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Throughput Optimization Using Metaheuristic-Tabu Search in the Multicast D2D Communications Underlying LTE-A Uplink Cellular Networks

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Abstract: The sum throughput of a cellular network can be improved when nearby devices employ direct communications using a resource sharing technique. Multicast device-to-device (M-D2D) communication is a promising solution to accommodate higher transmission rates. In an M-D2D communication, a multicast group is formed by considering a transmitter that can transmit the same information to multiple receivers by considering the transmission link conditions. In this paper, we focus on the uplink interference generated due to the non-orthogonal sharing of resources between the cellular users and M-D2D groups. To mitigate the interference, we propose a spectrum reuse-based resource allocation and power control scheme for M-D2D communication underlying an uplink cellular network. We formulate the throughput optimization problem by considering the fractional frequency reuse (FFR) method within a multicell cellular network. In addition, a metaheuristic-tabu search algorithm is developed that maximizes the probability of finding optimal solutions by minimizing uplink interference. To analyze fairness resource distribution among users, we finally consider Jain's fairness index. Simulation results show that the proposed scheme can improve the coverage probability, success rate, spectral efficiency, and sum throughput of the network, compared with a random resource allocation scheme without a metaheuristic-tabu search algorithm.

Keywords: device-to-device communication; resource reuse; multicasting; metaheuristic-tabu search algorithm; coverage probability; throughput; spectral efficiency

1. Introduction

Due to the increasing demands for various types of high data rate services, cellular networks are facing the problem of resource limitations. For solving these problems, multicast device-to-device (M-D2D) communications underlying long-term evolution-advanced (LTE-A) cellular networks have become enormously favorable [1]. In M-D2D communication, nearby devices form an M-D2D group where D2D receivers in the group can receive the same data from the D2D transmitter over a direct link, without relying on the evolved node B (eNB). There are two approaches of M-D2D communications: With network assistance and without network assistance [2]. In the network-assisted M-D2D communications, M-D2D groups are placed in the coverage area of the eNB. Thus, the eNB maintains information to generate peer discovery, mode selection, scheduling, and so on. The key benefits of network-assisted M-D2D communications are: The reusing of resources between M-D2D groups and cellular users, and the reduction of power consumption. On the other hand, in M-D2D communications without network assistance, M-D2D groups are not placed in the coverage area of the eNB. The main limitation of the M-D2D communications without network assistance is that the D2D communication is prone to security issues. Moreover, M-D2D communications can be categorized into: Single rate and

multi-rate transmissions [3]. In the single-rate transmission, the D2D transmitter in a multicast group transmits the same data rate to its corresponding receivers. Whereas, in the multi-rate transmission, the D2D transmitter in a multicast group transmits multiple data rates according to the receiver's demands. Compared to a unicast (point-to-point) communication system, where a transmitter sends the signal to a single receiver, M-D2D communication reduces overhead and increases spectral efficiency. This concept is envisaged as the promising solution for the incoming 5G system and Internet of Things (IoT) technology. However, the system faces challenges in coordinating conventional cellular communication and D2D communication over a single resource simultaneously. The interference from the cellular user to D2D receivers in a multicast group and interference from the M-D2D transmitter to the eNB are incorporated as the main challenge. Therefore, there is a need for an effective solution that guarantees D2D communications will not generate deleterious interference to conventional users and also between M-D2D groups [4]. In [5], the authors proposed a multi-carrier code-division multiple access (MC-CDMA) transmission scheme in M-D2D communication. The results showed that their proposed scheme achieves a better signal-to-interference-plus-noise ratio (SINR) compared with a conventional scheme. Interference coordination mechanisms for M-D2D communication underlaying uplink cellular networks are discussed in [6]. A dynamic power control scheme was introduced to mitigate interference from M-D2D to a cellular network. Comparing the result of this scheme with that of a conventional multicast transmission scheme shows the improvement of the system throughput.

Cooperative relay-based D2D communications have attracted the interest of new mobile broadband communications systems. In relay-based D2D communications, nearby devices can communicate through multi-hops instead of a single hop over the eNB. Such communication technology can improve cell throughput and coverage for the users located far away from the eNB. In [7], an optimization problem was proposed to find the optimal solution by taking into account both the relay social-trust level and propagation link condition. The problem with this study is: Interference scenarios are not considered distinctly. Some new limitations with respect to D2D communications are high energy consumption and computational complexity. To reap low computational complexity, heuristic algorithms are rapidly gaining popularity as a promising solution. In D2D communications, heuristic algorithms can achieve an optimal solution by providing best resources' pairing between cellular users and D2D users. An energy-efficient multicast transmission for underlay D2D communications was proposed in [8] and a heuristic algorithm was introduced to incorporate both the energy constraint and social relationship. The multicast cluster formation was analyzed based on the social knowledge of the D2D communication underlaying a cellular network. However, in this scheme, the energy consumption of the conventional cellular users in the system was not analyzed. The work in [9] proposed an energy-efficient cluster-oriented solution for multimedia delivery in an LTE D2D environment. In their work, the performance of the battery lifetime and system energy consumption was evaluated. Energy harvesting with simultaneous wireless information and a power transfer technique with D2D communication was studied in [10], and the results showed that the proposed technique improved the coverage and energy efficiency.

Furthermore, the concept of content sharing and content delivery has recently acquired great interest to offload the traffic in the D2D communication system. For efficient content delivery in D2D communications, it is important to analyze the common interests and social relations of the users. In [11], D2D content delivery in a cellular network was proposed based on the dynamic arrival and departure nature of the content. Also, the multicast content delivery strategy was analyzed to improve the utilization rate and delivery efficiency. The authors in [12] designed a technique to efficiently deliver multicast traffic in a 5G network. The single-frequency operation technique was analyzed to improve the overall network energy efficiency. The results showed that their proposed method improved the network energy efficiency with respect to a conventional multicast scheme. However, due to single frequency operation, the network is not spectrally efficient.

In this paper, we discuss the problem of throughput optimization for M-D2D communications underlaying uplink cellular networks to achieve high throughput and spectrum efficiency. In particular, the main contributions of our work are summarized as follows:

- First, we consider a network-assisted M-D2D communications system that allows transmission of the same data to multiple receivers by reusing uplink cellular resources;
- as a promising solution of future cellular networks, we introduce the FFR technique to mitigate inter-cell interference between the cellular users and M-D2D groups, while sharing the resources between the cellular users and M-D2D groups. In the FFR scheme, the entire cell area is divided into two non-overlapping regions and both regions are served by the directional antennas. The FFR scheme can accommodate higher spectrum utilization, thus it can achieve higher throughput;
- we formulate the sum throughput optimization problem by simplifying the resource allocation method. Resource allocation is performed by assuming upper and lower bounds of the power level;
- we propose a low-complexity metaheuristic-tabu search algorithm to locate the most likely cellular users to find the optimal solution. Tabu search is an efficient metaheuristic technique that finds an optimal and near-to-optimal solution of diverse practical applications. In the metaheuristic-tabu search algorithm, a neighborhood function is defined to overcome the possibility of being trapped at a local optimum. The main benefits of proposing the metaheuristic-tabu search algorithm in our work are that it requires less computation time and is efficient for a large problem size network; and
- extensive analysis over various system parameters show that the proposed scheme can achieve the highest success rate, system throughput, and maximum utilization of the available system resources compared with other schemes.

The remainder of the paper is organized as follows. Section 2 presents related works. Section 3 provides the proposed scheme. Jain's fairness index is presented in Section 4. Section 5 provides the performance analysis for the outage probability, system throughput, and spectrum efficiency, and Section 6 draws the conclusions.

2. Related Works

Extensive studies on cellular resource allocation have been done in the literature. Some of the related works on fractional frequency reuse and multicast transmissions are concisely presented in the following.

2.1. Resource Allocation

An adaptive radio resource allocation scheme for multiple-input multiple-output orthogonal frequency-division multiplexing (MIMO-OFDM) based wireless multicast systems was proposed in [13]. A dynamic subcarrier and power control algorithm for the M-D2D group was discussed. The problem of this work is that the power control method introduced in the paper was not optimal. A joint resource allocation and power control scheme for an underlay M-D2D communication was studied in [14]. The paper discussed a maximum weight bipartite matching-based resource allocation scheme and heuristic-based resource allocation scheme. However, in this paper, the fractional frequency reuse (FFR) method was not used in the network. Therefore, the system performance is distorted due to the co-channel interference. In [15], a random linear network coding mechanism for M-D2D communication was presented. The paper discussed the short representation and law dependent probability that reduces the overhead for multicast transmission. However, the paper did not assume the distance dependent multicast transmission technique.

A multi-objective resource allocation scheme for M-D2D was studied in [16] to guarantee the quality of service (QoS) in a cellular network. In this study, the resource optimization problem was

formulated through maximizing system capacity and minimizing power consumption. Regarding the co-channel interference mitigation solution based on the resource allocation, many of the literature works exploit the knowledge of the resource reuse region in terms of its radius to perform interference-aware resource allocation [17]. Additionally, the paper considered the power control technique to maintain the transmit power of cellular users and D2D pairs, which reduces interference into a considerable rate. In [18], an interference-aware resource-sharing scheme was proposed for multiple D2D group communications underlaying cellular networks. In their work, the interference alignment for the D2D communications was analyzed based on the grouping method. Comparing the result of this scheme with that of the random resource sharing scheme demonstrates the improvement in cell throughput. In [19], the authors proposed a resource allocation scheme for M-D2D by considering content sharing in cellular networks based on the social behavior and physical characteristics. The optimization problem was formulated by considering cluster formation by considering the channel allocation method. However, this scheme is not spectrally efficient. In [20], the authors proposed a resource allocation scheme for multiple D2D cluster multicast communications. In their work, an outage probability problem was formulated by maintaining a certain QoS of the conventional cellular users. The results showed that their introduced scheme achieved near optimal sum effective throughput. The disadvantage of this scheme is that the network model considered only an omnidirectional antenna. Therefore, it cannot avoid severe interference.

2.2. Fractional Frequency Reuse

Many studies have shown that the utilization of cellular resources in fractional form for unicast D2D communications improves the utilization of available resources in a cellular network [21]. In the FFR method, the whole area of a cell is divided into two non-overlapping regions: A region near the eNB known as the cell inner region and a region far away from the eNB known as the cell outer region. The FFR scheme assures that the users of the adjacent cell do not interfere with each other while reusing the cellular frequency by the D2D pairs. Co-channel interference and inter-cell interference are the main challenges while reusing cellular frequency resources in D2D communications underlaying cellular networks. This type of interference cannot be mitigated if there is an absence of a dedicated spectrum band for each section of the cell. For example, allocating a dedicated spectrum to users close to the eNB and allocating a different spectrum band to users far away from the eNB.

In the literature, various methods have been discussed to mitigate these interferences. In [22], the authors proposed an SC-FDMA-based resource allocation scheme for D2D communication. In their work, the frequency reuse factor of three was analyzed to increase the system spectrum efficiency and capacity. The disadvantage of this scheme is that the system throughput goes to a steady state with the increase of the number of D2D pairs. In [23], the authors proposed a scalable D2D communications with a frequency reuse much greater than 1. In their study, scalable admission and power control methods were analyzed. The results showed that their proposed methods improve the network spectral efficiency. However, the network model considered only an omnidirectional antenna, thus it cannot mitigate inter-cell interference. The systematic frequency reuse mechanism with a frequency reuse factor of 2 was proposed in [24]. In this study, the authors focused on the distance based resource allocation and power control phenomenon. Comparing the result of the proposed resource allocation scheme with the FFR scheme for the frequency reuse factor of 1 improves the spectrum efficiency. An FFR scheme for D2D communication underlaying a cellular on wireless multimedia sensor networks was proposed in [25]. The authors discussed the non-orthogonal use of a cellular link by the D2D users to improve system throughput. In their network, the cell coverage was divided into six zones for interference management and the results showed that their proposed scheme improved the throughput and minimized the inter-cell interference.

2.3. Multicasting

With the introduction of M-D2D communications into conventional cellular networks, the door is opened to motivate various use cases. Some of the well-known applications of the M-D2D communication are media-rich applications, such as local multimedia content sharing of photos and music, and also high-quality video sharing applications, such as video multicasting in social platforms. The main issues and challenges in a multicast communications environment are summarized in [26]. The paper classifies the existing multicast protocols based on several distinct features and performance parameters. In [27], the authors discussed the modeling and analysis of M-D2D communication and an optimization problem was formulated based on the mobility and network assistance issues. Comparing the result of this scheme with that of the static network demonstrated the enhancement of the mean number of covered receivers. The problem with this study is that the interference coordination function was not applied. A millimeter wave (mmWave) small cell is becoming popular as a promising solution for D2D communications due to the availability of the abundant spectrum. In [28], the authors proposed an energy-efficient multicast scheduling scheme to achieve high energy efficiency. Also, the transmission power control method of the multi-hop D2D transmission paths was analyzed. The results showed that their proposed scheme improved the energy efficiency in the network. The disadvantage of their scheme is that the mmWave communications have high path loss problems. In [29], the authors proposed an optimized opportunistic multicast scheduling over wireless cellular networks. The homogeneous network was partitioned into rings and uses different channel links. An optimization problem was formulated to achieve the optimal solution and results showed that their proposed scheme achieved a significant performance gain.

3. Proposed Scheme

This section presents the proposed network model. Details of users' distribution have been given. The problem formulation is discussed later in this section. To make this paper easy to follow, we present some frequently used notations in the proposed scheme in Table 1.

Table 1. Notations used in the problem formulation.

Notation	Definition
R	Radius of outer region of cell
r	Radius of inner region of cell
P_B	Transmission power of eNB
$P_{g^{edge}}$	Transmission power of M-D2D group g^{edge}
$l_{c^{in},B}$	Distance between cellular user c^{in} and eNB
$l_{g_t^{edge},B}$	Distance between M-D2D transmitter g_t^{edge} and eNB
$l_{g_t^{edge},g_r^{edge}}$	Distance between M-D2D transmitter g_t^{edge} and receiver g_r^{edge}
$l_{c^{in},g_r^{edge}}$	Distance between cellular user c^{in} and M-D2D receiver g_r^{edge}
$l_{c^{in},B}^{min}$	Minimum possible distance of cellular user from the eNB
$H_{c^{in},B}$	Channel coefficient between cellular user c^{in} and eNB
$H_{g_t^{edge},B}$	Channel coefficient between M-D2D transmitter g_t^{edge} and eNB
$H_{g_t^{edge},g_r^{edge}}$	Channel coefficient between M-D2D transmitter g_t^{edge} and receiver g_r^{edge}
$H_{c^{in},g_r^{edge}}$	Channel coefficient between cellular user c^{in} and M-D2D receiver g_r^{edge}
α	Path loss coefficient
σ_n^2	Noise power
γ_{Th}	Minimum SINR requirement of a user defined by the system

3.1. Network Model

We consider a multi-cell network that has seven hexagonal-shaped cells in which eNB are placed at the center of the cell as shown in Figure 1a. Figure 1b shows the deployment of the available spectrum using the FFR method. In the FFR scheme, the cell coverage region is divided into two regions: Inner

and outer, which is covered by three 120° directional antennas. We consider two different radii for the inner and outer region of each cell to minimize the interference between cellular users and D2D users. Moreover, the network spectrum is partitioned into two bands, namely S_0 and S_1 . The spectrum band, S_0 , is used to serve users in the inner region and the spectrum band, S_1 , is used to serve users in the outer region. Additionally, these bands are divided into six equal sub-bands, namely $S_{0,0}$, $S_{0,1}$, $S_{0,2}$, $S_{1,0}$, $S_{1,1}$, and $S_{1,2}$. Figure 2 shows the M-D2D transmission model and uplink interference scenarios generated due to the integration of D2D communications into the conventional cellular networks. We consider whether the network allows both cellular communications and D2D communications at the same time.

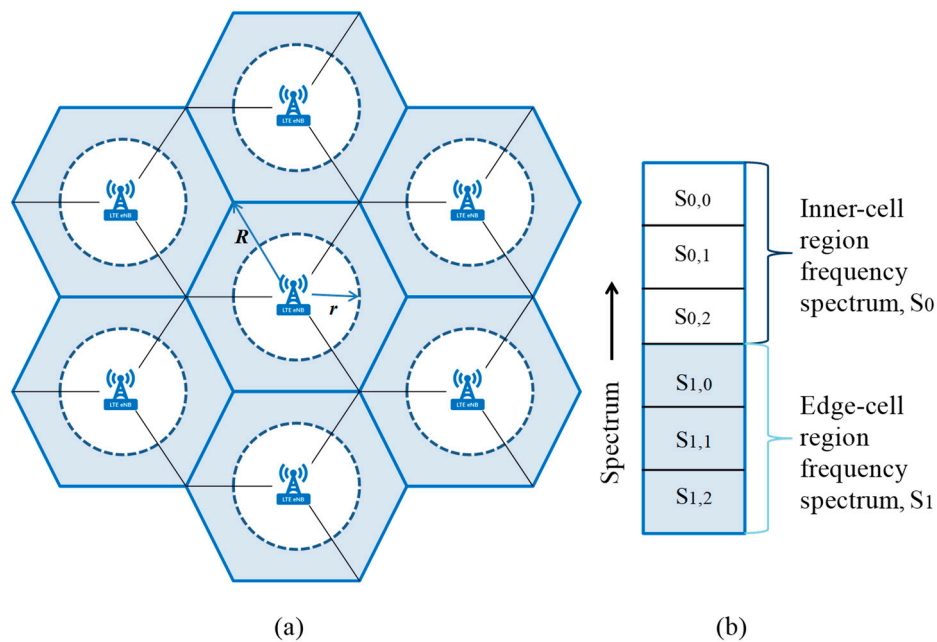


Figure 1. (a) The structure of the multi-cell D2D communication network; (b) spectrum partitioning.

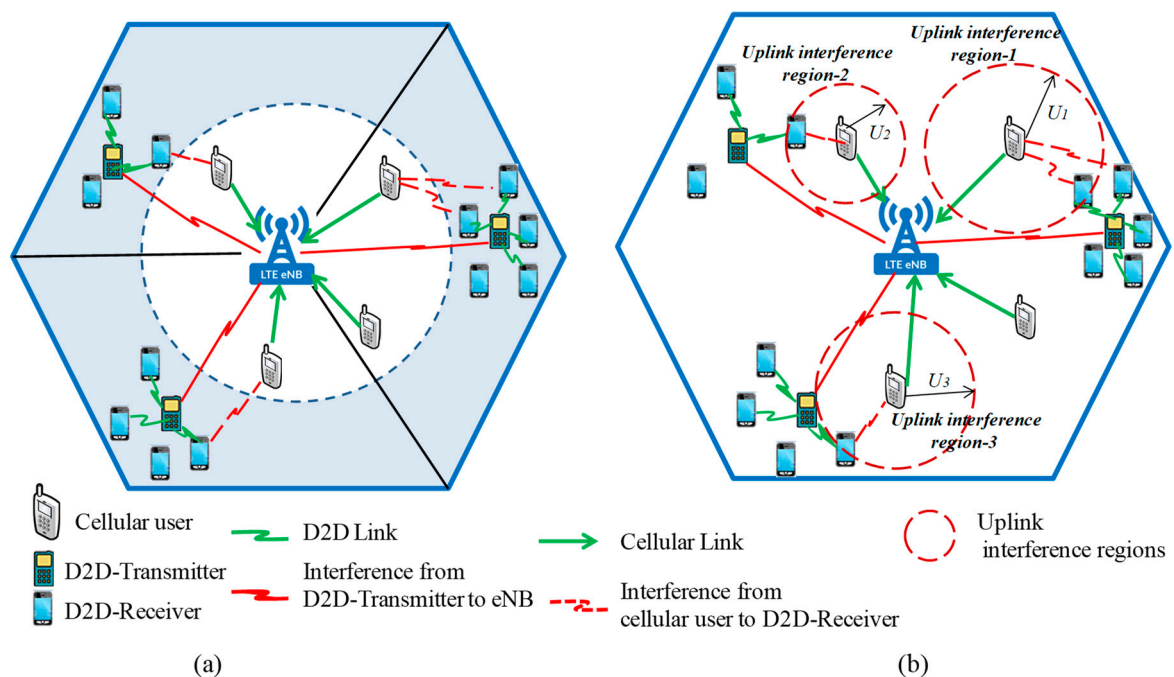


Figure 2. (a) M-D2D transmission by reusing uplink cellular resource; (b) uplink interference scenarios.

For easy analysis, we assume cellular users as primary users that can access the available resources assigned by the eNB and D2D users as the secondary users that can reuse the cellular resources to generate a transmission. Suppose in each cell there are totally N_C cellular users constituting a set, C , where $C = \{1, 2, \dots, N_C\}$, the total number of D2D users constituting a set, D , where $D = \{1, 2, \dots, N_D\}$, and the total number of M-D2D groups constituting a set, G , where $G = \{1, 2, \dots, N_G\}$. We assumed that all cellular users and D2D users are uniformly distributed in each cell. In each M-D2D group, we selected a D2D user as the multicast transmitter, which transmits the same signal to multiple receivers in the group. Thus, the total sum throughput increases with the number of successful communications of the group. We assumed that one M-D2D group can reuse only one cellular link at a time.

In the network model, we assume that the available resources are allotted to cellular users by the eNB in an orthogonal manner. Therefore, there is no intra-cell interference between the cellular users. For the resource reuse method, we assume that the M-D2D communication is allowed to reuse only the inner region cellular resource and the M-D2D group has to be located within the outer region of each cell. In order to calculate the number of resource blocks assigned to different sub-bands, it is necessary to analyze the density of cellular users in the inner region of each cell. Hence, the probability density function (PDF) of the cellular user, c^{in} , in polar coordinates $(l_{c^{in},B}, \theta)$ is expressed as [30]:

$$f(l_{c^{in},B}) = \frac{2(l_{c^{in},B} - l_{c^{in},B}^{min})}{(r - l_{c^{in},B}^{min})^2}, \forall l_{c^{in},B}^{min} \leq l_{c^{in},B} \leq r \quad (1)$$

and:

$$f(\theta) = \frac{1}{(\frac{2\pi}{3})}, \forall 0 \leq \theta \leq \frac{2\pi}{3} \quad (2)$$

where θ is the angle of the cellular user location and $l_{c^{in},B}$ is the distance between the cellular user, c^{in} , in the inner region of a cell and the eNB.

In the proposed scheme, we considered that the uplink interference of a cellular network is known and is defined by the matrix, \mathbf{I} , as:

$$\mathbf{I} = \begin{bmatrix} I_{1,1}, & I_{1,2}, \dots, & I_{N_G,1} \\ I_{1,2}, & I_{1,2}, \dots, & I_{N_G,2} \\ \vdots & \vdots & \vdots \\ I_{1,N_C}, & I_{1,N_C}, \dots, & I_{N_G,N_C} \end{bmatrix} \quad (3)$$

The main goal of this paper is to minimize the interference into the least value so as to improve the system performance. Considering the interference matrix, we assumed a communication scenario where an M-D2D group reuses the resource of a cellular user. Then, the resource assignment matrix, \mathbf{Z} , is defined as:

$$\mathbf{Z} = \begin{bmatrix} Z_{1,1}, & Z_{1,2}, \dots, & Z_{N_G,1} \\ Z_{1,2}, & Z_{1,2}, \dots, & Z_{N_G,2} \\ \vdots & \vdots & \vdots \\ Z_{1,N_C}, & Z_{1,N_C}, \dots, & Z_{N_G,N_C} \end{bmatrix} \quad (4)$$

To formulate the problem of an optimal resource allocation scheme, we assume one M-D2D group reuses at most one cellular resource, and each resource can be reused by at most one M-D2D group. That is:

$$\left. \begin{aligned} \sum_{c=1}^{N_C} Z_{c,g} &\leq 1, \forall g \in G \\ \sum_{g=1}^{N_G} Z_{c,g} &\leq 1, \forall c \in C \end{aligned} \right\} \quad (5)$$

It is important to note that the number of receivers in a group should be more than one; if the number of receivers in a group is equal to one then the system is in a unicast communication scenario.

In the system model, each cellular communication has a serving eNB and we considered that the D2D transmitters are reusing cellular links. Each D2D transmitter has the same signal for all the determined D2D receivers and the serving eNB has the knowledge of the multicast message of each D2D transmitter. In the proposed method, to guarantee the QoS requirements of the cellular users and D2D users, D2D users are allowed to reuse the resources only when the distance between cellular users and D2D users is far enough. If cellular users and D2D users are close to each other, considerable interference will generate.

3.2. Problem Formulation

To enhance the system performance, we minimized both co-channel interference and inter-cell interference. Thus, we can find the optimal resource sharing pair between cellular users and M-D2D groups. In the general case, to find the resource sharing partner for the M-D2D communications, we suppose in each cell, there are totally R_T uplink interference regions as shown in Figure 2b, constituting a set R_U , where $R_U = \{1, 2, \dots, R_T\}$. Within these regions, the D2D receivers are interfered with by cellular users, thus D2D communications cannot guarantee the system QoS [31]. Without loss of generality, in the proposed method, we assume one of the uplink interference regions, say uplink interference region-1, having the radius, U_1 . To avoid high interference from cellular users to D2D receivers, we should maintain an adequate distance between cellular users and M-D2D groups. Therefore, we assumed that the M-D2D groups in the cell outer-region can only reuse the resources of cellular users that exist in the cell inner-region. The reusing of cellular resource by the M-D2D groups in the same section of the cell is not allowed.

Proposition 1. The radius, U_1 , of the uplink interference region-1 can be expressed as:

$$U_1 = \frac{\gamma_{Th}^{\frac{2}{\alpha}} \cdot l_{cin,B} \cdot l_{g_t^{edge}, g_r^{edge}}}{l_{g_t^{edge}, B}} \quad (6)$$

where γ_{Th} is the threshold SINR.

Proof. The proof is presented in Appendix A. \square

In cellular communication, the received power, P_R , is the multiplication of the transmitted power, P_T , and channel gain, L , as:

$$P_R = P_T \times L \quad (7)$$

where $L = l^{-\alpha} \times |H|^2$. The term, l , is the channel distance and H is the channel coefficient. Therefore, we can express the SINR as:

$$\gamma = \frac{P_R}{I + \sigma_n^2} \quad (8)$$

where I is the interference in the network.

To maintain reliable transmission, in the proposed method, we assume that the M-D2D groups are located in the cell outer region and cellular users are located in the cell inner region. According to Figure 2, we can express the SINR of the cellular user, c^{in} , and the M-D2D group, g^{edge} , as:

$$\gamma_{c^{in}} = \frac{P_B \cdot l_{c^{in}, B}^{-\alpha} \cdot |H_{c^{in}, B}|^2}{P_{g^{edge}} \cdot l_{g_t^{edge}, B}^{-\alpha} \cdot |H_{g_t^{edge}, B}|^2 + I_{c, B} + \sigma_n^2} \quad (9)$$

and:

$$\gamma_{g^{edge}} = \frac{P_{g^{edge}} \cdot l_{s_t^{edge}, s_r^{edge}}^{-\alpha} \cdot |H_{s_t^{edge}, s_r^{edge}}|^2}{P_B \cdot l_{c^{in}, g_r^{edge}}^{-\alpha} \cdot |H_{c^{in}, g_r^{edge}}|^2 + I_{g,m} + \sigma_n^2} \quad (10)$$

where $I_{c,B}$ denotes co-channel interference from eNBs to the cellular user and $I_{g,m}$ denotes co-channel interference from D2D transmitters in the upper layers of the network to M-D2D receivers. We can express $I_{c,B}$ and $I_{g,m}$ as:

$$I_{c,B} = \sum_{n \neq c, n=1}^6 P_B \cdot l_{n,B}^{-\alpha} \cdot |H_{n,B}|^2 \quad (11)$$

and:

$$I_{g,m} = \sum_{m=1}^6 P_m \cdot l_{g,m}^{-\alpha} \cdot |H_{g,m}|^2 \quad (12)$$

3.3. Coverage Probability

Coverage probability is defined as the probability that a user can successfully transmit the signal from a transmitter to its corresponding receiver, with the SINR equal to or higher than the threshold SINR.

In other words, the coverage probability of a system is complementary of the outage probability. Therefore, the coverage probability, P^{Cov} , can be expressed as:

$$P^{Cov} = 1 - P^{Out} \quad (13)$$

where:

$$P^{Out} = \sum_{c^{in}=1}^{N_C} P_{c^{in}}^{Out} + \sum_{g^{edge}=1}^{N_G} P_{g^{edge}}^{Out} \quad (14)$$

where P^{Out} is the outage probability of the system.

Substituting $\bar{\gamma} = \frac{P_B \cdot l_{c^{in},B}^{-\alpha}}{\sigma_n^2}$ into Equation (9), we have:

$$\gamma_{c^{in}} = \frac{|H_{c^{in},B}|^2}{\frac{P_{g^{edge}} \cdot l_{s_t^{edge},B}^{-\alpha}}{P_B \cdot l_{c^{in},B}^{-\alpha}} \cdot |H_{s_t^{edge},B}|^2 + \frac{I_{c,B}}{P_B \cdot l_{c^{in},B}^{-\alpha}} + \frac{1}{\bar{\gamma}}} \quad (15)$$

Let $Y = \frac{\left(\frac{P_{g^{edge}} \cdot l_{s_t^{edge},B}^{-\alpha}}{P_B \cdot l_{c^{in},B}^{-\alpha}} + I_{c,B} \right)}{P_B \cdot l_{c^{in},B}^{-\alpha}}$, then according to [32], the outage probabilities for the cellular user, c^{in} ($P_{c^{in}}^{Out}$), can be expressed as:

$$P_{c^{in}}^{Out} = 1 - \frac{1}{1 + Y \cdot \gamma_{Th}} e^{(-\frac{\gamma_{Th}}{\bar{\gamma}})} \quad (16)$$

Substituting all the values of Y and $\bar{\gamma}$ in Equation (16), we have:

$$P_{c^{in}}^{Out} = 1 - \frac{1}{1 + \frac{\left(\frac{P_{g^{edge}} \cdot l_{s_t^{edge},B}^{-\alpha}}{P_B \cdot l_{c^{in},B}^{-\alpha}} + I_{c,B} \right) \gamma_{Th}}{P_B \cdot l_{c^{in},B}^{-\alpha}}} e^{(-\frac{\sigma_n^2 \cdot \gamma_{Th}}{P_B \cdot l_{c^{in},B}^{-\alpha}})} \quad (17)$$

Similarly, the outage probability of the M-D2D group, g^{edge} ($P_{g^{edge}}^{Out}$), in terms of their respective SINR can be expressed as:

$$P_{g^{edge}}^{Out} = 1 - \frac{1}{1 + \frac{(P_B \cdot l_{cin, sr}^{-\alpha} + I_{g,m}) \gamma_{Th}}{P_{g^{edge}} \cdot l_{st, sr}^{-\alpha} \gamma_{Th}}} e^{\left(-\frac{\sigma_n^2 \cdot \gamma_{Th}}{P_{g^{edge}} \cdot l_{st, sr}^{-\alpha} \gamma_{Th}}\right)} \quad (18)$$

Substituting Equations (17) and (18) into Equation (14), we have:

$$P^{Out} = \sum_{cin=1}^{N_C} 1 - \frac{1}{1 + \frac{(P_{g^{edge}} \cdot l_{st, B}^{-\alpha} + I_{c,B}) \gamma_{Th}}{P_B \cdot l_{cin, B}^{-\alpha} \gamma_{Th}}} e^{\left(-\frac{\sigma_n^2 \cdot \gamma_{Th}}{P_B \cdot l_{cin, B}^{-\alpha} \gamma_{Th}}\right)} + \sum_{g^{edge}=1}^{N_G} 1 - \frac{1}{1 + \frac{(P_B \cdot l_{cin, sr}^{-\alpha} + I_{g,m}) \gamma_{Th}}{P_{g^{edge}} \cdot l_{st, sr}^{-\alpha} \gamma_{Th}}} e^{\left(-\frac{\sigma_n^2 \cdot \gamma_{Th}}{P_{g^{edge}} \cdot l_{st, sr}^{-\alpha} \gamma_{Th}}\right)} \quad (19)$$

Therefore, Equation (13) can be listed as:

$$P^{Cov} = 1 - \left[\sum_{cin=1}^{N_C} 1 - \frac{1}{1 + \frac{(P_{g^{edge}} \cdot l_{st, B}^{-\alpha} + I_{c,B}) \gamma_{Th}}{P_B \cdot l_{cin, B}^{-\alpha} \gamma_{Th}}} e^{\left(-\frac{\sigma_n^2 \cdot \gamma_{Th}}{P_B \cdot l_{cin, B}^{-\alpha} \gamma_{Th}}\right)} + \sum_{g^{edge}=1}^{N_G} 1 - \frac{1}{1 + \frac{(P_B \cdot l_{cin, sr}^{-\alpha} + I_{g,m}) \gamma_{Th}}{P_{g^{edge}} \cdot l_{st, sr}^{-\alpha} \gamma_{Th}}} e^{\left(-\frac{\sigma_n^2 \cdot \gamma_{Th}}{P_{g^{edge}} \cdot l_{st, sr}^{-\alpha} \gamma_{Th}}\right)} \right] \quad (20)$$

The throughputs of the cellular user, c^{in} (T_{cin}), and the D2D group, g^{edge} ($T_{g^{edge}}$), can be respectively listed as:

$$T_{cin} = \log_2 \left(1 + \frac{P_B \cdot l_{cin, B}^{-\alpha} \cdot |H_{cin, B}|^2}{P_{g^{edge}} \cdot l_{st, B}^{-\alpha} \cdot |H_{st, B}|^2 + I_{c,B} + \sigma_n^2} \right) \quad (21)$$

and:

$$T_{g^{edge}} = \log_2 \left(1 + \frac{P_{g^{edge}} \cdot l_{st, sr}^{-\alpha} \cdot |H_{st, sr}|^2}{P_B \cdot l_{cin, sr}^{-\alpha} \cdot |H_{cin, sr}|^2 + I_{g,m} + \sigma_n^2} \right) \quad (22)$$

3.4. Throughput Optimization

Combined with the SINR expressions of both the cellular users and M-D2D groups, we formulated the overall throughput optimization problem as follows:

$$T = \arg_{c^{in} \in C, g^{edge} \in G} \max \left(\sum_{cin=1}^{N_C} T_{cin} + \sum_{g^{edge}=1}^{N_G} T_{g^{edge}} \right) \quad (23)$$

subject to:

$$\left. \begin{aligned} P_B^{min} \leq P_B \leq P_B^{max}, P_{g^{edge}}^{min} \leq P_{g^{edge}} \leq P_{g^{edge}}^{max}, \forall g^{edge} \in G, \\ \gamma_{Th} \leq \gamma_{cin}, \forall c^{in} \in C, \\ \gamma_{Th} \leq \gamma_{g^{edge}}, \forall g^{edge} \in G, \end{aligned} \right\} \quad (24)$$

where P_B^{min} and $P_{g^{edge}}^{min}$ denote the minimum transmit power of the eNB and M-D2D group, g^{edge} , respectively. P_B^{max} and $P_{g^{edge}}^{max}$ denote the maximum transmit power of the eNB and M-D2D group, g^{edge} , respectively. In the power control mechanism, the M-D2D transmitter in a group selects its transmission power such that the signal power at the destined receivers will be under a predefined range. From the optimization problem formulated in (23), we observed that the resource allocation and power control approach are closely related with each other. During resource pairing between cellular users and D2D users, the variation of the interference scenario can impact on the transmit power.

Proposition 2. The transmit power of the eNB and M-D2D group, g^{edge} , in Equation (24) can be recalculated as follows:

$$\left. \begin{aligned} P_B^{min} &\leq \frac{\sigma_n^2 \cdot \gamma_{cin}^{Th} \cdot \beta_{s_t, edge, B} \left(\beta_{s_t, edge, s_r} \cdot \gamma_{cin}^{Th} + \gamma_{g^{edge}} \right) + \gamma_{cin}^{Th} \cdot \beta_{s_t, edge, B} \cdot \gamma_{g^{edge}} \left(I_{B, c} \cdot \gamma_{cin}^{Th} \cdot \beta_{s_t, edge, s_r} + I_{g, m} \right)}{\left(\beta_{cin, B} \cdot \beta_{s_t, edge, s_r} - \gamma_{cin}^{Th} \cdot \beta_{s_t, edge, B} \cdot \gamma_{g^{edge}} \cdot \beta_{cin, s_r, edge} \right)} \leq P_B^{max} \\ P_{g^{edge}}^{min} &\leq \frac{\sigma_n^2 \cdot \gamma_{g^{edge}} \left(\beta_{cin, B} \cdot \gamma_{g^{edge}} + \gamma_{cin}^{Th} \cdot \beta_{cin, s_r, edge} \right) + I_{c, B} \cdot \gamma_{cin}^{Th} \cdot \gamma_{g^{edge}} \cdot \beta_{cin, s_r, edge}}{\left(\beta_{s_t, edge, s_r} \cdot \beta_{cin, B} - \gamma_{cin}^{Th} \cdot \beta_{s_t, edge, B} \cdot \gamma_{g^{edge}} \cdot \beta_{cin, s_r, edge} \right)} \leq P_{g^{edge}}^{max} \end{aligned} \right\} \quad (25)$$

Proof. The proof is presented in Appendix B. \square

The pseudo code of the proposed resource allocation is shown in Algorithm 1. The overall resource allocation mechanism includes optimal matching of sub-channel resources between cellular users and D2D groups and the SINR assignment. At the beginning of the sub-channel resource allocation, the eNB collects the information of all M-D2D groups and matches one sub-channel resource of the cellular user to the M-D2D group. This phenomenon repeats for all available M-D2D groups. The main objective of the optimal resource allocation is to improve the aggregate D2D throughput and achieve higher values of SINR. After the sub-channel resource allocation is completed, the optimal SINR is determined. Then, we calculated the outage probability in terms of the SINR for each M-D2D group and cellular user. Finally, we formulated the aggregate throughput optimization problem.

Algorithm 1 Pseudo code of the resource allocation algorithm**Initialization**

C: The set of cellular users

D: The set of D2D users

G: The set of D2D groups

Resource allocation**for** $c^{in} \in C, g^{edge} \in G$ **do**Calculate $\gamma_{c^{in}}, \gamma_{g^{edge}}$ Calculate $p_{c^{in}}^{Out}, p_{g^{edge}}^{Out}, p^{Out} = \sum_{c^{in}=1}^{N_C} p_{c^{in}}^{Out} + \sum_{g^{edge}=1}^{N_G} p_{g^{edge}}^{Out}$ **if** ($p^{Out*} \leq \arg_{c^{in} \in C, g^{edge} \in G} \min p^{Out}$) **then**Calculate $T_{c^{in}}, T_{g^{edge}}, T = \arg_{c^{in} \in C, g^{edge} \in G} \max(\sum_{c^{in}=1}^{N_C} T_{c^{in}} + \sum_{g^{edge}=1}^{N_G} T_{g^{edge}})$ **else if** ($p^{Out*} > \arg_{c^{in} \in C, g^{edge} \in G} \min p^{Out}$) **then**Recalculate $\gamma_{c^{in}}, \gamma_{g^{edge}}$ Recalculate $p_{c^{in}}^{Out}, p_{g^{edge}}^{Out}, p^{Out} = p_{c^{in}}^{Out} + p_{g^{edge}}^{Out}$ Recalculate $T_{c^{in}}, T_{g^{edge}}, T = \arg_{c^{in} \in C, g^{edge} \in N_G} \max(\sum_{c^{in}=1}^{N_C} T_{c^{in}} + \sum_{g^{edge}=1}^{N_G} T_{g^{edge}})$ **end if****end for****3.5. Computational Complexity**

In this sub-section, we analyze the computational complexity of our proposed algorithm. The complexity of the sub-channel resource allocation to cellular users and M-D2D groups is $O(N_C \times N_G)$. Then, $[N_D \times O(N_G)]$ is the complexity of the matching-based sub-channel resource allocation within the M-D2D group. These resource allocations are conducted in parallel. Therefore, the overall complexity of the proposed scheme is $[O(N_C \times N_G) + N_D \times O(N_G)]$. This is due to the exhaustive search for the resource reuse partner and hence makes the proposed scheme impractical for the dense networks. Therefore, in order to minimize the complexity of the proposed scheme, we proposed a metaheuristic-tabu search algorithm.

3.6. Metaheuristic-tabu Search Algorithm

The metaheuristic-tabu search algorithm is an optimization algorithm, which maintains a short term memory of the definite changes of the existent search procedure within a specific region. Thus, it prevents nullification of the definite changes in the next search steps and controls the embedded heuristic technique. In addition, this algorithm can reduce interference from cellular users to D2D users while reusing uplink cellular resources. The pseudo code of the metaheuristic-tabu search algorithm is given in Algorithm 2. The metaheuristic-tabu search starts with an initial viable solution and solves the optimization problem by managing the neighborhood exploration heuristic. Then, a tabu list is initialized with this initial solution. The tabu list is dynamic in nature and is used to browse the solution space efficiently, thus it prevents the cycling of search steps. If the tabu list is very long, then all moves will become forbidden. On the other hand, if the tabu list is very short, then the search mechanism ends up examining a local optimum.

The main factor that affects the tabu list is the size of the neighborhood of the current solution. Therefore, adjusting the length of the tabu list is considered as a critical approach in finding an optimal solution. Once the tabu list is full, previous elements of the list are removed and generate a neighborhood solution, which has the highest matching with the optimal solution for the newly added solution. If the neighborhood solution does not match with the current solution, then another solution that has the highest matching value becomes the best solution. In the literature, a tabu-search-based metaheuristic algorithm was presented to find the optimal solution for a scalable video coding multicast system [33]. The paper proposed a multicast transmission scheme by converting a simplified problem into a well-defined orienteering problem over relay-based wireless networks. The pseudo code of the

proposed metaheuristic-tabu search algorithm is presented in Algorithm 2. The tabu list structure considered in the proposed scheme followed the first-in-first-out (FIFO) mechanism.

Algorithm 2 Metaheuristic-tabu search algorithm

Initialization

E : The number of iterations

A : The initial solution % generate initial solution and stored in a temporary location

$COST_{best} \leftarrow COST(A)$

$B \leftarrow A$ % consider the initial solution as the best solution

$L_T \leftarrow \emptyset$ % initialization of TABULIST

Search for an optimal solution from the valid move

while TABUSEARCH()

do $V_{move} \leftarrow \{i \in E\}$, $V_{move} \notin L_T$ % find a valid move with an iteration

if $V_{move} \neq \emptyset$

then $C \leftarrow V_{move}$ % obtained a solution from the valid move

$L_T \leftrightarrow C \mid L_T \leftarrow C$ % exchanging or replacing new solution for all elements of TABULIST

CHECK $\{COST(C') \leq COST(C'')\}$ % select best solution among C' and C''

UPDATE TABULIST(A')

if $COST(A, A') < COST_{best}$

then $B \leftarrow A'$

$COST_{best} \leftarrow COST(A')$

$A \leftarrow A'$

return B

end

end

end

4. Jain's Fairness Index

A fairness distribution of resources is an important basis in designing cellular networks, where two or more devices must share the same sub-channel resource. In this section, we introduce Jain's fairness index to analyze the fair distribution of resources among M-D2D groups [24]. In the proposed scheme, while allocating a sub-channel resource to the M-D2D group, the receivers in the group should attain an aggregate throughput, $T_{g^{edge}}$. Therefore, in order to analyze the fair distribution of sub-channel resources, we introduce Jain's fairness index (JFI) for the system as follows:

$$JFI = \frac{\left| \sum_{g^{edge}=1}^{N_G} T_{g^{edge}} \right|^2}{N_G \cdot \sum_{g^{edge}=1}^{N_G} T_{g^{edge}}^2}, \forall g^{edge} \in G \quad (26)$$

Substituting Equation (22) in Equation (26), we have:

$$JFI = \frac{\left| \sum_{g^{edge}=1}^{N_G} \log_2 \left(1 + \frac{P_{g^{edge}} \cdot I_{s_t, s_r}^{-\alpha} \cdot |H_{s_t, s_r}^{edge}|^2}{P_B \cdot I_{c^{in}, s_r}^{-\alpha} \cdot |H_{c^{in}, s_r}^{edge}|^2 + I_{g,m} + \sigma_n^2} \right) \right|^2}{N_G \sum_{g^{edge}=1}^{N_G} \left(\log_2 \left(1 + \frac{P_{g^{edge}} \cdot I_{s_t, s_r}^{-\alpha} \cdot |H_{s_t, s_r}^{edge}|^2}{P_B \cdot I_{c^{in}, s_r}^{-\alpha} \cdot |H_{c^{in}, s_r}^{edge}|^2 + I_{g,m} + \sigma_n^2} \right) \right)^2}, \forall g^{edge} \in G \quad (27)$$

The value of JFI is confined between 0 and 1. If all M-D2D groups receive the same amount of resources, then JFI is 1, which means the overall resource allocation is 100% fair.

5. Performance Discussion

In this section, we present simulation parameters and several simulation results to verify the performance of the proposed resource sharing scheme.

5.1. Simulation Environment

We consider a multi-cell cellular network in which the available resources are allocated to the cellular users and there is no interference between the cellular users. The main simulation parameters are listed in Table 2. The path loss model for cellular users and D2D users are considered to be in the line of sight (LOS) model. In the proposed scheme, all the users are uniformly placed in a cell and each simulation result is analyzed by averaging over a large number of iterations. The proposed algorithm for M-D2D communications has been implemented in Matlab using Monte-Carlo simulation. Other simulation parameters are selected based on the 3rd generation partnership project evolved universal terrestrial radio access (3GPP E-UTRA) regulation [34].

Table 2. Main simulation parameters and values.

Parameters	Values
Noise power	−174 dBm/Hz
D2D grouping radius	1~50 m
Total number resource blocks	50 [34]
Link bandwidth	180 kHz
The maximum transmission power of D2D user	15 dBm
The maximum transmission power of cellular user	25 dBm
Number of D2D groups	20
Number of D2D receivers in a group	2~5
User distribution	Uniform
Channel bandwidth	10 MHz [34]
Path loss exponent	4

5.2. Simulation Results

In this subsection, we compare our proposed spectrum reuse-based throughput optimization for M-D2D communications against the random resource allocation scheme discussed in [20]. The study analyzed a cluster formation based resource allocation method, which allocates the resources randomly. For performance comparison, we level our proposed scheme as RA w/ MH-TS. Specifically, we denote our proposed resource allocation scheme before introducing the metaheuristic-tabu search algorithm as RA w/o M-TS. We denote the reference scheme [20] as RRA w/ MH-TS and RRA w/o MH-TS.

The variation of coverage probability of M-D2D users with respect to the threshold SINR is shown in Figure 3a. From Figure 3a, we can see that our proposed scheme attains the highest coverage probability as compared with other schemes. Moreover, we observe that as the threshold SINR increases the coverage probability decreases. Specifically, for all the methods, M-D2D users achieved 63.54% to 87.76% of the coverage probability at the threshold SINR of 5dB. Figure 3b depicts the variation of the coverage probability of cellular users with respect to the threshold SINR. It can be seen from Figure 3b that for all the methods, the cellular user with the metaheuristic-tabu search algorithm attained 65% to 86.84% of the coverage probability at the threshold SINR of -5dB. As shown in Figure 3a,b, the coverage probability becomes worse for both M-D2D and cellular users with the increase in the threshold SINR of the network. Finally, we observe that for the given threshold SINR, the coverage probabilities of M-D2D communications are greater than those for cellular communications. This is due to the fact that the communication distances in M-D2D communications are less.

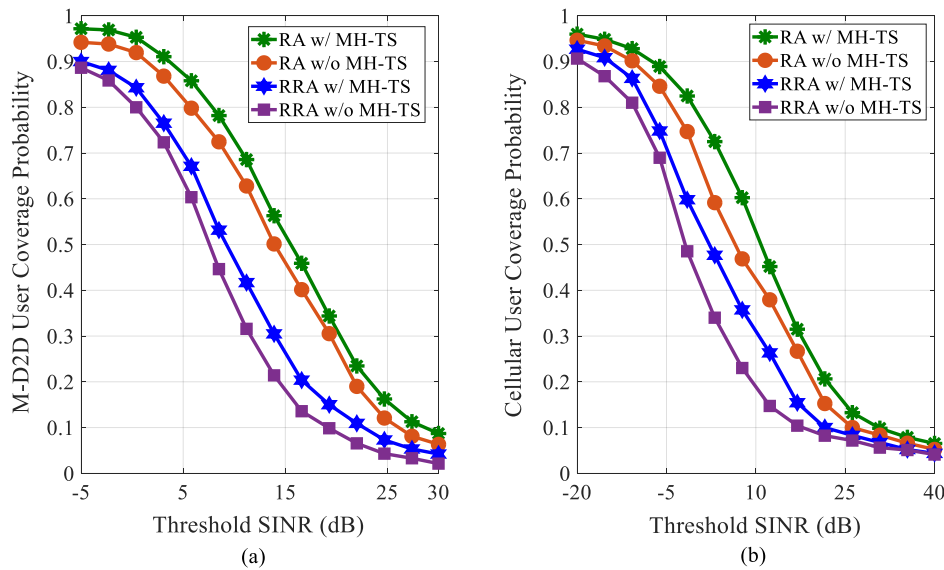


Figure 3. (a) Coverage probability of M-D2D user with varying threshold SINR, and (b) coverage probability of cellular users with varying threshold SINR.

The variation of the average throughput of M-D2D users as a function of the number of M-D2D groups in a cell is shown in Figure 4a. We observe that the throughput increases as the number of M-D2D groups in a cell increases. Moreover, it is seen that the throughput of our proposed resource allocation scheme shows a trend of a continuous increase. Therefore, we can conclude from our observation that the FFR technique was significantly employed for designing a high throughput cellular network. In Figure 4b, we plot the average throughput achieved by the cellular user as a function of the number of M-D2D groups in a cell. With the increase in the number of M-D2D groups in a cell, the cellular user throughput decreases. This is due to the fact that the M-D2D transmitter generates uplink interference to the eNB, which directly impacts on the performance of cellular users.

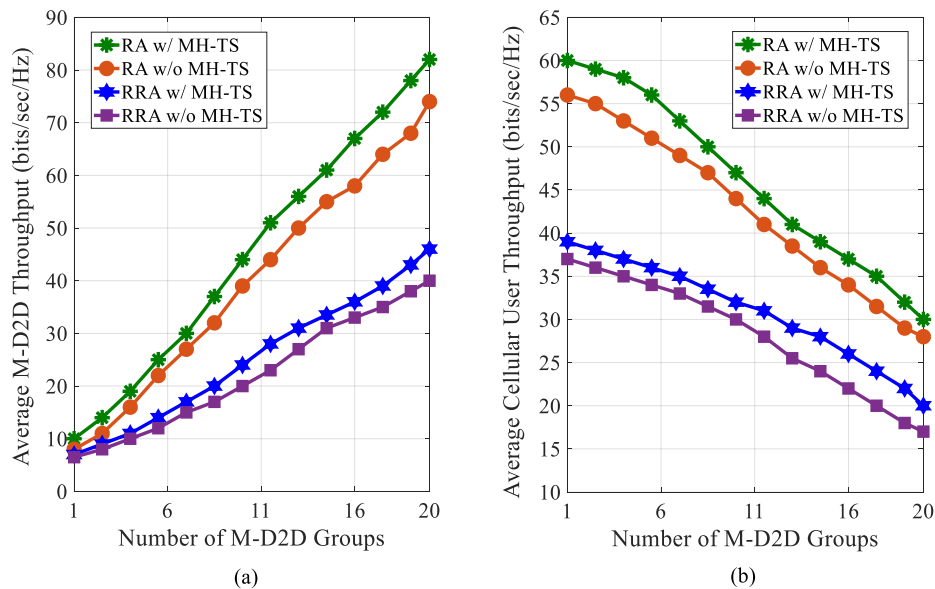


Figure 4. (a) Average throughput of M-D2D users as a function of the number of M-D2D groups in a cell; (b) average throughput of cellular users as a function of the number of M-D2D groups in a cell.

Figure 5a shows the received SINR of the M-D2D user with respect to the variable distance between M-D2D receivers and the cellular user. As shown in Figure 5a, the received SINR of M-D2D increases with the increase of the distance between M-D2D receivers and cellular users. This is due to

the fact that the larger the distance, the lower the aggregate uplink interference from cellular users to M-D2D receivers. As observed from Figure 5a, our proposed resource allocation and metaheuristic-tabu search scheme has the best performance compared with other schemes. The variation of the received SINR of cellular users with respect to the distance between the M-D2D transmitter and eNB is plotted in Figure 5b. As can be seen, the received SINR increases as the distance increases and, compared with the RRA scheme, our proposed scheme can accommodate high SINR.

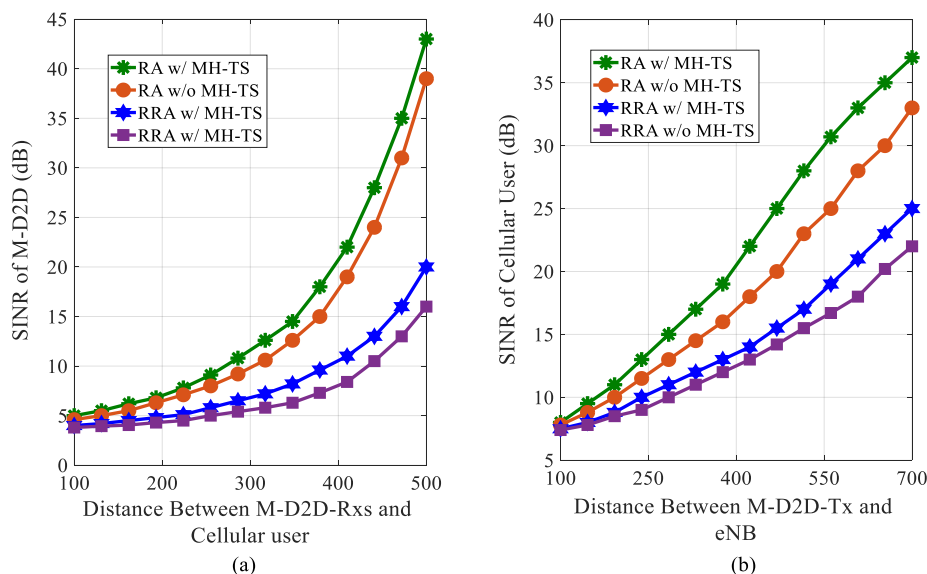


Figure 5. (a) Received SINR of M-D2D as a function of the distance between M-D2D receivers and the cellular user; (b) received SINR of a cellular user as a function of the distance between the M-D2D transmitter and eNB.

The total power consumption as a function of the distance between the D2D transmitter and its corresponding receivers in an M-D2D group is shown in Figure 6a. It is seen from Figure 6a that as the distance increases, the link quality decreases, therefore, the M-D2D transmitter must transmit data to its corresponding receivers with a higher transmission power. However, the overall power consumption of our proposed scheme is much lesser than the RRA scheme with and without the metaheuristic-tabu search algorithm. This is due to the fact that the metaheuristic-tabu search algorithm ignores certain repetitions while finding best resource reuse partners. Figure 6b shows the fairness of resource distribution against the distance between the D2D transmitter and receiver. For simple analysis, we assumed the optimal fairness index as 1. It can be seen from Figure 6b that as the distance between the D2D transmitter and receiver of a multicast group increases, the fairness index decreases drastically. We observe that our proposed scheme obtains a nearly optimal fairness index as compared with the existing scheme.

Figure 7a plots the spectral efficiency distribution of M-D2D users. Observed from Figure 7a, our proposed joint resource allocation and metaheuristic-tabu search algorithm has the best performance compared with other schemes. This is due to the fact that our proposed metaheuristic-tabu search algorithm finds the most promising resource sharing partner between cellular users and M-D2D users, which can reduce the total uplink interference. On the other hand, the RRA scheme without the metaheuristic-tabu search algorithm experiences lower spectral efficiency; this is due to the interference from cellular users to nearby M-D2D receivers. Finally, we notice that 70% of M-D2D users in our proposed scheme achieved a spectral efficiency of 71.08 bits/sec/Hz. The spectral efficiency distribution of cellular users is shown in Figure 7b. We can observe that our proposed scheme has the best throughput performance compared with existing schemes. This is because our proposed scheme aims at maximizing the user's throughput based on the resource partition technique. Also, from Figure 7b, it is seen that in the proposed communication scenario, 60% of users achieved

a spectral efficiency of 72.51bps/Hz. Finally, we notice that the spectral efficiencies of M-D2D users are greater than those for cellular users, due to generally smaller communication distances in M-D2D communications.

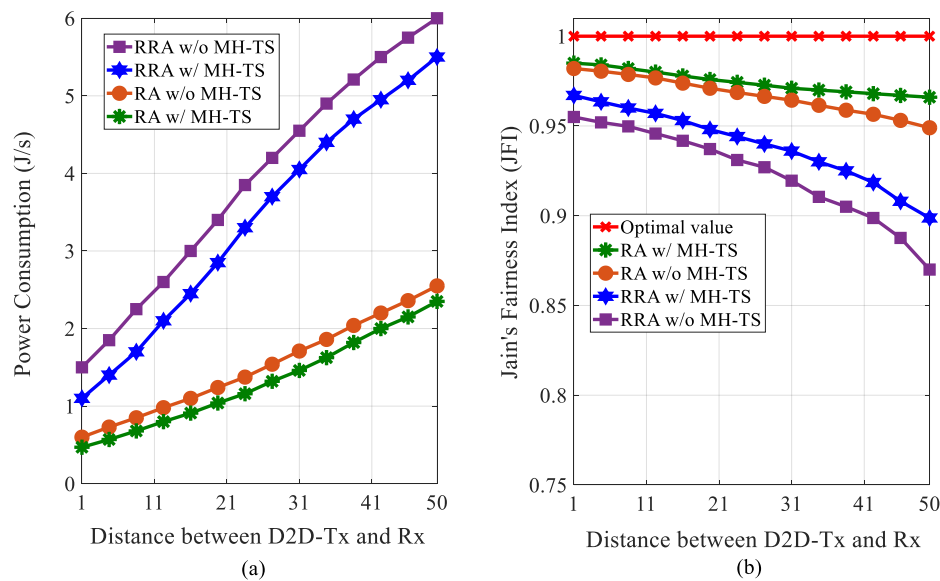


Figure 6. (a) Power consumption of the overall system as a function of the distance between the D2D transmitter and D2D receiver; (b) fairness as a function of the distance between the D2D transmitter and receiver.

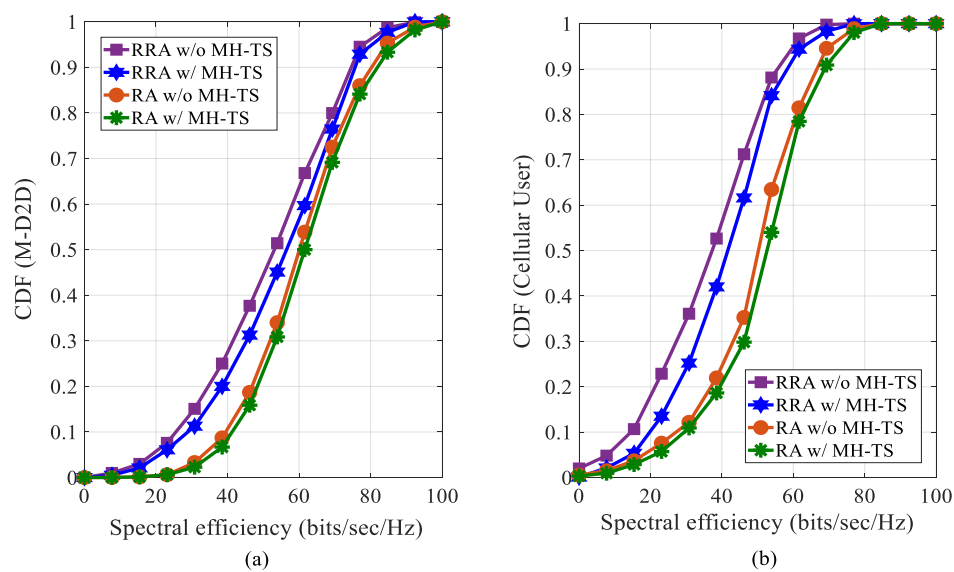


Figure 7. (a) Cumulative distribution of the spectral efficiency of an M-D2D user; (b) cumulative distribution of the spectral efficiency of a cellular user.

6. Conclusions

In this paper, we have considered joint resource allocation and the metaheuristic-tabu search algorithm for M-D2D communications reusing uplink cellular resources. The main drawback of M-D2D communications underlying a cellular network is the interference caused by D2D users to conventional cellular networks. To mitigate the interference, we proposed a spectrum reuse method based on the FFR technique. Then, to achieve higher system performance, we formulated a sum throughput optimization problem. However, the computational complexity of the optimization

problem was high due to the large number of iterations. To achieve low computational complexity, we introduced a metaheuristic-tabu search algorithm. Moreover, the fairness of the resource allocation was analyzed by using an efficient Jain's fairness index, which maintained a level of the required SINR. For analysis, we assumed the optimal value of the fairness index as 1. We performed extensive simulations in terms of the target SINR, the distance between the D2D transmitter and receiver, threshold SINR, and number of successful D2D receivers in an M-D2D group. We compared our proposed scheme with the RRA scheme with and without the metaheuristic-tabu search algorithm. The results demonstrated that our proposed scheme provides a good tradeoff between the interference mitigation and required throughput, thus it effectively increases overall system throughput and spectral efficiency. As a future work, this approach can be extended by assuming a resource reuse factor more than 1 for the M-D2D communications.

Author Contributions: D.D.N. organized and developed the proposal of the study, carried out the mathematical analysis, and performed simulations using Monte Carlo. S.S. provided guidance, key suggestions, and finalized the paper.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

For uplink interference region analysis, the general expressions of the received SINRs of a cellular user, c^{in} , and the D2D group, g , are calculated as follows:

$$\frac{P_B \cdot l_{c^{in},B}^{-\alpha}}{P_{g^{edge}} \cdot l_{g_t^{edge},B}^{-\alpha} + \sigma_n^2} \geq \gamma_{Th} \text{ and } \frac{P_{g^{edge}} \cdot l_{g_t^{edge},g_r^{edge}}^{-\alpha}}{P_B \cdot l_{c^{in},g_r^{edge}}^{-\alpha} + \sigma_n^2} \geq \gamma_{Th} \quad (A1)$$

Neglecting the noise power from Equation (A1), we have:

$$\frac{P_B \cdot l_{c^{in},B}^{-\alpha}}{P_{g^{edge}} \cdot l_{g_t^{edge},B}^{-\alpha}} \geq \gamma_{Th} \text{ and } \frac{P_{g^{edge}} \cdot l_{g_t^{edge},g_r^{edge}}^{-\alpha}}{P_B \cdot l_{c^{in},g_r^{edge}}^{-\alpha}} \geq \gamma_{Th} \quad (A2)$$

Solving Equation (A2), $l_{c^{in},g_r^{edge}}^{\alpha}$ can be expressed as:

$$\left. \begin{aligned} \frac{\gamma_{Th} l_{g_t^{edge},B}^{-\alpha}}{l_{c^{in},B}^{-\alpha}} &= \frac{l_{g_t^{edge},g_r^{edge}}^{-\alpha}}{\gamma_{Th} l_{c^{in},g_r^{edge}}^{-\alpha}} \\ l_{c^{in},g_r^{edge}}^{-\alpha} &= \frac{l_{g_t^{edge},g_r^{edge}}^{-\alpha} \cdot l_{c^{in},B}^{-\alpha}}{l_{g_t^{edge},B}^{-\alpha} \cdot \gamma_{Th}^2} \\ l_{c^{in},g_r^{edge}}^{\alpha} &= \frac{\gamma_{Th}^2 \cdot l_{g_t^{edge},B}^{-\alpha}}{l_{g_t^{edge},g_r^{edge}}^{-\alpha} \cdot l_{c^{in},B}^{-\alpha}} \end{aligned} \right\} \quad (A3)$$

Since the uplink interference region is defined by the distance between the cellular user and M-D2D receiver, we have:

$$U_1 = \frac{\gamma_{Th}^{\frac{2}{\alpha}} \cdot l_{c^{in},B} \cdot l_{g_t^{edge},g_r^{edge}}}{l_{g_t^{edge},B}} \quad (A4)$$

This completes the proof.

Appendix B

Substituting $\gamma_{cin} = \gamma_{cin}^{Th}$ and $P_B = P_B^{Th}$ in Equation (12), we have:

$$\gamma_{cin}^{Th} = \frac{P_B^{Th} \cdot l_{cin,B}^{-\alpha} \cdot |H_{cin,B}|^2}{P_{g^{edge}} \cdot l_{g_t^{edge},B}^{-\alpha} \cdot |H_{g_t^{edge},B}|^2 + I_{B,c} + \sigma_n^2} \quad (A5)$$

Let $\beta_{cin,B} = l_{cin,B}^{-\alpha} \cdot |H_{cin,B}|^2$ and $\beta_{g_t^{edge},B} = l_{g_t^{edge},B}^{-\alpha} \cdot |H_{g_t^{edge},B}|^2$, then Equation (A5) becomes:

$$\gamma_{cin}^{Th} = \frac{P_B^{Th} \cdot \beta_{cin,B}}{P_{g^{edge}} \cdot \beta_{g_t^{edge},B} + I_{B,c} + \sigma_n^2} \quad (A6)$$

$$P_{g^{edge}} = \frac{P_B^{Th} \cdot \beta_{cin,B}}{\gamma_{cin}^{Th} \cdot \beta_{g_t^{edge},B}} - \frac{I_{B,c}}{\beta_{g_t^{edge},B}} - \frac{\sigma_n^2}{\beta_{g_t^{edge},B}} \quad (A7)$$

From Equation (13), we have:

$$\gamma_{g^{edge}} = \frac{P_{g^{edge}} \cdot \beta_{g_t^{edge},g_r^{edge}}}{P_B \cdot \beta_{cin,g_r^{edge}} + I_{g,m} + \sigma_n^2} \quad (A8)$$

$$P_B^{Th} = \frac{P_{g^{edge}} \cdot \beta_{g_t^{edge},g_r^{edge}}}{\gamma_{g^{edge}} \cdot \beta_{cin,g_r^{edge}}} - \frac{I_{g,m}}{\beta_{cin,g_r^{edge}}} - \frac{\sigma_n^2}{\beta_{cin,g_r^{edge}}} \quad (A9)$$

Substituting Equation (A7) in (A9), we have:

$$P_{g^{edge}} = \frac{\left(\frac{P_{g^{edge}} \cdot \beta_{g_t^{edge},g_r^{edge}}}{\gamma_{g^{edge}} \cdot \beta_{cin,g_r^{edge}}} - \frac{I_{g,m}}{\beta_{cin,g_r^{edge}}} - \frac{\sigma_n^2}{\beta_{cin,g_r^{edge}}} \right) \cdot \beta_{cin,B}}{\gamma_{cin}^{Th} \cdot \beta_{g_t^{edge},B}} - \frac{I_{B,c}}{\beta_{g_t^{edge},B}} - \frac{\sigma_n^2}{\beta_{g_t^{edge},B}} \quad (A10)$$

$$P_{g^{edge}} \left(\beta_{g_t^{edge},g_r^{edge}} \cdot \beta_{cin,B} - \gamma_{cin}^{Th} \cdot \beta_{g_t^{edge},B} \cdot \gamma_{g^{edge}} \cdot \beta_{cin,g_r^{edge}} \right) = \sigma_n^2 \cdot \gamma_{g^{edge}} \left(\beta_{cin,B} \cdot \gamma_{g^{edge}} + \gamma_{cin}^{Th} \cdot \beta_{cin,g_r^{edge}} \right) + I_{B,c} \cdot \gamma_{cin}^{Th} \cdot \gamma_{g^{edge}} \cdot \beta_{cin,g_r^{edge}} \quad (A11)$$

$$P_{g^{edge}} = \frac{\sigma_n^2 \cdot \gamma_{g^{edge}} \left(\beta_{cin,B} \cdot \gamma_{g^{edge}} + \gamma_{cin}^{Th} \cdot \beta_{cin,g_r^{edge}} \right) + I_{B,c} \cdot \gamma_{cin}^{Th} \cdot \gamma_{g^{edge}} \cdot \beta_{cin,g_r^{edge}}}{\left(\beta_{g_t^{edge},g_r^{edge}} \cdot \beta_{cin,B} - \gamma_{cin}^{Th} \cdot \beta_{g_t^{edge},B} \cdot \gamma_{g^{edge}} \cdot \beta_{cin,g_r^{edge}} \right)} \quad (A12)$$

Similarly, from Equation (A9), we have:

$$P_B^{Th} = \frac{\left(\frac{P_B \cdot \beta_{cin,B}}{\gamma_{cin}^{Th} \cdot \beta_{g_t^{edge},B}} - \frac{I_{B,c}}{\beta_{g_t^{edge},B}} - \frac{\sigma_n^2}{\beta_{g_t^{edge},B}} \right) \cdot \beta_{g_t^{edge},g_r^{edge}}}{\gamma_{g^{edge}} \cdot \beta_{cin,g_r^{edge}}} - \frac{I_{g,m}}{\beta_{cin,g_r^{edge}}} - \frac{\sigma_n^2}{\beta_{cin,g_r^{edge}}} \quad (A13)$$

$$P_B^{Th} \left(\beta_{cin,B} \cdot \beta_{g_t^{edge},g_r^{edge}} - \gamma_{cin}^{Th} \cdot \beta_{g_t^{edge},B} \cdot \gamma_{g^{edge}} \cdot \beta_{cin,g_r^{edge}} \right) = \sigma_n^2 \cdot \gamma_{cin}^{Th} \cdot \beta_{g_t^{edge},B} \left(\beta_{g_t^{edge},g_r^{edge}} \cdot \gamma_{cin}^{Th} + \gamma_{g^{edge}} \right) + \gamma_{cin}^{Th} \cdot \beta_{g_t^{edge},B} \cdot \gamma_{g^{edge}} \left(I_{B,c} \cdot \gamma_{cin}^{Th} \cdot \beta_{g_t^{edge},g_r^{edge}} + I_{g,m} \right) \quad (A14)$$

$$p_B^{Th} = \frac{\sigma_n^2 \cdot \gamma_{c_{in}}^{Th} \cdot \beta_{s_t, B}^{edge} \left(\beta_{s_t, s_r}^{edge} \cdot \gamma_{c_{in}}^{Th} + \gamma_{s, edge} \right) + \gamma_{c_{in}}^{Th} \cdot \beta_{s_t, B}^{edge} \cdot \gamma_{s, edge} \left(I_{B, c} \cdot \gamma_{c_{in}}^{Th} \cdot \beta_{s_t, s_r}^{edge} + I_{g, m} \right)}{\left(\beta_{c_{in}, B} \cdot \beta_{s_t, s_r}^{edge} - \gamma_{c_{in}}^{Th} \cdot \beta_{s_t, B}^{edge} \cdot \gamma_{s, edge} \cdot \beta_{c_{in}, s_r}^{edge} \right)} \quad (A15)$$

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