ is not optimal anymore similar to sum rate optimization problem, because the numerator is a logarithmic function of q_4 while the denominator of the cost function is a linear function of q_4. Hence, the energy efficiency will not improve with the increasing the q_4 and hence we cannot employ the maximum value for q_4. But, knowing the fact that inequality $0 \le q_4 \le P_s^{max}$ is always established, it is possible to adopt the bisection algorithm to achieve q_4 and subsequently the other parameters based on algorithm 2. As a result, we employ the bisection with the combination of Dinkelbach algorithm to solve the optimization problem in (22).

Algorithm 2 suboptimal power allocation in energy efficiency maximization problem based on Dinkelbach algorithm

1. Set iteration number $k = 0$
2. **Initialize** $\boldsymbol{q}^{(0)} = \boldsymbol{0}$ **and** $\lambda^{(0)} = 0$.
3. Set ${q_4}_{LB}^{(0)} = 0$ and ${q_4}_{UB}^{(0)} = P_s^{max}$
4. **Repeat** Steps (5) to (12) until $\big|H\big(\boldsymbol{q}^{(k+1)}\big)\big| \le \epsilon_1$
5. **While** ${q_4}_{UB}^{(k)} - {q_4}_{LB}^{(k)} \ge \epsilon_2$ **do**
6. Set ${q_4}^{(k)} = \Big({q_4}_{LB}^{(k)} + {q_4}_{UB}^{(k)}\Big)/2$
7. Define convex approximation of $H^{(k)}(\boldsymbol{q})$ at $\boldsymbol{q}^{(k)}$ as $H^k(\boldsymbol{q}) = M(\boldsymbol{q}) - N^k(\boldsymbol{q}) - \lambda^{(k)}\big({q_4}^{(k)} + P_c\big) = M(\boldsymbol{q}) - N\big(\boldsymbol{q}^{(k)}\big) - \nabla N^T\big(\boldsymbol{q}^{(k)}\big)\big(\boldsymbol{q} - \boldsymbol{q}^{(k)}\big) - \lambda^{(k)}\big({q_4}^{(k)} + P_c\big)$
8. Solve the convex problem
   $$\boldsymbol{q}^{(k+1)} = \underset{\boldsymbol{q}}{argmax}\, H^k(\boldsymbol{q})$$
   $$s.t. \quad C1 - C5 \text{ of } (19)$$
9. **if** $R_1^{(k)} \le R_1^{min}$ **then**
   set ${q_4}_{LB}^{(k)} = \Big({q_4}_{LB}^{(k)} + {q_4}_{UB}^{(k)}\Big)/2$
   else
   set ${q_4}_{UB}^{(k)} = \Big({q_4}_{LB}^{(k)} + {q_4}_{UB}^{(k)}\Big)/2$
10. $\lambda^{(k+1)} = \big(M(\boldsymbol{q}) - N^{(k)}(\boldsymbol{q})\big)/\big({q_4}^{(k)} + P_c\big)$
11. **if** $R_1^{(k)} \le R_1^{min}$ **then**
    set ${q_4}_{LB}^{(k+1)} = {q_4}_{LB}^{(k)}$ and ${q_4}_{UB}^{(k+1)} = P_s^{max}$
    else
    set ${q_4}_{LB}^{(k+1)} = 0$ and ${q_4}_{UB}^{(k+1)} = {q_4}_{UB}^{(k)}$
12. $k \leftarrow k + 1$

In algorithm 2, LB and UB indices address the lower bound and upper bound, respectively.

Feasibility and Computational Complexity

As we know, a feasible solution for an optimization problem is a solution that satisfies all constraints that the program is subjected to, where it does not violate even a single constraint. In the sum rate optimization problem, the constraint on the maximum power of BS ($q_4 = P_s^{max}$) is always satisfied as equality. But it should be noted that for the satisfaction of the other constraints, inequalities $q_{i+1} \ge q_i$, $i = 1,2,3$ must be established. Hence, the feasibility occurs when these inequalities are satisfied that are dependent on the values of $\{R_i^{min}, i = 1, \dots, 4\}$, $\{I_i, i = 1, \dots, 5\}$, and also channels' gains. Moreover, another condition for the satisfaction of the constraints C_2 and C_3 is that $2^{-R_2^{min}} q_2 + \frac{\big(2^{-R_2^{min}} - 1\big) I_2}{|h_{Br_2}|^2 \beta_{r_2}} \ge \frac{I_1\big(2^{R_1^{min}} - 1\big)}{|h_{Br_1}|^2 \beta_{r_1}}$ to guarantee the accuracy of the obtained value for q_1. In the case of energy efficiency, conditions for the constraints are similar to the sum rate optimization, except that the constraint on the P_s^{max} must be satisfied in the form of inequality.

The computational complexity of the optimization problems depends on the utilized algorithms for solving the problems. Hence, we describe the complexity order for each employed algorithm in the proposed optimization problems. From the general convergence properties of the DC algorithm, it has a linear convergence and only relies on a few basic operations, which leads to a low computational cost [39]. In fact, the DC programming optimization problem can be solved by using standard algorithms from convex optimization theory such as the interior point method and sequential quadratic programming [37]. Therefore, the complexity of the DC algorithm within some tolerance measured by ϵ is in the order of $\mathcal{O}(\sqrt{N}\log(N/\epsilon))$ [40], where N is the number of optimization problem parameters. On the other hand, the bisection line search is known to find an ϵ-accurate solution within the number of iterations bounded by $\mathcal{O}(\log(\epsilon_0/\epsilon))$, where $\epsilon_0 = |b-a|$ is the initial difference between the upper and lower bounds in the bisection method. Therefore, the overall complexity is bounded by $\mathcal{O}(N\log(\epsilon_0/\epsilon))$, which is linear in N [41]. It is worth noting that in our problem, $N = 1$ for the bisection method; because only one of the parameters is obtained by bisection.

Moreover, the convergence rate of Dinkelbach algorithm is super linear [42]. Assuming upper and lower bounds of the maximum energy efficiency value are available as U and L, we could find the optimal values updating λ according to the bisection method, instead of using Dinkelbach's update criterion. Although bisection converges typically slower than Dinkelbach method [42], it provides an estimate of Dinkelbach algorithm. By using the bisection method, the overall asymptotic complexity can be found within a tolerance ϵ with $\mathcal{O}(N\log(\lceil(U-L)/\epsilon\rceil))$ iterations [42]. As can be seen, the employed algorithms have appropriate conditions from the complexity point of view.

Results and Discussion

Simulation results are illustrated in this section to validate our theoretical works in terms of sum rate and energy efficiency. We consider a single-cell scenario employing NOMA-FD-EH with the distributed users in the cell. It is assumed that the cell-center and cell-edge users are randomly distributed within a disk with radius 5 meters and a ring with radii 5 and 10 meters, respectively [43].

The Path loss exponent is considered as 2 [26] and the noise power N_0 is 0.25. Energy harvesting efficiency η is set to 0.5 [44], and the minimum target data rate (R_i^{min}) is equal for all users where is considered to be $R_i^{min} = 0.5\ bps/Hz$ and $R_i^{min} = 1\ bps/Hz$ [26] in the simulations. As we mentioned, energy harvesting is based on the PS method for which the power splitting factor is set to $\beta_{r_1} = \beta_{r_2}$. In addition, circuit power consumption is set to $P_c = 0.1$ Watt. The OMA and optimal NOMA (optimal four users NOMA scheme with sum power and minimum achievable rate constraints) are two techniques that are considered for comparison with the proposed scheme. It is worth noting that the simulations are generated from 100000 independent realizations of different channel conditions. Also, the iteration error tolerances ϵ_1 and ϵ_2 are 0.001 [26];

Fig. 2 illustrates the sum rate performance of the proposed scheme versus the splitting factor for different SNRs (the maximum available power at the BS to the noise ratio) and various minimum target data rates. It can be seen that the optimum splitting factors for both $R_i^{min} = 0.5\ bps/Hz$ and $R_i^{min} = 1\ bps/Hz$ are achieved at the low values of the splitting factor. It means that more harvested power leads to improving the sum rate performance, especially in low SNR regimes, where the BS power is low and hence the requirement to relaying is more sensible. On the other hand, with the reduction of the minimum target data rate, the sum rate increases. Moreover, the performance is approximately the same for the different splitting factors in the high SNR values. It should be noted that, when the splitting factor is very small and approximately all of the BS power is employed for relaying, the performance degrades a little; where the cell-center users' rates approach zero. These results are used in the following simulations.

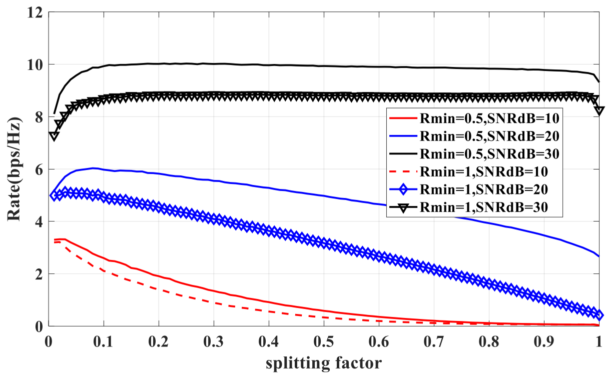

Fig. 2: Sum rate of the proposed scheme versus splitting factor for different SNRs and minimum target data rates ($R_i^{min} = 0.5, 1\ bps/Hz$).

In Fig. 3, the sum rate performance of the proposed scheme over SNR is compared with the OMA and optimal NOMA with the splitting factor of 0.15 in two cases as $R_i^{min} = 0.5\ bps/Hz$ and $R_i^{min} = 1\ bps/Hz$. As can be seen from this figure, the proposed scheme considerably outperforms the OMA and optimal NOMA schemes, especially in low SNR values for both minimum target data rates.

Also, the performance of the sum rate improves with the increase of SNR. On the other hand, it is obvious that the only proposed scheme has non-zero values in the SNR values less than 10dB, while the other schemes have zero values in this SNR regime.

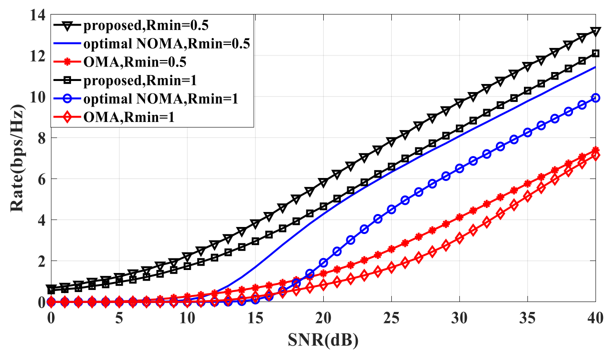

Fig. 3: Comparison of the proposed scheme with the OMA and optimal NOMA schemes in terms of sum rate over SNR for two minimum target data rates ($R_i^{min} = 0.5$,1 bps/Hz).

Fig. 4 illustrates the performance in terms of energy efficiency for the proposed scheme based on splitting factor for different SNRs and minimum target data rates where $R_i^{min} = 0.5\ bps/Hz$ and $R_i^{min} = 1\ bps/Hz$. For both minimum target data rates and with the increasing of the SNR, energy efficiency achieves higher values at the larger splitting factors. It means that in the low SNR regimes we need a smaller splitting factor and vice versa for achieving better performance. On the other hand, when the splitting factor has a high value and the harvesting is ignored, energy efficiency approaches zero in all cases. Moreover, the maximum energy efficiency in the case of $R_i^{min} = 0.5\ bps/Hz$ achieves with a larger splitting factor in comparison with the case $R_i^{min} = 1\ bps/Hz$.

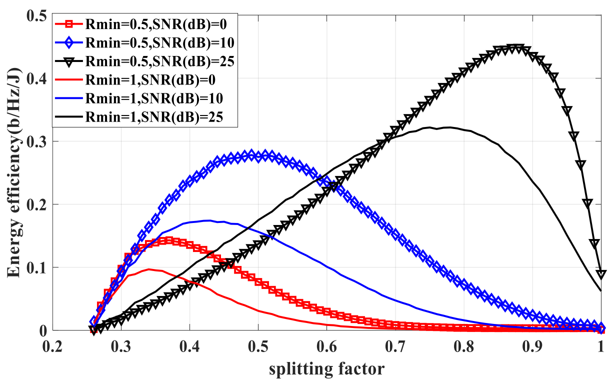

Fig. 4: Energy efficiency of the proposed scheme versus splitting factor for different SNRs and minimum target data rates ($R_i^{min} = 0.5$,1 bps/Hz).

As can be seen, there is no same optimum value for the splitting factor in all SNR regimes. As a result, we adopt a moderate value for the splitting factor to be employed in the energy efficiency.

In Fig. 5, the energy efficiency performance of the proposed scheme versus SNR is compared with the OMA and optimal NOMA in two cases as $R_i^{min} = 0.5\ bps/Hz$ and $R_i^{min} = 1\ bps/Hz$ with a splitting factor of 0.6 and 0.5, respectively. It can be seen from the figure that in both minimum target data rates the proposed scheme considerably outperforms the OMA in all SNR regimes and achieves higher values in comparison to the optimal NOMA in almost all ranges of SNR. However, in the very high SNR regimes, optimal NOMA approaches a constant value, while the proposed scheme has small values. This probably stems from that in the proposed scheme we don't subtract the harvested power of the unselected cell-center user in each signaling from the total BS transmit power. Moreover, based on the results in the Fig. 4 if we employed the smaller splitting factor, the performance would improve in the low SNR regimes and by utilizing the larger value for the splitting factor, energy efficiency would increase in the high SNR values.

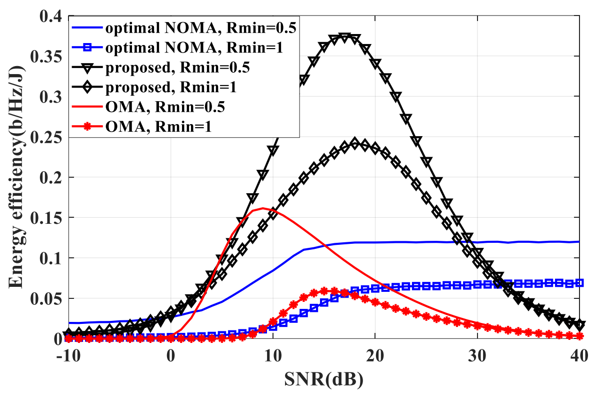

Fig. 5: Comparison of the proposed scheme energy efficiency with the OMA and optimal NOMA over SNR for $R_i^{min} = 0.5\ bps/Hz$ and $R_i^{min} = 1\ bps/Hz$.

Fig. 6 and Fig. 7 show the performances of the proposed, OMA, and NOMA schemes versus the the cell radius. It should be noted that all distances among nodes scale with the increase of the cell radius from 10 meters to 40 meters. Also, the minimum target data rates are set to $R_i^{min} = 0.5\ bps/Hz$ and $R_i^{min} = 1\ bps/Hz$ and SNR is considered as 20 dB for the sum rate and as 30 dB for the energy efficiency. Moreover, for the energy efficiency analysis in the Fig. 7, the splitting factors are considered as 0.6 and 0.5 for $R_i^{min} = 0.5\ bps/Hz$ and $R_i^{min} = 1\ bps/Hz$, respectively. As can be seen from the Fig. 6 and Fig. 7, increasing the cell radius leads to a decrease in the performance for both the sum rate and energy efficiency. However, the proposed scheme achieves better performance in terms of sum rate and energy efficiency for all cell radius values in both cases where $R_i^{min} = 0.5\ bps/Hz$ and $R_i^{min} = 1\ bps/Hz$. However increasing the cell radius up to 40 meters results in energy efficiency degradation for all schemes, the speed of this reduction is very slower in the proposed scheme. In addition, when the radius of the cell increases from 10 up to 15 meters, the performance of the proposed scheme improves. This likely stems from the less optimal transmitted power from the BS, because the sum rate decreases with the increase of the cell dimension.

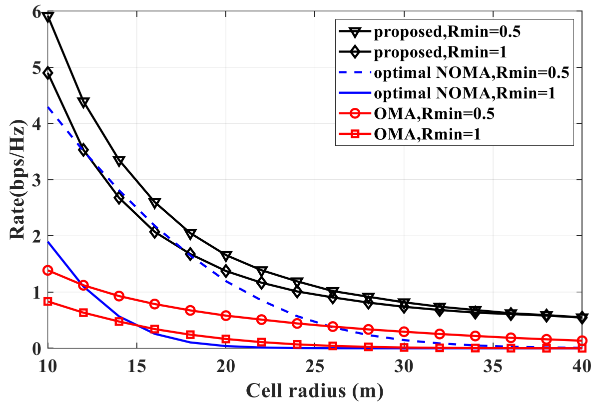

Fig. 6: Sum rate versus the cell radius for the proposed, OMA and optimal NOMA schemes with $R_i^{min} = 0.5\ bps/Hz$ and $R_i^{min} = 1\ bps/Hz$ and SNR of 20 dB.

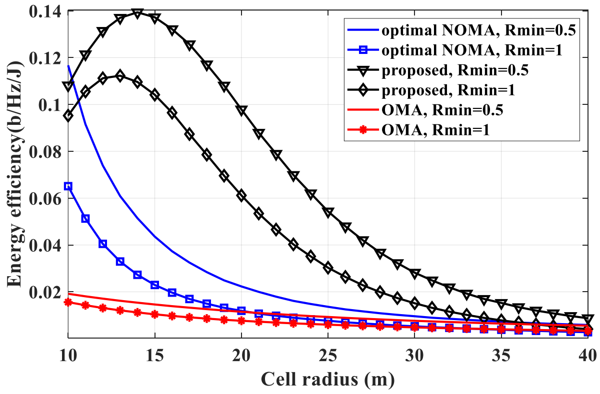

Fig. 7: Energy efficiency versus the cell radius for the proposed, OMA and optimal NOMA schemes with $R_i^{min} = 0.5\ bps/Hz$ and $R_i^{min} = 1\ bps/Hz$ and SNR of 30 dB.

Fig. 8 depicts the sum rate versus energy conversion efficiency for different SNRs and minimum target data rates as $R_i^{min} = 0.5\ bps/Hz$ and $R_i^{min} = 1\ bps/Hz$. It can be concluded from the figure that obviously approaching the η to the value of 1 improves the performance. It is worth noting that the same result is achieved for the energy efficiency over the value of η.

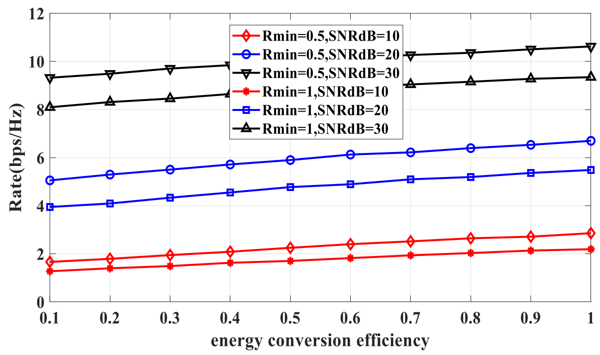

Fig. 8: Sum rate versus energy conversion efficiency for different SNRs and minimum target data rates as $R_i^{min} = 0.5\ ,1\ bps/Hz$.

Conclusion

This paper investigated a communication scheme, which efficiently combines cooperative NOMA, FD relaying, and EH techniques. Employing cooperative NOMA, the BS aims to broadcast the information to the mobile users that are distributed in a cell. Two users deployed in the near of the BS while two other users located at the far locations. In each signalling interval, one of the cell-center users is paired with a cell-edge user where the cell-center user employing PS protocol retransmits the cell-edge user's data. The DC programming and an efficient combination of DC, bisection method, and Dinkelbach algorithm were proposed to assign the suboptimal power allocations for maximizing the sum rate and energy efficiency performances, respectively. The numerical results demonstrated that when the SNR is 30dB, the square cell dimension is 10 meters, and $R_i^{min} = 1\ bps/Hz$, the proposed scheme using the appropriate values splitting factor significantly enlarges the system sum rate by 33% over optimal NOMA. This superiority approaches to 120% at SNR equal to 20dB. Moreover, the energy efficiency enhancement of the proposed scheme over optimal NOMA for $R_i^{min} = 1\ bps/Hz$, cell dimension equal to 10 meters, and SNR as 30dB and 20dB approach 200% and 40%, respectively. However, MIMO NOMA can be considered in the proposed schemes. Also, achieving the unequal optimal splitting factors is a suggestion for future works.

Author Contributions

This paper has been exploited from the M. B. Noori Shirazi's Ph.d. thesis supervised by M. R. Zahabi. M. B. Noori Shirazi and M. R. Zahabi proposed the main idea of the paper. M. B. Noori Shirazi performed the analyses and simulations and wrote the manuscript. M. R. Zahabi interpreted the results and corrected the manuscript.

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Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

Abbreviations

NOMA	Non-Orthogonal Multiple Access
BS	Base Station
PD	Power Domain
FD	Full-Duplex
DF	Decode and Forward

EH	Energy Harvesting
PS	Power Splitting
IoT	Internet of Things
SIC	Successive Interference Cancellation
MIMO	Multiple-Input–Multiple-Output
AF	Amplify-and-Forward
SWIPT	Simultaneous Wireless Information and Power Transfer
TS	Time Switching
FDR	Full Duplex Relay
CR	Cognitive Radio
ISIC	Imperfect Successive Interference Cancellation
PSIC	Perfect Successive Interference Cancellation
DC	Difference of Convex
SI	Self-Interference
SNR	Signal to Noise Ratio
SINR	Signal to Interference plus Noise Ratio

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Biographies

Mohammad Bagher Noori Shirazi received the B.S. degree in electrical engineering from University of Guilan, Rasht, Iran, in 2012, and M.S. degree in communications engineering from Khajeh Nasir Toosi University of technology, Tehran, Iran, in 2015. He is currently a Ph.D. student in the Department of Electrical and Computer Engineering, Babol Noshirvani University of Technology, Babol, Iran. His current research interests include wireless communications, cooperative based wireless networks, NOMA strategies and, energy harvesting protocols.

- Email: moh.noori.sh@gmail.com
- ORCID: 0000-0002-2900-8538
- Web of Science Researcher ID: NA
- Scopus Author ID: NA
- Homepage: NA

M. Reza Zahabi received his B.Sc. and M.Sc. degrees in electrical engineering from K.N. TOOSI University of Technology and Amir Kabir University of Technology, Tehran, Iran, respectively. He received his Ph.D. degree in 2008 in electrical engineering from Université de Limoges, France. Currently, he is a faculty member in Babol Noshirvani University of Technology. His current areas of interest are wireless communications, MIMO systems, 5G networks, coding protocols, and analog decoders.

- Email: zahabi@nit.ac.ir
- ORCID: 0000-0003-2811-8783
- Web of Science Researcher ID: NA
- Scopus Author ID: NA
- Homepage: https://ostad.nit.ac.ir/home.php?sp=370385

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