Sub-Granting Radio Resources in Overlay D2D-Based V2V Communications

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RESEARCH

Sub-Granting Radio Resources in Overlay D2D-Based V2V Communications

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Abstract

Capacity, reliability, and latency are seen as key requirements of new emerging applications, namely Vehicle-to-Everthings (V2X) and Machine Type Communication (MTC) in future cellular networks. Device-to-Device (D2D) communication is envisaged to be the enabler to accomplish the requirements for the aforementioned applications. Due to the scarcity of radio resources, hierarchical radio resource allocation, namely the sub-granting scheme, has been considered for the overlay D2D communication. In this paper, we investigate the assignment of un-utilized radio resources to Device-to-Infrastructure (D2I) users, i.e., beneficiary user, for moving users in a dynamic environment. The sub-granting assignment problem is mathematically cast as the uplink cell throughput maximization problem. To this end, two heuristics are proposed: 1) Dedicated Sub-Granting Radio Resource (DSGRR) in a centralized manner, and 2) Open Sub-Granting Radio Resource (OSGRR) in a distributed fashion. Simulation results show improved cell throughput for the OSGRR compared with the DSGRR yet less overhead while having reasonable tightness to the maximum achievable uplink throughput.

Keywords: D2D communication; Radio resource allocation; Sub-granting scheme

Introduction

Capacity, reliability, and latency are the major requirements of applications for future wireless communications. D2D communication is foreseen as the first realization for the new emerging applications, e.g., vehicle to everything and machine type communication [2]. Due to the increasing demand for spectral efficiency and the massive number of users, efficient utilization of the spectrum has attracted attention in industry and academia. Radio resource management is one of the avenues that aid in addressing the scarcity of spectral efficiency in future cellular networks. *Overlay* and *underlay* are two radio resource allocation mechanisms that are considered for the integration of D2D in wireless communications. In the underlay technique, a D2I shares radio resources with D2D users. This approach increases spectral efficiency; however, it causes interference between D2D and D2I users. One solution to mitigate this interference is to assign dedicated radio resources to the D2D users, i.e., overlay. However, in this approach, the number of available radio resources for D2I users is reduced, and the allocated resources may not be sufficiently used by D2D users. To address this problem, authors in [3] proposed a new resource allocation technique based on energy sensing and mode selection, in which every user can measure received signal strength of each radio resource configured by evolved Node B (eNB). After that, the cellular user performs a D2I/ D2D mode selection based on the measured received signal strength in a distributed manner. In [4], further study was taken wherein both centralized and distributed radio resource allocations are studied. The authors proposed to allocate radio resources based on geographical areas so to improve spectral efficiency. Results reveal the superiority of the distributed algorithm in terms of the spectral efficiency for applications with periodic traffic compared with the centralized algorithm.

Typically, many new applications are characterized by small payload, and thus current subframe granularity in Long Term Evolution (LTE) is too coarse for the traffic payload in such applications [2]. As a result, a part of allocated resources is wasted, especially for the overlay radio resource allocation. In [5], a new idea of sub-granting has been proposed wherein the allocated but not fully utilized resources are granted in a finer granularity to the other nearby users, i.e., beneficiary users. Further studies have been conducted in [6] and [7] to improve the efficiency of the sub-granting scheme. In [6], the sub-granting and shortening Transmision Time Interval (TTI) are compared in terms of uplink cell throughput in a scenario with the users having a small traffic payload. The results show

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†A short and preliminary version of this work was presented in the conference publication [1].

that the uplink cell throughput degrades in the shortening TTI scheme compared with the sub-granting scheme when the radio resources are assigned to the D2D users in a semi-persistent manner. Inspired by this study, a new customized subframe in [7] is proposed by which better results in terms of overhead, uplink cell throughput, and latency can be achieved. In the previous works, it was assumed that a nearby beneficiary user with the highest modulation scheme is always available, which can utilize the sub-granting resources. Note that in a dynamic environment, multiple beneficiary users with different bandwidths and modulation coding schemes exist. Thus a higher spectral efficiency can be achieved when the sub-granting is granted to a full buffer beneficiary user with the highest modulation coding scheme. With this aim, a new DSGRR algorithm is suggested in [1]. Therein, the Base Station (BS) as a central controller chooses a beneficiary user for every D2D user, i.e., sub-grant provider, based on some criteria and accordingly informs the sub-grant provider about the candidate beneficiary users.

Consequently, the sub-grant provider disseminates the unused resources information along with the selected beneficiary user identity. Note that the Channel Quality Index (CQI) between the beneficiary and sub-grant provider users are unknown or can be measured at the cost of high signaling overhead on the cellular network. Henceforth, a new error-Limited Area (eLA) is proposed. The eLA is a geographical area wherein the beneficiary user can decode the sub-granting signaling reliably. In [1], a scenario where all users are stationary is considered. However, to have a precise eLA in a dynamic scenario, every entity should transmit the measurement information, e.g., positioning and Channel State Information (CSI), more frequently, which results in incurring huge overhead on the cellular network. Therefore, a distributed approach needs to be considered since the process can not be performed centrally. In this paper, we further study a new OSGRR scheme where a sub-grant provider user openly broadcasts the sub-granting resources, and all beneficiary users become involved to select the beneficiary user candidate for a specific time interval in a cooperative manner. A short and preliminary version of this work was presented in the conference publication [1]. The main contributions of this study are summarized as follows:

- We formulate the beneficiary user selection problem for the sub-granting scheme as an optimization problem. The optimization problem aims to select the beneficiary users subject to some constraints in order to maximize the uplink cell throughput.
- Two new algorithms are proposed and compared in terms of uplink cell throughput, the number of selected beneficiary users, and sub-granting errors considering mobility, measurement transmission interval.
- The overhead is formulated for both algorithms. We calculate the overhead of both algorithms, taking into account positioning information, CSI measurements, sub-granting signaling, bidding information in a dynamic environment while D2D and D2I users are moving.

The remainder of this paper is organized as follows. In Section 1, the system model is described. We explain the problem formulation in Section 2. In Section 3, the proposed algorithms are presented. The results are discussed in Section 4. Finally, in Section 6, some concluding remarks are presented.

1 Scenarios and System Model

1.1 Scenarios

In this section, we analyze different sub-granting scenarios considering the communication type for beneficiary users and sub-grant provider users. The sub-grant provider user and the beneficiary user could be either D2D or D2I communication, whereby four types of sub-granting scenarios are defined. Table 1 illustrates the sub-granting scenarios and use cases. Generally, in a D2I communication, the eNB has global knowledge of the location, signal level, and buffer status of the user based on the measurements received from the cellular users in every measurement interval. In contrast, in D2D communication, the eNB is not aware of some information, namely user buffer status report and channel measurement between two communicating, or this information can be achieved at the cost of high measurement and signaling overhead on the eNB. In the DSGRR algorithm, the eNB selects a beneficiary user based on the available measurement information to increase the overall uplink throughput. Note that although the eNB has initially scheduled radio resources for the D2D users, the radio link condition and traffic buffer status of the D2D communication may change, and thus the D2D communication information becomes outdated quickly. This reason makes the D2D user an inappropriate candidate for the beneficiary user in a centralized scenario. In contrast, the D2D user can independently decide and grant unutilized resources to the beneficiary user selected by the BS, whereby the D2D user becomes a suitable candidate as the sub-grant provider in a centralized scenario. In a decentralized approach, i.e., DSGRR, the eNB is not involved in the beneficiary user selection procedure. Thus the sub-grant provider user and the beneficiary user can be either a D2D or a D2I user, and thus four different scenarios can be defined.

Different use cases can apply the sub-granting scheme. One example is sub-granting radio resources from Vehicle-to-Vehicle (V2V) user to Pedestrian to Infrastructure (P2I), Machine-to-Machine (M2M), Vehicle-to-Infrastructure (V2I) user, and vice versa. In the following sections, the centralized and decentralized approaches are compared in terms of the uplink cell throughput, overhead, and the average number of the selected beneficiary user in a dynamic scenario. In this study, we consider the D2D and the D2I User Equipment (UE) as the sub-grant provider and the beneficiary user, respectively, in order to have a fair comparison between two algorithms.

1.2 System Model

We consider a single-cell environment with M D2I users (D2I-UEs) and N D2D users (D2D-UEs) denoted by sets $C = \{1, ..., M\}$ and $D = \{1, ..., N\}$, respectively. All users are uniformly distributed over the cell. We assume users also randomly move through the cell. Figure 1 graphically shows an example of the network. Let us assume there are F Resource Block (RB)s in the uplink direction for both D2D and D2I users. The eNB coordinates L RBs for D2D pairs and the remaining $(F-L)$ RBs for D2I-UEs. The eNB orthogonally schedules uplink radio resources for D2I users at every scheduling time by any reasonable scheduling scheme. To avoid scheduling delays, the eNB assigns one RB to every D2D-UEs for a specific time (See Label (1) in Figure 1). We assume that the D2D-UEs can disseminate the signaling information indicating the allocated but unused resources, i.e., sub-granting (See Label (2) in Figure 1), to the all nearby D2I-UEs, i.e., beneficiary user (See Label (3) in Figure 1). Also, the D2I-UEs are a side-link capable user who can communicate with other users in proximity through the side-link communication [8].

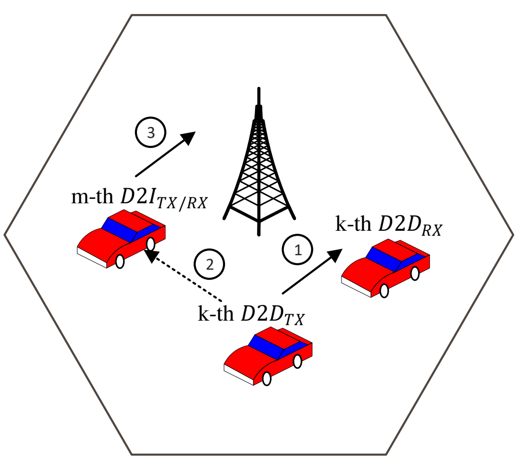

Figure 1. A typical network is consisting of one eNB, one D2D-UE, and one D2I-UE. The k-th D2D user sub-grants the un-used radio resources to the m-th D2I user.

The further assumptions in this study are made as follows:

- All D2I-UEs are full buffer users with best-effort traffic payload.
- D2D-UEs have small traffic payload with the same reliability and latency requirements, e.g., ultra-reliable and low-latency applications.
- All D2D and D2I users are synchronized in time and frequency from the eNB.
- All users' velocities are assumed to be constant during movement. At the initiating position and the cell border, the users choose an arbitrary route on a random basis.
- The processing time for decoding sub-granting signaling message and encoding data S_{Min} is assumed to be less than the time of two symbols for the beneficiary user.
- We assume the channel condition remains unchanged during the beneficiary user selection process. Besides, the amplitude of the received signal with distance is assumed to follow an exponential decay as follows:

$$G = \text{c} \times r^{-\alpha}|\mu|, \tag{1}$$

  where c is a constant value, and r is the distance between two entities, α represents a path-loss exponent, and μ captures the large- and small-scale fading phenomena.
- We assume an open-loop power control mechanism that the transmission power of every communicating entities is controlled by the path-loss [9].
- We assume that the eNB is aware of the CQI and buffer status report of D2I users. Besides, all users are equipped with a Global Positioning System (GPS), and thus be able to send the positioning information to the central network in every (pre-)configured time interval.
- To reduce the processing time due to blind decoding during the sensing procedure, it is assumed that energy-sensing is only performed on (pre-)configured radio resources by the eNB.
- The notations used in this study are summarized in Table 2.

2 The Problem Formulation

In [1], it is proposed to decompose the uplink cell throughput into the aggregated throughput of the D2I and D2D users within the cell. Therein, a scenario with stationary users was studied in which the radio link condition does not vary significantly, and thus the overhead due to the user radio link measurement, i.e., channel state information and positioning transmission, was ignored. In this study, we consider a scenario that all users are moving within the cell. Therefore, the radio link condition and the positioning information of all users need to be transmitted to the cellular network more often. The measurement transmission incurs a significant overhead on the cellular network, which results in cell throughput degradation. Considering the measurement and positioning information overhead, the uplink

Table 1. Different scenarios of the sub-granting scheme

Sub-grant Provider	**Beneficiary User**	**Use Cases**
D2D	D2D	V2V, V2I, MTC, P2I
D2D	D2I	
D2I	D2D	
D2I	D2I	

Table 2. List of Notations

Notation	Interpretation
D	The set of D2D users where $d_k \in D$ for $k = 1,...,N$
C	The set of D2I users where $c_m \in C$ for $m = 1,...,M$
L	The set of allocated RBs to D2D communication
F	The set of available RBs on eNB
B_w	Allocated bandwidth
b	Allocated RBs to every entities where $b = 1,...,F$
$\mathbb{X}$	Allocation indicator for sub-granting
α_c	Path loss component for D2I user
α_d	Path loss component for D2D user
μ_c	Fading component for D2I user
μ_d	Fading component for D2D user
σ_0	White Gaussian noise
σ	Shadowing term
P_m	Transmission power of D2I transmitter, $m = 1,...,M$
P^C_{max}	Power threshold limit for D2I transmitter
P_k	Transmission power of D2D transmitter, $k = 1,...,N$
q	Modulation and coding scheme of every entities
ε	General term for Bit Errors Rate (BER)
ε^D_{th}	Minimum BER threshold for D2D communication
ε^{sg}_{th}	Minimum BER threshold for sub-granting
ε_{mk}	Measured BER between D2D and D2I users
T	Subframe transmission time
τ	Transmission duration
T_{me}	Channel state information measurement interval
T_{pos}	Positioning measurement interval
T_{br}	Bids transmission interval
S_{Min}	Processing time for all entities
$\mathscr{Z}$	Unique number of a cellular user in network

cell throughput stated in [1] can be reformulated as:

$$R_{cell}(\varepsilon,\tau) = \sum_{m=1}^{M} \left(R_m(\varepsilon,\tau) - \hbar_m(\tau)\right) + \sum_{k=1}^{N} \left(R_k(\varepsilon,\tau) - \hbar_k(\tau)\right), \tag{2}$$

where R_m is the achievable data rate of D2I user at every scheduling time τ for a specific bit errors rate ε and yields as follows [10]:

$$R_m(\varepsilon,\tau) = B_w \log_2\left(1 + \frac{GP_m}{\sigma_0 B_w \Gamma}\right), \tag{3}$$

where G is the radio channel gain that is calculated from equation (1), P_m is the transmission power of every D2I users, B_w and σ_0 stand for the allocated bandwidth in Hz and white Gaussian noise, respectively. And, $\Gamma = \frac{-ln(\varepsilon)}{1.5}$ [10]. In case of D2D user with small traffic payload, the equation (3) is not accurate enough, thus the achievable throughput R_k for D2D user is reformulated as follows [11]:

$$R_k(\varepsilon,\tau) = B_w \log_2\left(1 + \frac{GP_k}{\sigma_0 B_w}\right) - \sqrt{\frac{B_w V}{\tau}} Q^{-1}(\varepsilon)\log_2(e), \tag{4}$$

where $Q^{-1}(.)$ is the inverse Gaussian Q-function, and V reflects stochastic variability of the channel given by:

$$V = 1 - \frac{1}{1 + \left(\frac{GP_k}{\sigma_0 B_w}\right)^2}. \tag{5}$$

In equation (2), $\hbar_k$ and $\hbar_m$ are the overhead due to the sub-granting signaling, the positioning information and radio link measurement reports transmitted by the D2I and D2D users. In [1], it has been manifested that the user throughput is proportional to qb over the transmission time, τ where q is the Modulation and Coding Scheme (MCS), and captures the bit error rate ε. Moreover, b stands for the number of allocated RBs. Consequently, the sub-granting throughput R_{mk} yields from $q_m b_k$ over the transmission duration $(T - \tau_k)$, where b_k is the sub-granted RBs from the k-th D2D user and q_m is MCS of the m-th D2I beneficiary user. Additionally, a binary variable of $\mathbb{X}_{mk}$ for resource allocation from k-th D2D user to the m-th D2I beneficiary user is defined:

$$\mathbb{X}_{mk} = \begin{cases} 0, & \text{if } T - \tau_k < S_{Min}, \\ 1, & \text{otherwise.} \end{cases} \tag{6}$$

Where S_{Min} is a processing time of a UE that depends on equipment and the number of allocated resources in time and frequency domain [12]. We now rewrite equation (2) for the dedicating and open sub-granting considering the D2I and D2D overhead as follows:

$$R_{cell}(\varepsilon,\tau) = \sum_{m=1}^{M} \left(R_m(\varepsilon,\tau) - \hbar_m(\tau)\right) + \sum_{m=1}^{M}\sum_{k=1}^{N} \mathbb{X}_{mk} R_{mk}(\varepsilon, T - \tau_k) + \sum_{k=1}^{N} \left(R_k(\varepsilon,\tau) - \hbar_k(\tau)\right). \tag{7}$$

Equation (7) considers the case where the D2D users are ultra-reliable and low-latency communications with absolute reliability and latency requirements, while D2I users have the best-effort traffic. More precisely, we assume that the reliability requirements for D2D users are satisfied if the bit error rate of D2D communication ε_k is smaller than the configured threshold ε_{th}^{D}. Then, D2D users can grant $T-\tau$ of the allocated but unused resources in symbols basis to the D2I users. However, in the case of the erroneous environment, the D2I users may fail to decode the sub-granting signaling message. Therefore, we adopt the general approach initially proposed in [10] to calculate the upper bound bit error rate (ε) between D2D and D2I users as follows:

$$\varepsilon \leq 0.2e^{\frac{-1.5\delta}{q-1}}, \tag{8}$$

where $\delta = \frac{GP}{\sigma_0 B_w}$. We then proceed to maximize the sum rate of the cell by selecting the best beneficiary users. To optimize the throughput in (7), we only need to maximize the second term since the first and third terms are constant and have no effect on the solution. The optimization problem can be expressed as follows:

$$\underset{(m,k)\in C\times D}{\text{maximize}} \sum_{m=1}^{M}\sum_{k=1}^{N} \mathbb{X}_{mk} R_m\left(\varepsilon, T-\tau_k\right), \tag{9a}$$

subject to

$$\varepsilon_{mk} < \varepsilon_{th}^{sg},\ \forall\, m=1,...,M, k=1,...,N, \tag{9b}$$

$$\mathbb{X}_{mk} \in \{0,1\}\ \forall\, m=1,...,M, k=1,...,N, \tag{9c}$$

$$\sum_{m=1}^{M} \mathbb{X}_{mk} = 1,\ \forall\, k=1,...N, \tag{9d}$$

$$\sum_{k=1}^{N} P_m + \mathbb{X}_{mk} \times \frac{\left(P_{max}^{C} - P_m\right)}{b_m} < P_{max}^{C},\ \forall\, m=1,...,M, \tag{9e}$$

where (9b) is constraint showing errors limit for the D2D sub-granting signalling. Constraint (9c) denotes that the available resources for sub-granting should be greater than the processing time required by the beneficiary users. It is assumed that only one beneficiary user is allowed to use a sub-granted resource (constraint (9d)). Note that the power headroom indicates how much a beneficiary user is allowed to increase the transmission power in addition to the current allocated transmission power, i.e., $P_{max}^{C} - P_m$. Generally, the transmission power of every entity is proportional to the number of allocated RBs [9]. Thus, the additional transmission power due to the sub-granted resources to the beneficiary users should not increase the beneficiary user transmission power beyond the power constraint P_{max}^{C} (constraint (9e)).

The optimization problem in equation (9) aims to find a list of beneficiary users that maximizes cell throughput. This problem can be defined as a Maximum Weighted Matching (MWM) problem in bipartite graphs with some non-linear constraints. When there exists a large number of D2I and D2D users, an exhaustive search becomes intractable due to its high computational complexity. To avoid drawbacks in using an exhaustive search solution, in the following sections, two algorithms are suggested in centralized and distributed fashions to address the beneficiary user selection problem in the sub-granting scheme.

3 Sub-Granting Radio Resource Algorithms

In this section, first, the operational functionality of the beneficiary user and the sub-grant provider user in the proposed heuristic algorithms is briefly explained. Then, we describe some basics in the bipartite graph whose maximum weighted matching problem of the beneficiary user selection in the sub-granting scheme is simpler to solve in the bipartite graph. Finally, two heuristic algorithms that, in our opinion, can address the beneficiary selection problem in the sub-granting scheme are discussed.

Figures 2 demonstrates the operational state-machine of a beneficiary user in the centralized algorithm, i.e., dedicated sub-granting. In the dedicated sub-granting algorithm, every UE provides the BS with their actual position information and CQI towards the eNB over every selected time interval. Afterward, the eNB considers a hypothetical geographical area around every sub-grant provider users and seeks for a beneficiary user within this area to increase the overall cell throughput and informs every selected beneficiary users about the paired sub-grant provider users. The beneficiary user monitors the sub-granting signaling at every selected time interval and then utilizes the sub-granting resources until the next selection time interval.

In a mobile scenario, the positioning and CSI information need to be transmitted more frequently, resulting in additional overhead on the cellular network. To reduce the overhead arising from the positioning and CSI information transmission, a distributed sub-granting algorithm, i.e., open sub-granting, is suggested. Figure 3 shows the state-machine of the beneficiary user functionality for the open sub-granting algorithm. In general, each beneficiary user assesses on the received signal from the nearby sub-grant provider users to calculate a bid value based on the measured received signal strength from the sub-grant provider and the eNB. The calculated bid value, along with the desired sub-grant provider identity, is shared with other nearby beneficiary users. Then the beneficiary user who offers the highest value among nearby beneficiary users is allowed to transmit on the sub-granting resource for a selected time interval.

In both algorithms, the sub-grant provider only informs the nearby beneficiary users about the unused resources and plays no role in the beneficiary user selection process. To be more specific, in the dedicated sub-granting, the selected beneficiary user identity and the number of free symbols are conveyed by the sub-granting signaling. Whereas in the open dedicated algorithm, only the number of free symbols and the sub-grant provider identity are transmitted. Figure 4 depicts the functionality of the sub-grant provider in the dedicated and open sub-granting algorithms.

Many problems can be cast as a matching problem in a bipartite graph. For example, in radio resource allocation, the relation between the users and the resources is modeled by a bipartite graph in order to maximize the number of allocated resources [13]. Similarly, in this study, the relation between the sub-grant provider users and the beneficiary users is first modeled by a time-varying bipartite graph wherein the edge of the graph is weighted differently based on the beneficiary user selection algorithm, i.e., dedicated or open sub-granting algorithm, at every selection time instant. In the sequel, the concept of the weighted bipartite graph is introduced first.

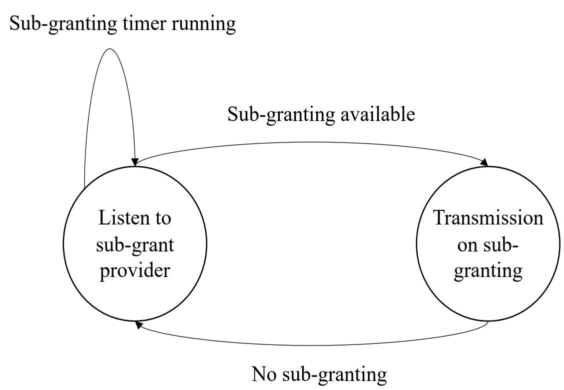

Figure 2. State-machine diagram of a beneficiary user functionality on the dedicated sub-granting algorithm.

Definition 3.0.1 *The bipartite graph is a graph with two independent disjoint vertices U and V such that every edge E connects a vertex in U to one in V. We denote a graph with $G = (U,V,E)$.*

Definition 3.0.2 *Two edges of a bipartite graph are said to be independent when they have no common end vertex and loop. A matching is a set of independent pair edges of a graph. A matching with maximum cardinality is called maximum matching.*

Figure 5 is an illustration of the system model in the form of a graph model, where the edge of the graph is being updated in every selection time instant. The sub-grant provider D and beneficiary users C construct two vertices

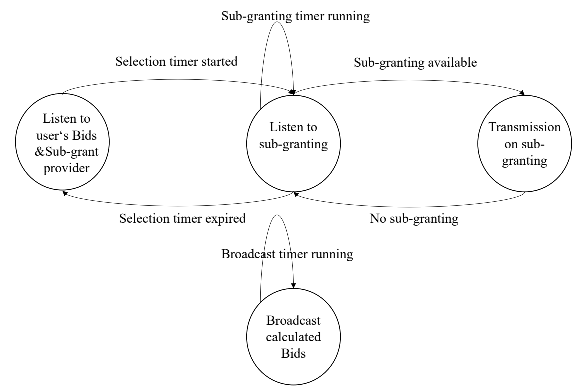

Figure 3. State-machine diagram of a beneficiary user functionality on the open sub-granting algorithm.

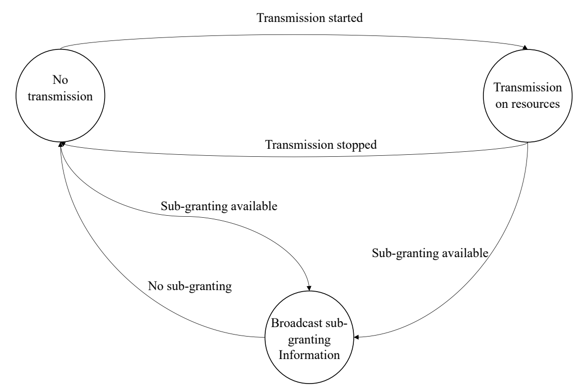

Figure 4. State-machine diagram of sub-grant provider functionality.

of the graph. Every user in D is connected to the users in C. In the following sections, we discuss two heuristic algorithms to achieve the maximum matching to address the sub-granting problem. General background on maximum weighted matching and bipartite graphs can be found in [14].

3.1 Dedicated Sub-Granting Radio Resource (DSGRR) Algorithm

In this section, we discuss the centralized dedicated sub-granting radio resource algorithm to address the beneficiary user selection problem of the sub-granting scheme indicated in equation (9). The optimization problem is decomposed into two stages. In the first stage, a hypothetical geographical area, an error- limited area, for every sub-grant provider is calculated wherein the sub-granting signaling can be reliably received. In the second stage, edges of the constructed bipartite graph are weighted by the beneficiary user data rate, and are being updated in every beneficiary user selection time interval. The beneficiary selection problem is then solved using the proposed algorithm, and the maximum number of the beneficiary users to achieve the highest cell throughput is obtained.

3.1.1 error-Limited Area (eLA)

As previously discussed, CQI between the sub-grant provider and the beneficiary user is not known or, at least can be achieved at the cost of additional signaling overhead on the cellular network. To avoid such an overhead, a hypothetical circle around every sub-grant users based on the maximum error probability criterion, i.e., ε_{th}^{sg}, is calculated. To this end, we use equation (8) to calculate the signal to noise level δ_{th}^{sg} related to ε_{th}^{sg} on the margin of hypothetical circle. Then, considering equation (1) and the channel model parameters for D2D communication in [15], the eLA (r_{eLA}) is bounded as:

$$| r_{eLA} | \leq \left(\frac{cP_k \mid \mu_d \mid}{\sigma_0 B_w \delta_{th}^{sg}} \right)^{\alpha_d^{-1}}, \ k = 1, ..., N. \tag{10}$$

Algorithm 1 explains the dedicated beneficiary user selection procedure. When the beneficiary user is inside the hypothetical circle of the sub-grant provider, i.e., eLA. An edge $e \in E$ is weighted with $q_m.b_k$, if there exists at least one vertex $c_m \in C$ inside the eLA (see lines (1) to (10)) in Algorithm 1. Additionally, we take the power constraint (9e) into consideration. Next, the algorithm chooses the beneficiary user c_m with maximum weighted edge e_{mk} associated to every sub-grant providers d_k in a greedy manner. Then, it is iteratively run and ended when all beneficiary users c_m are successfully selected. Also, in every iteration in order to find the maximum matching, the allocated edge is removed from all the sub-grant provider vertices, $d_k \in D$. Finally, every sub-grant provider users are informed about the selected beneficiary users $\mathbb{X}$.

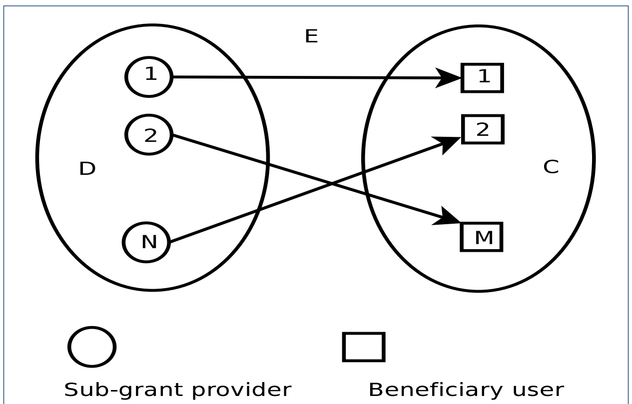

Figure 5. An Illustrative example of graph model.

3.1.2 Overhead

Due to the mobility of all users, the positioning and measurement information of users should be transmitted in a shorter time interval, which results in the additional overhead. As previously discussed in section 2, the beneficiary user overhead is shown by $\hbar_m$ and yields.

Algorithm 1 Dedicated Sub-Granting Radio Resource

```
1:  procedure BENEFICIARY USER SELECTION
    Input: d_k ∈ D^{1×N}, c_m ∈ C^{1×M}, ε_th^sg
    Initialization:
2:      Calculate error limited area radius for
        d_k ∈ D, k = 1,...,N (Equation (10))
3:      E ← φ
4:    for d_k ∈ D do
5:      for c_m ∈ C do
6:        if (c_m ∈ eLA_k) & (Constraint (9e)) then
7:            e_mk = q_m.b_k
8:            E ← (E ∪ e_mk)
9:        endif
10:     endfor
11:   endfor
    Repeat:
12:   X ← φ
13:   for d_k ∈ D do
14:     Find c_m ∈ C with Maximum e_mk
15:     X_mk = 1 & X ← X ∪ X_mk
16:     E ← E − ∪_{k=1}^N e_mk
17:   endfor
    Output: Transmit X_mk to every d_k
```

$$\hbar_m(\tau) = \frac{\mathbb{X}_{me} \times O_{me} + \mathbb{X}_{pos} \times O_{pos}}{T}, \tag{11}$$

where O_{me} and O_{pos} are the constant overhead values due to the channel state measurement and positioning information. $\mathbb{X}_{me}$ and $\mathbb{X}_{pos}$ are the measurement time interval T_{me} and positioning information time interval T_{pos}. Similarly, the sub-granting provider transmits the positioning information to the BS and disseminates the unused radio resources, which incurs additional overhead the cellular network. In Section (2), this overhead is shown by $\hbar_k$ and yields:

$$\hbar_k(\tau) = \frac{\sum_{m=1}^{M} \mathbb{X}_{mk} \times O_{sg} + \mathbb{X}_{pos} \times O_{pos}}{T - \tau}, \tag{12}$$

where O_{sg} is the sub-granting signalling overhead in the every sub-granting occurrences $\mathbb{X}_{mk}$ as explained in equation (6) and constraint $(9d)$. Also, the denominator term $T - \tau$ stands for the remaining transmission time.

3.1.3 Time complexity

In the proposed algorithm, nested loops are considered where the sub-grant provider and beneficiary users are the outer and inner loops within the algorithm, respectively. Thus, the central controller requires to run the algorithm $\mathscr{O}(N \times M)$ operations to complete the beneficiary users' selection process.

3.2 Open Sub-Granting Radio Resource (OSGRR) Algorithm

Recently the auction theory, which initially developed in the economy, has attracted many scholars' attention and has been applied to various problems in engineering. The essence of an auction environment consists of auctioneers or sellers, bidders, commodities to be sold, and a set of rules which give rise to the game among all the bidders. In some auctions, there exists one seller that can perform the role of auctioneer. As a result, auctioneer and seller terms can be used interchangeably. An auction theory, a sub-field of economics, is a useful tool to model and optimize radio resource allocation in wireless communication wherein radio resources can be allocated among different users, following some rules regulated in the market. One well-known auction is the Vickrey-Clarke-Groves (VCG) auction [16], which requires gathering global information from all entities and performing centralized computations.

In this study, we consider one-shot open-cry auction in which the bidders advertise their offers at once and openly based on a bidding strategy in a distributed manner. Let D be a set of distinct objects which offer some commodities, say sub-granting resources, for sale. Moreover, C be a set of buyers wherein each buyer, say beneficiary user, is assumed to assign a valuation $\mathbf{s}_{mk}$ to each seller, i.e., sub-grant provider user, where $k \in D$ and $m \in C$. Every beneficiary user monitors other bids and advertises a selected sub-grant provider after the exclusion of the assigned sub-grant provider users indicated in the broadcast bid. Note that every bid contains information that indicates the preferred sub-grant provider user of every beneficiary user. In this study, it is assumed that a sub-grant provider does not ask for any cost from the beneficiary user on the sub-granting radio resources. Furthermore, the achieved throughput of every beneficiary user from the sub-granting resources is reflected in a bid generated employing the strategy function. Recall that symmetric equilibrium wherein all players use the same bidding strategy function [16], the strategy function in every beneficiary users s_{mk} yields:

$$s_{mk} = \frac{\beta q_m b_k + (1-\beta) q_{mk}}{q_{max}} + \gamma_m, \ \forall m = 1, \ldots, M, k = 1, \ldots, N, \quad (13)$$

where q_m and q_{mk} are modulation and coding scheme of m-th the beneficiary user towards the BS and the sub-grant provider user, which are normalized to maximum modulation and coding rate q_{max}. The number of sub-granted resources from the sub-grant provider to the beneficiary user is denoted by b. The term β takes a value between 0 and 1 that shows the impact of the multiplied terms in the bidding strategy function and is configured by the BS. In the first term of the equation, we consider two factors, the first factor guarantees the sub-granting gain, and the latter ensures to choose a sub-grant provider with the higher signal strength to reduce the probability of the sub-granting errors.

Note that if two beneficiary users have the same MCS, the first term of the equation may return the same value resulted in a collision between two beneficiary users due to transmission on the same sub-granting resource. To avoid a tie situation in the equation, a small value of γ_m is added to the first term of bidding strategy function, calculated from the reverse of a unique cellular user-specific number $\mathscr{Z}_m$, say, a Temporary Mobile Subscriber Identity (TMSI) [17].

Figure 6 shows an illustrative example of the equilibrium bidding value of the strategy function, considering a specific TMSI value for every beneficiary user.

Remark: The highest cell throughput is achieved when the sub-granting resources are granted to the beneficiary users offering the highest bid value. A

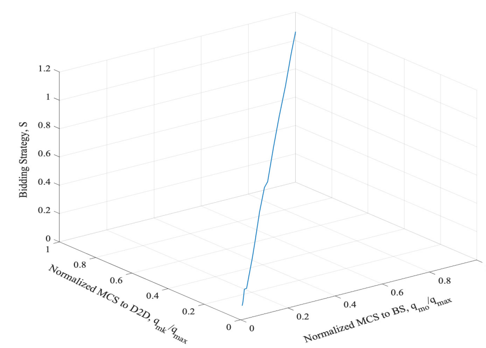

Figure 6. An Illustrative example of bidding strategy function.

bipartite graph is used to model the beneficiary user selection problem in the sub-granting radio resource wherein the beneficiary users, bidders, and the sub-grant provider users, sellers, or auctioneers, are two vertices of a graph as illustrated in figure 5. The edges of the graph are weighted by bidding values obtained from the bidding strategy function. This way, the problem is transformed into the maximum matching in the bipartite graph. Now we propose a closed-form heuristic algorithm, say, open sub-granting radio resource to address the beneficiary user selection problem in the sub-granting radio resource as stated in Equation (9).

Algorithm 2 shows the principle of operation of the open sub-granting radio resource. The beneficiary user's unique value γ_m, β, and bid transmission start time are configured by the BS. Where the bid transmission start time is a time value between two consecutive selection time instances in which every beneficiary user is allowed to transmits the bid value. Also, this value ensures that two beneficiary users do not start transmission at the same time. Thus any possible collision due to a half-duplex communication in the D2D communication is avoided. Then, every beneficiary user calculates a bid value s_{mk} associated to every sub-grant provider users using the equation (13) considering the bit errors rate and power head room stated in constraints ($9b$) and ($9e$) in equation (9). Note that every beneficiary user chooses a maximum bid value S_{mk} associated to the sub-grant provider user and disseminates the bid value along with the corresponding sub-grant provider user identity. The beneficiary user informs the nearby users about the bid value s_{mk} through D2D communication on the scheduled uplink radio resource at the configured bid transmission start time. Next, the edges of the graph are updated based on its bid value, and other monitored beneficiary users bid values (see Lines (1) to (15) in the Algorithm 2). Finally, every beneficiary user constructs a list of maximum bid values corresponding to the monitored beneficiary users and the associated sub-grant provider users, i.e., matching list $\mathbb{X}_{mk}$. Note that, a beneficiary user having the biggest bid value on the matching list is allowed to transmit on the sub-granting radio resources over the beneficiary user-selection time interval configured by the eNB (see Lines (16) to (20) in Algorithm 2).

Algorithm 2 Open Sub-Granting Radio Resource

1: **procedure** BENEFICIARY USER SELECTION
Input: Configure β value used in Equation (13)
Initialization:
2: Calculate $\gamma_m = \frac{1}{\mathscr{Z}_m}$, $m = 1, ..., M$
3: $E \leftarrow \phi$
4: **for** $d_k \in D$ **do**
5: **if** Constraints ($9b$) & ($9e$) **then**
6: Calculate bid value s_{mk} from Equation (13)
7: Update edge value of graph, $E \leftarrow (E \cup s_{mk})$
8: **endif**
9: **endfor**
10: Select maximum bid value s_{mk} and broadcast
11: Update edge value of graph, $E \leftarrow E - \cup_{j=1}^{N} s_{mj}, \forall j \neq k$
12: **for** $c_{m_{-1}} \in C$ **do**
13: Monitor bid value $s_{m_{-1}k}$ of other beneficiary user
14: Update edge value of graph, $E \leftarrow (E \cup s_{m-1k})$
15: **endfor**
Selection:
16: $\mathbb{X} \leftarrow \phi$
17: **for** $d_k \in D$ **do**
18: Select $c_m \in C$ with maximum bid value s_{mk}
19: $\mathbb{X}_{mk} = 1$ and $\mathbb{X} \leftarrow \mathbb{X} \cup \mathbb{X}_{mk}$
20: **endfor**
Output: *Macthing List* $\mathbb{X}$

3.2.1 Overhead

The overhead in the open sub-granting algorithm is mainly due to bidding messages that are exchanged among the beneficiary users and also sub-granting signaling messages. Therefore, the imposed overhead on the beneficiary users $\hbar_m$ yields:

$$\hbar_m(\tau) = \frac{\mathbb{X}_{br} \times O_{br}}{T}, \tag{14}$$

where O_{br} stands for the overhead value owing to bidding message exchanged among the beneficiary users, and $\mathbb{X}_{br}$ is a value that is set to 1 at every broadcast time interval T_{obr}. Moreover, in case of the sub-granting scheme overhead on the D2D communication h_k, positioning information is not transmitted to the BS, and thus equation (12) can be rewritten as follows:

$$\hbar_k(\tau) = \frac{\sum_{m=1}^{M} \mathbb{X}_{mk} \times O_{sg}}{T - \tau}, \tag{15}$$

3.2.2 Time complexity

This section explains the steps required to execute the algorithm. The OSGRR algorithm includes two terms, which each runs in $O(N)$ and $O(M)$ time, respectively. Therefore, the algorithm takes about $O(N+M)$ to find a match list. For $N >> M$ or $M >> N$, the complexity is simply $O(N)$ or $O(M)$ respectively.

4 Simulation Parameters and Performance Metrics

We assume a single cell system with a carrier frequency centered at 2.6 GHz. There are 100 RBs available, and 40 RBs are allocated to 40 D2D users so that each D2D user is assigned an RB in a semi-persistent manner. The remaining RBs are scheduled among 60 D2I users equally. In this topology, the cell radius is 300 meters, and all users are uniformly distributed within the cell and move in random directions with constant speeds. At the cell border, the UEs select a random direction towards inside the cell and continue moving inside the cell. The channel models in [15] are used for the path-loss and large-scale fading, i.e., shadowing effects. More specifically, the indoor hot-spot non-line-of-sight (InH-NLOS) and the urban micro hexagonal cell layout non-line-of-sight (UMi-NLOS) models are regarded as channel gains for the D2D and D2I communications, respectively [15]. Besides, we consider the Rayleigh and Rician fading models to capture the small-scale fading effects, but without loss of generality, we assume that the channel conditions do not vary during the sub-granting signaling and bid information transmission. For both D2D and D2I communications, LTE open loop power control is assumed [9]. The transmission power distribution of D2I users is shown in Figure 8. In this paper, a traffic model based on the requirements given in [18] is considered (See Table 3). Figure 7 illustrates the distribution of traffic payload generated by D2D users over the simulation run.

To avoid any non-uniformity in user distribution due to mobility inside the cell and have more realistic outcomes, the simulator is run ten times in which the simulation duration is 4000ms, and then the results are averaged over every simulation run. Simulation parameters are summarized in Table 3.

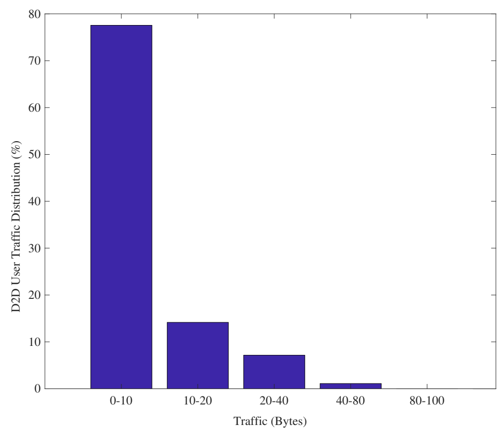

Figure 7. D2D Traffic Distribution.

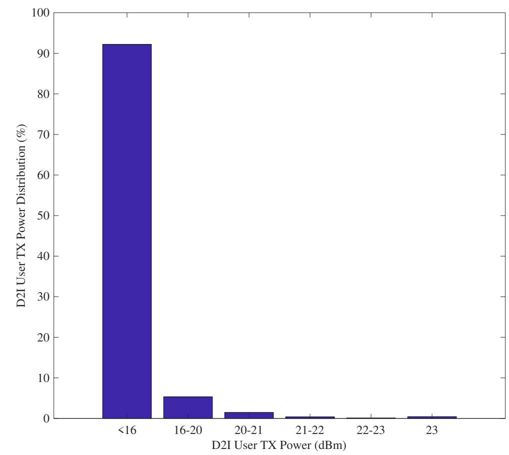

Figure 8. D2I Transmission Power Distribution.

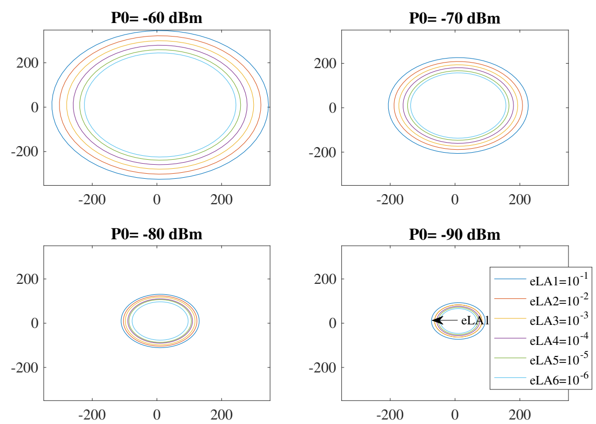

Figure 9. Impact of P0 on eLA. P0 is the desired received signal in the open-loop power control equation [9].

4.1 Performance Metrics

The following metrics are studied in our study:

- Uplink cell throughput.
- Average throughput of beneficiary user.
- Number of selected beneficiary users.
- Sub-granting signalling errors rate.
- Overhead rate.

5 Results and Discussion

As indicated in the DSGRR algorithm, for every sub-grant provider, a geographical area eLA is specified, wherein the sub-granting signaling message can be reliably decoded. Figure 9 shows the relationship between the eLA and desired received power, $P0$, in the open-loop power control equation. Considering a specified signaling error value (i.e., ε_{th}^{sg}), a bigger eLA area is achieved at the cost of higher D2D transmission power (higher $P0$). Despite the circular eLA shape shown in Figure 9, the realistic spatial geometry of the eLA is amorphous rather than circular. The reason is because of large-scale fading phenomena, i.e., shadowing, employed in the Equation 10, different signal power around the sub-grant provider is received. Thus the spatial geometry of the eLA area is distorted. In our analysis, we assume an identical shadowing around a sub-grant provider in every eLA estimation interval whereby a circular eLA is formed.

As discussed in Algorithm (2), the value β should be set in a way to achieve the maximum gain from the sub-granting resources. Figure 10 illustrates the impact of β value on the uplink cell throughput. When β value is set to 0.1, the achieved throughput is 3.5% less compared with the β value of 0.9. It is because, in the latter one, the beneficiary users with better CQI value towards the BS are selected. Although the difference between the achieved throughput with β values of 0.9 and 0.5 is marginal, the results show the slightly higher uplink throughput when β value is set at 0.9.

Table 3. Network parameters used in the simulator.

Parameter	**Value**
Frequency, fc and BW	2.6 GHz, 20 MHz
Number of users	60 D2I, 40 D2D
Cell Radius	300 m
D2D Distance (d)	20 m
Channel Model [15]	UMi-NLOS α_c: 3.67 $\mu_c : \sigma = 4\ dB$, Rayleigh InH-NLOS α_d: 4.33 $\mu_d : \sigma = 4\ dB$, Rician, K=20 dB
User Velocity	30Kmph
Traffic Model	Packet size=10B, λ=1ms, $\varepsilon_{th}^{\mathbb{D}}=10^{-5}$ [2]
Power Control	Open Loop Power Control $D2D$ ($P0$ = -90 dBm/RB) $D2I$ ($P0$ = -107 dBm/RB)
Noise Power Density (σ_0)	-174 dBm/Hz
Noise Figure	5 dB
MAX UE TX Power	23 dBm
D2D and D2I Antenna Gain	1 dB
eNB Antenna Gain	10 dB
ε_{th}^{sg}	10^{-3}
Simulation Runs (i)	4000
T_{me}, T_{pos}, T_{br}	480ms
β	0.9

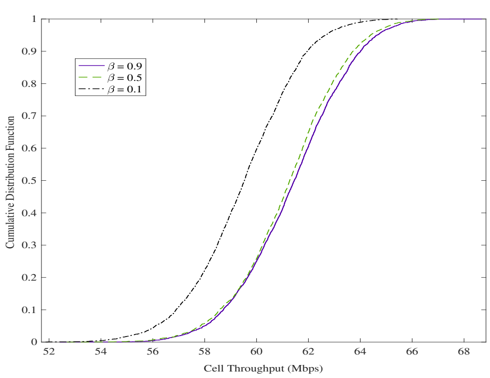

Figure 10. Impact of beta value on cell throughput for the OSGRR. The highest cell throughput is achieved at a value of β 0.9.

Although using a central approach could achieve an optimal solution for the beneficiary users' selection problem, it will increase the burden of overhead arise from the measurement. Therefore, an eLA based beneficiary selection algorithm, i.e., DSGRR, was proposed in [1] where the overhead is reduced. However, in the DSGRR algorithm, a large-scale fading can only be estimated, whereas, in the OSGRR algorithm, both large- and small-scale are captured in the measurement signal from the sub-grant provider users. Due to the small-scale fading in the OSGRR, the probability of receiving signal of the sub-grant provider is higher, and thus, the average coverage radius of a sub-grant provider might be larger in the OSGRR than the eLA area in the DSGRR. Figure 11 shows an illustrative example of a coverage area for the OSGRR and DSGRR algorithms. Given the above explanation, more beneficiary

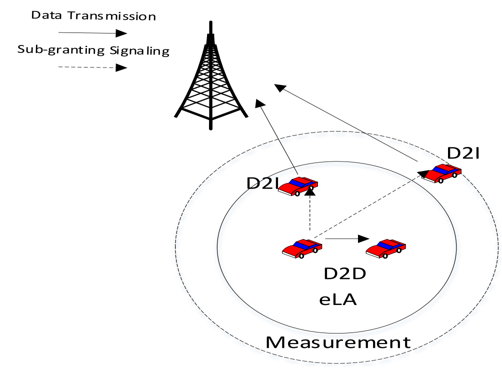

Figure 11. An Illustrative example of the sub-grant provider coverage area for measurement-and eLA-based approach.

users may receive the sub-grant provider signal, through which the number of candidate beneficiary users increases in the case of the OSGRR algorithm.

The advantage of the measurement on the algorithm is approved by a ten-times simulation experiment in which the number of the beneficiary users around the sub-grant provider users for both algorithms are averaged. As shown in Figure 12, the number of candidate beneficiary users is higher in the OSGRR compared with the DSGRR. The reason is that the measurement-based method, i.e., OSGRR, would increase the probability of receiving the sub-granting provider signal. It is worth noting that relaxing the uniform large-scale fading assumption in the eLA computation, may contribute to having less number of candidate beneficiary users in the DSGRR which leads to further performance degradation in the DSGRR algorithm.

Further investigation is conducted aiming to show the performance of both algorithms when the effect of the small-scale fading and overhead for both algorithms is relaxed. The simulation is run for one-thousand milliseconds, and the results are averaged over ten-times simulation run. The results show that both algorithms achieve almost the same uplink cell throughput in the studied scenario (See Figure13). Note that the marginal difference is due to the stochastic essence of the large-scale fading in both algorithms, whereby the different number of beneficiary users may be selected.

In the dedicated sub-granting algorithm, i.e., DSGRR, every entity transmits CSI and positioning measurements to the BS at a time interval of 480ms. After that, the

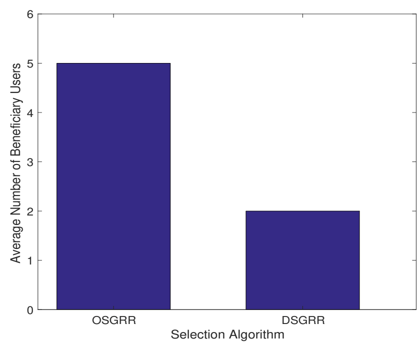

Figure 12. An Illustrative example of the average number of candidate beneficiary users for every sub-grant provider.

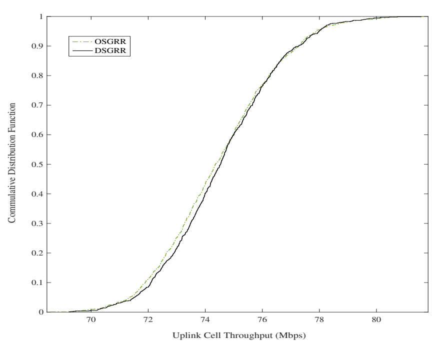

Figure 13. An Illustrative example of comparison of the uplink cell throughput for both algorithms in a scenario w/o considering overhead and small-scale fading for the stationary users.

BS transmits control information indicating the beneficiary user for every sub-grant provider user. These measurements and control information is carried on the uplink/downlink LTE physical layer control channels. In this study, we assume bandwidth one resource block and modulation coding scheme QPSK-1/2 to carry the control information and measurement information in downlink and uplink, respectively. For example, the overhead due to the uplink measurement, is calculated by (sub-carrier) * (OFDMA symbols) * (modulation order) * (code rate) = (12*14*2*1/2):8 = 21 bytes and considering 3 bytes as Cyclic Redundancy Check (CRC), total overhead has amounted to 24 bytes [9].

The BS informs the sub-grant providers about the selected beneficiary users through downlink signaling information. Similarly, in the downlink, the overhead is $(12*3*2*(1/2)):8 = 5$ bytes, and 3 bytes is added as CRC resulted in 8 bytes overhead for the beneficiary user selection signaling.

Also, assuming a global navigation satellite system provides timing and positioning information for every cellular user, every entity can provide the cellular network with location information (e.g., location estimate, pseudo-range, velocity) together with time information. To have a fair comparison, we only consider the uplink user-assisted information, which is required by the location server in order to estimate the exact position of users (c.f. section 6.5.2.5 in [19]). Also, the overhead caused by the transmission of messages between the server and the base station is not taken into consideration. Considering the Mac layer and physical layer overhead, about 40 bytes are required to acquire the positioning information of every cellular user. We assume that the network can obtain a sufficiently accurate position of ever users by employing user-assisted information, and the position error in the algorithm is negligible.

In the open sub-granting algorithm, i.e., OSGRR, every beneficiary user offers a bid value on the advertised sub-granting resources, and a beneficiary user with the highest offer can utilize the sub-granting resource for an interval time of 480ms. Therefore, the overhead scales up by increasing the number of beneficiary users exchanging signaling messages. Considering the bid value formulated in the OSGRR algorithm, one byte is needed to indicate the CQI values, and about 4 bytes are used to address the beneficiary user's unique number γ_m. In other words, only 5 bytes are required to address different beneficiary users' bid. Consequently, 6 bytes are needed to capture the physical and the Medium Access Control (MAC) layer overhead [9], which resulted in 11 bytes overhead in the OSGRR algorithm. Note that the sub-granting signaling imposes the same overhead on both algorithms, which amounted to 1 byte [5]. Table 4 illustrates components and size of the overhead in both algorithms.

Table 4. An Illustration of overhead components and size in the OSGRR and DSGRR.

Selection Algorithm	Overhead Components	Size(Byte)
DSGRR	Positioning Information Measurement Information (e.g., buffer status, power head room) Beneficiary user selection signaling Sub-grant signaling	40 24 8 1
OSGRR	Bidding Information Sub-grant signaling	11 1

Figure 14 compares the overall overhead rate between the OSGRR and the DSGRR algorithms. Besides, the figure illustrates the impact of measurement and positioning interval on the DSGRR algorithm. It can be seen that the overhead on the DSGRR algorithm is higher than the OSGRR algorithm when the measurement and bid transmission time interval are equal for both algorithms. The reason is that in

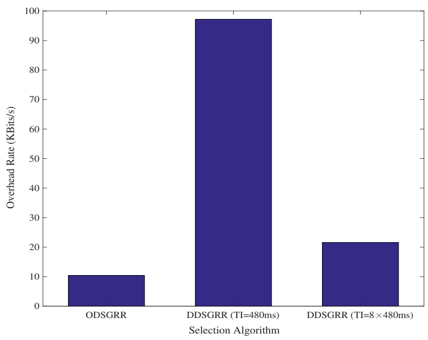

Figure 14. Overhead comparison between open sub-granting and dedicated sub-granting algorithms.

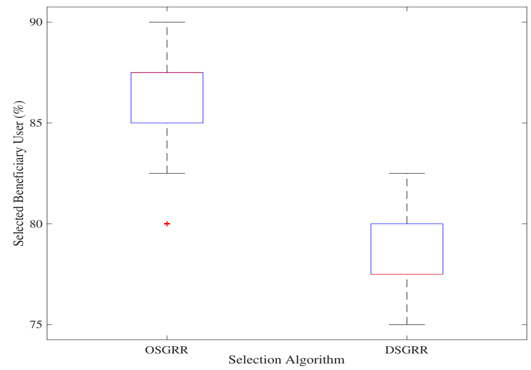

Figure 15. Comparison of the average number of selected beneficiary users between the DSGRR and OSGRR algorithms.

the beneficiary user selection process, the volume of information exchanged between users and the base station in the DSGRR algorithm is higher than the data transmitted between users in the OSGRR algorithm.

The overhead on the DSGRR is reduced when the measurement transmission interval increases from 480ms to 8 $\times$ 480ms; however, the result still shows less overhead in the OSGRR algorithm compared with the DSGRR. The reason is that the OSGRR needs a few bytes to broadcast the bids and does not impose any CSI and positioning measurement overhead on the BS. Although in the DSGRR, the overhead can be further reduced by incrementing measurement transmission interval, the performance will deteriorate as the outdated measurement information is used for the beneficiary user selection.

Figure 15 demonstrates the number of selected beneficiary users for both algorithms. The results show that the average number of selected beneficiary users in the OSGRR algorithm is about 10% higher than that of the DSGRR algorithm. As previously discussed, the OSGRR has a higher number of beneficiary user candidates for every sub-grant provider compared with the DSGRR due to a measurement-based selection. For example, in the DSGRR, if a beneficiary user is the only candidate at the border of the overlap eLA area of two sub-grant providers, the beneficiary user can be selected by one of the sub-grant providers. In contrast, in the OSGRR, farther beneficiary user candidates might be able to receive a sub-grant provider without any candidate resulted in increasing the number of beneficiary users selected by the sub-grant providers. Also, the results confirm that the OSGRR algorithm can serve a higher number of beneficiary users than the DSGRR algorithm.

Figure 16 compares the sub-granting error rate for the OSGRR and DSGRR algorithms. Also, the impact of positioning and measurement interval is illustrated in the figure. In general, the DSGRR shows a lower error rate compared with the OSGRR when both algorithms use the same transmission time interval for positioning, CSI measurement, and bid information. The reason is that in the OSGRR, farther beneficiary users are selected, which increases the probability of not decoding the sub-granting information owing to the fading between the sub-grant provider and the beneficiary user. In the DSGRR, when CSI and positioning measurement time interval increases by eight times, the sub-granting signaling error rate increase by slightly more than two times due to using the outdated eLA information during the beneficiary selection process.

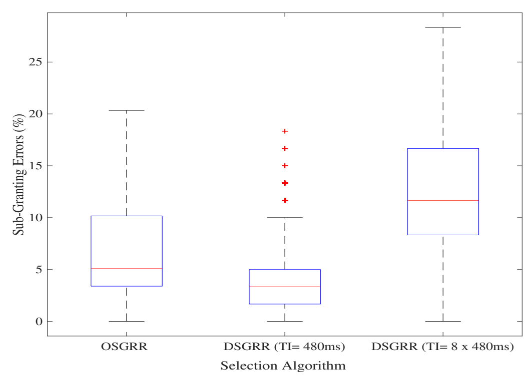

Figure 16. Sub-granting errors rate comparison between the DSGRR and OSGRR algorithms.

Figure 17 shows the impact of the measurement and positioning interval on the DSGRR throughput and compares both DSGRR and OSGRR algorithms in terms of cell throughput. Also, the closeness of both algorithms to the maximum achievable cell throughput is evaluated. To this end, the cell throughput of the DSGRR and OSGRR algorithms are compared with the case w/o any sub-granting algorithm and the maximum achievable cell throughput when all the allocated radio resources are fully utilized. Considering the same transmission interval and speed, as shown in

Table 3 for both algorithms, the OSGRR shows slightly better results than the DSGRR. The overhead and the number of selected beneficiary users are two factors that contribute to the cell throughput reduction in the DSGRR compared with the OSGRR. As indicated in Figure 14, the overhead contributes only to about 5% of the cell throughput reduction in the DSGRR. The remaining reduction is due to the number of selected beneficiary users, which resulted in a higher throughput in favor of the OSGRR.

When the measurement transmission interval increases by eight times, the cell throughput in the DSGRR gradually decreases over the simulation runs. The results show about a 10% reduction on the cell throughput compared with the one with shorter measurement interval. In contrast, the cell throughput remains almost constant in the OSGRR over the simulation runs. The results show that the OSGRR could achieve around 85% of the maximum cell throughput. The remaining 15% reduction is mainly due to the sub-granting signaling overhead and lack of a beneficiary user candidate or an optimum beneficiary user. It is noteworthy to mention that 35% of the allocated radio resources are wasted w/o sub-granting scheme (See Figure 17).

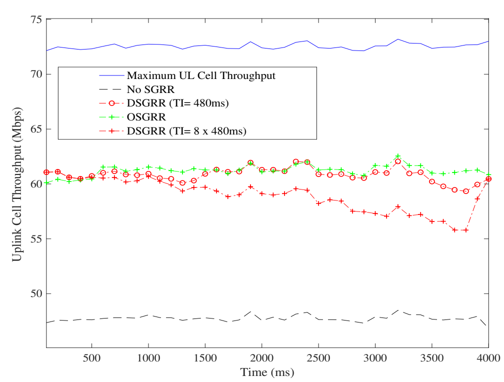

Figure 17. Impact of measurement/positioning transmission interval on cell throughput.

Figure 18 depicts the average throughput of the beneficiary user for both algorithms considering the same transmission time interval. Both algorithms show about 55% increase compared with no Sub-Granting Radio Resource (SGRR). This is due to the re-utilization of the unused resources in both algorithms. Although the OSGRR shows higher signaling errors compared with the DSGRR (See Figure16), the average beneficiary user throughput is slightly higher than that achieved by the DSGRR algorithm. The reason is mainly that more beneficiary users are selected in the OSGRR compared with the DSGRR, and thus the more beneficiary users can re-utilize the sub-granting radio resources resulted in achieving a higher throughput in the OSGRR.

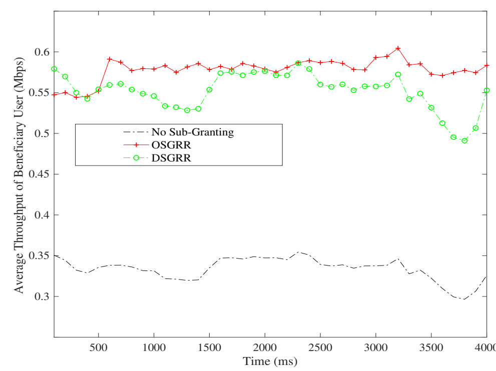

Figure 18. Comparison of the average uplink throughput of a beneficiary user.

6 Conclusions

This paper investigates the sub-granting radio resource allocation for D2D communication whose radio resources are allocated in a semi-persistent manner in an overlay mode. Next, the sub-granting radio resource allocation is formulated as a maximum weighted matching in a bipartite graph problem. Also inspired from auction theory, an OSGRR in a distributed manner is proposed. The overhead is formulated mathematically for the proposed algorithms and calculated based on some assumptions. The simulation results and analyses show the superiority of the distributed algorithm over the centralized one. To show the efficiency of both algorithms, the tightness of both algorithms to the maximum achievable uplink cell throughput is examined. Developing a new machine learning-based algorithm considering new parameters for the beneficiary user selection in a multiple cells scenario is worth investigating in future works.

Availability of data and materials

All results are included in this published article; the results raw output is available from the corresponding author on reasonable request.

Abbreviations

BS Base Station
GPS Global Positioning System
LTE Long Term Evolution
MAC Media Access Control
UE User Equipment
MTC Machine Type Communication
D2D Device-to-Device
D2I Device-to-Infrastructure
CSI Channel State Information
V2X Vehicle-to-Everthings
V2I Vehicle-to-Infrastructure
V2V Vehicle-to-Vehicle
TTI Transmision Time Interval
MCS Modulation and Coding Scheme
M2M Machine-to-Machine
P2I Pedestrian to Infrastructure
eNB evolved Node B
MAC Medium Access Control
RB Resource Block

BER Bit Errors Rate
CQI Channel Quality Index
SGRR Sub-Granting Radio Resource
OSGRR Open Sub-Granting Radio Resource
DSGRR Dedicated Sub-Granting Radio Resource
eLA error-Limited Area
MWM Maximum Weighted Matching
TMSI Temporary Mobile Subscriber Identity
CRC Cyclic Redundancy Check

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Figure Title and Legends

Figure 1: System Model.
A typical network is consisting of one eNB, one D2D-UE, and one D2I-UE. The k-th D2D user sub-grants the un-used radio resources to the m-th D2I user.

Figure 2:
State-machine diagram of a beneficiary user functionality on the dedicated sub-granting algorithm.

Figure 3:
State-machine diagram of a beneficiary user functionality on the open sub-granting algorithm.

Figure 4:
State-machine diagram of sub-grant provider functionality.

Figure 5:
An Illustrative example of graph model.

Figure 6:
An Illustrative example of bidding strategy function.

Figure 7:
D2D Traffic Distribution.

Figure 8:
D2I Transmission Power Distribution.

Figure 9:
Impact of P0 on eLA. P0 is the desired received signal in the open-loop power control equation.

Figure 10:
Impact of beta value on cell throughput for the OSGRR. The highest cell throughput is achieved at a value of β 0.9.

Figure 11:
An Illustrative example of the sub-grant provider coverage area for measurement-and eLA-based approach.

Figure 12:
An Illustrative example of the average number of candidate beneficiary users for every sub-grant provider.

Figure 13:
An Illustrative example of comparison of the uplink cell throughput for both algorithms in a scenario w/o considering overhead and small-scale fading for the stationary users.

Figure 14:
Overhead comparison between open sub-granting and dedicated sub-granting algorithms.

Figure 15:
Comparison of the average number of selected beneficiary users between the DSGRR and OSGRR algorithms.

Figure 16:
Sub-granting errors rate comparison between the DSGRR and OSGRR algorithms.

Figure 17:
Impact of measurement/positioning transmission interval on cell throughput.

Figure 18:
Comparison of the average uplink throughput of a beneficiary user.

Competing interests
The authors declare that they have no competing interests.

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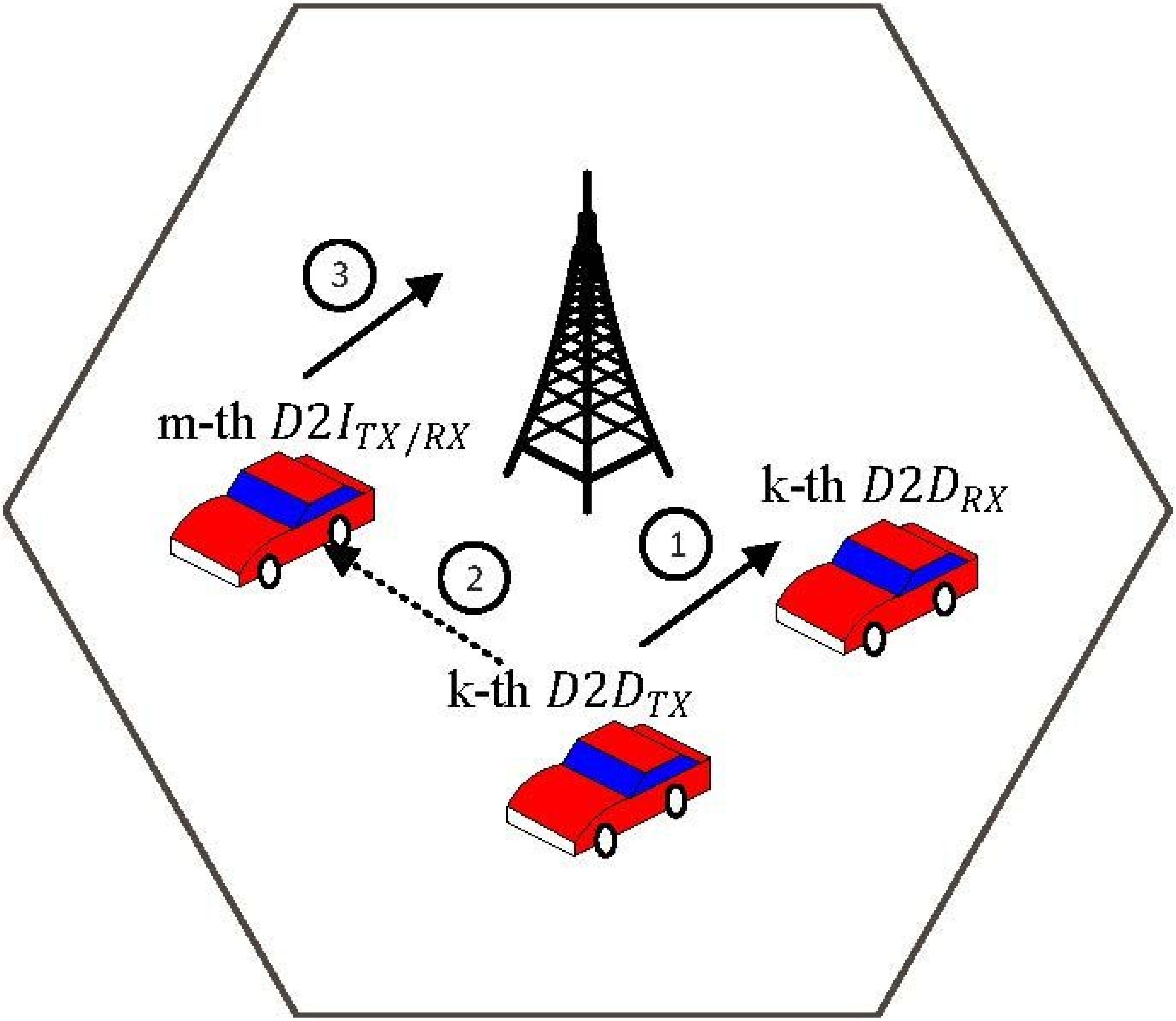
Author's contributions
All authors have reviewed and edited the manuscript and have approved the final manuscript.

Figures



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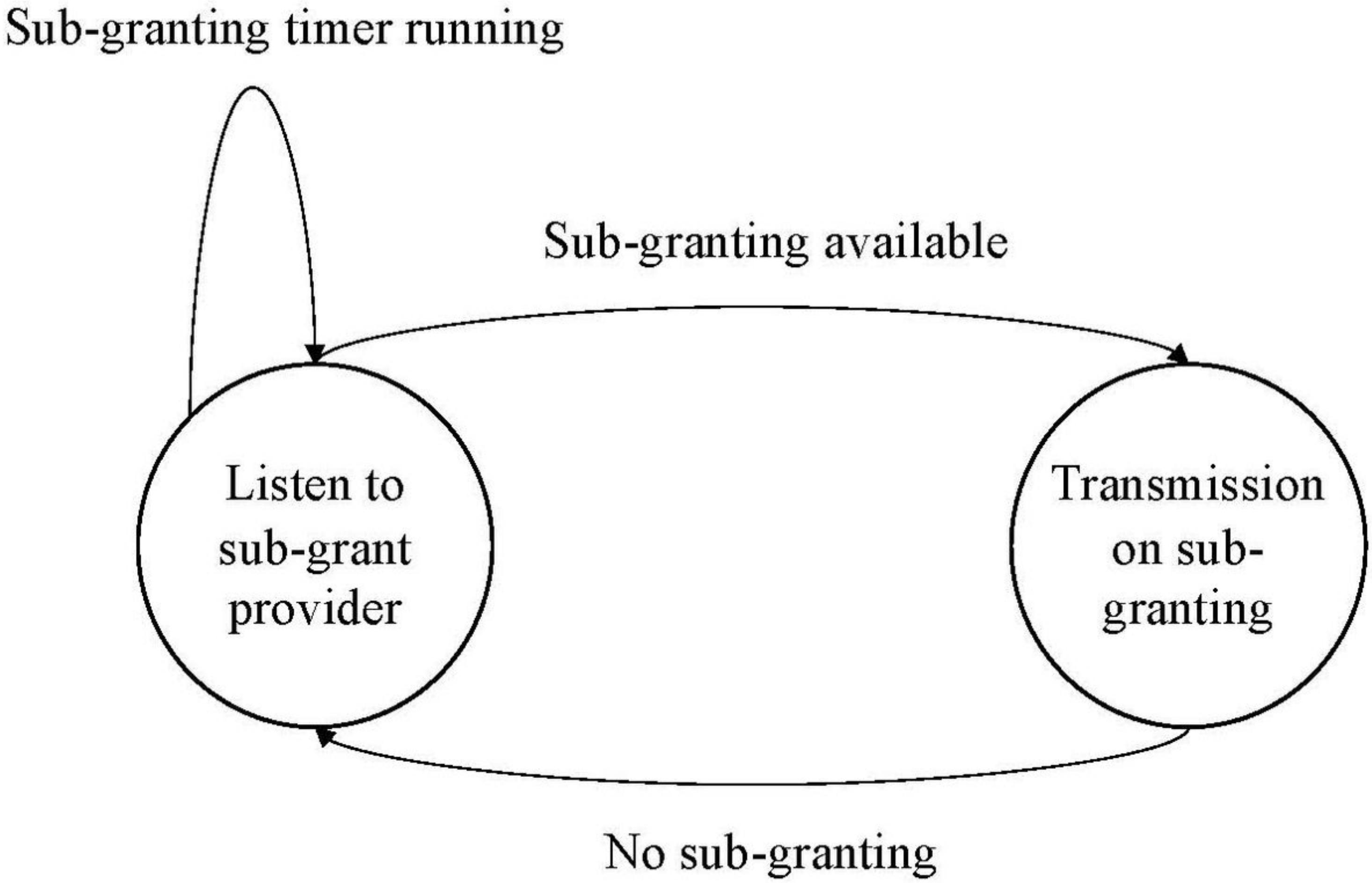
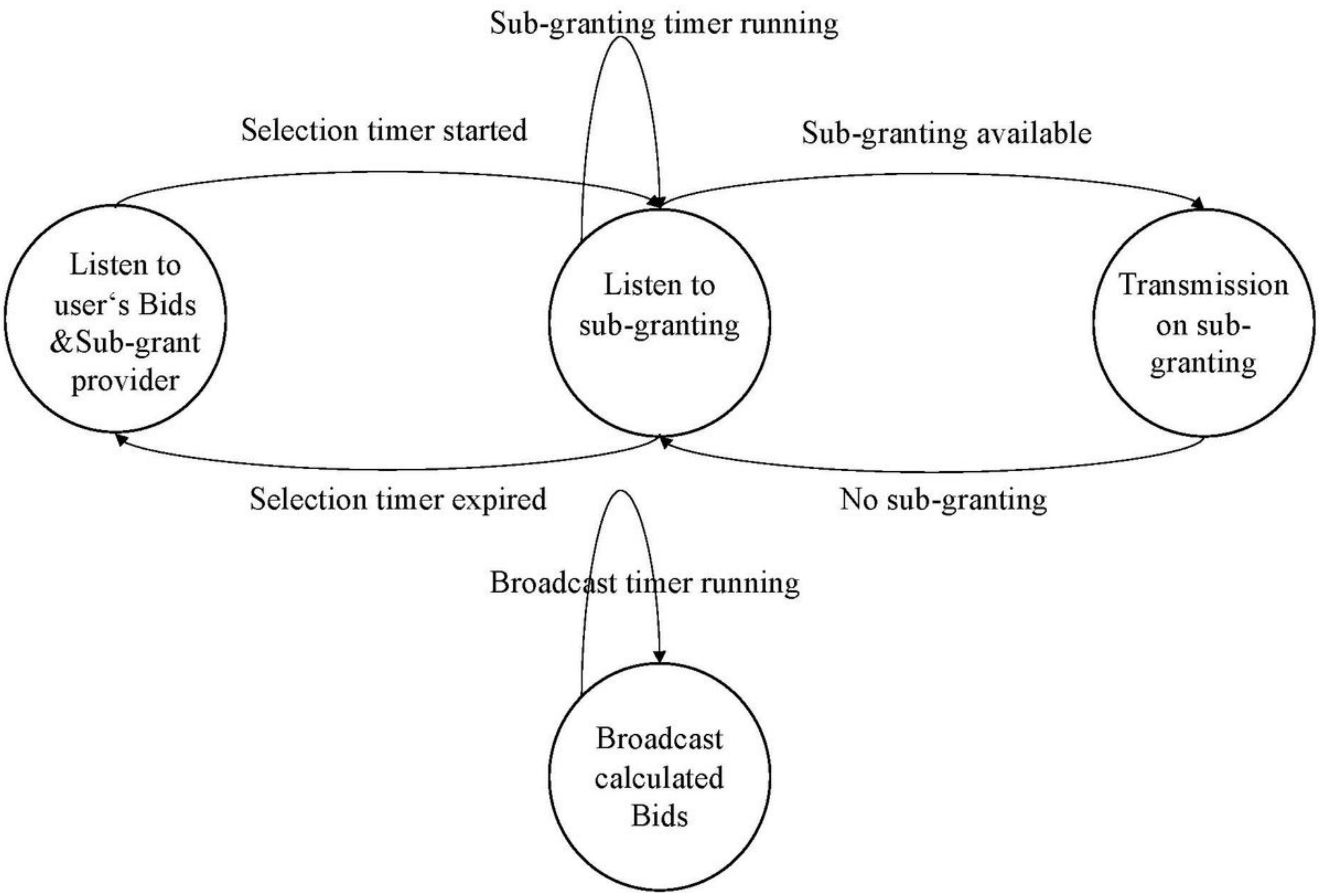


Figure 2

State-machine diagram of a beneficiary user functionality on the dedicated sub-granting algorithm.



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State-machine diagram of a beneficiary user functionality on the open sub-granting algorithm.

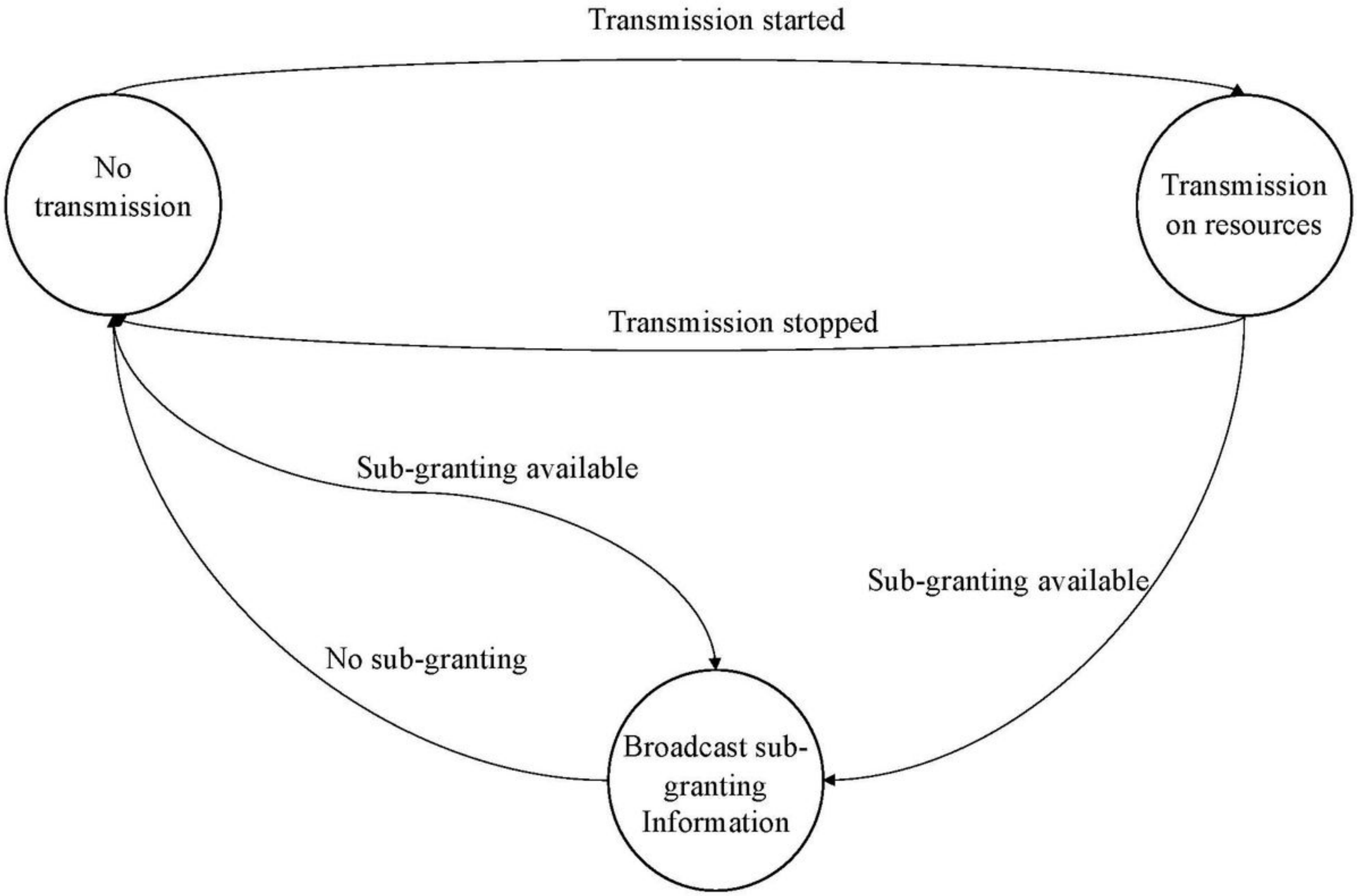
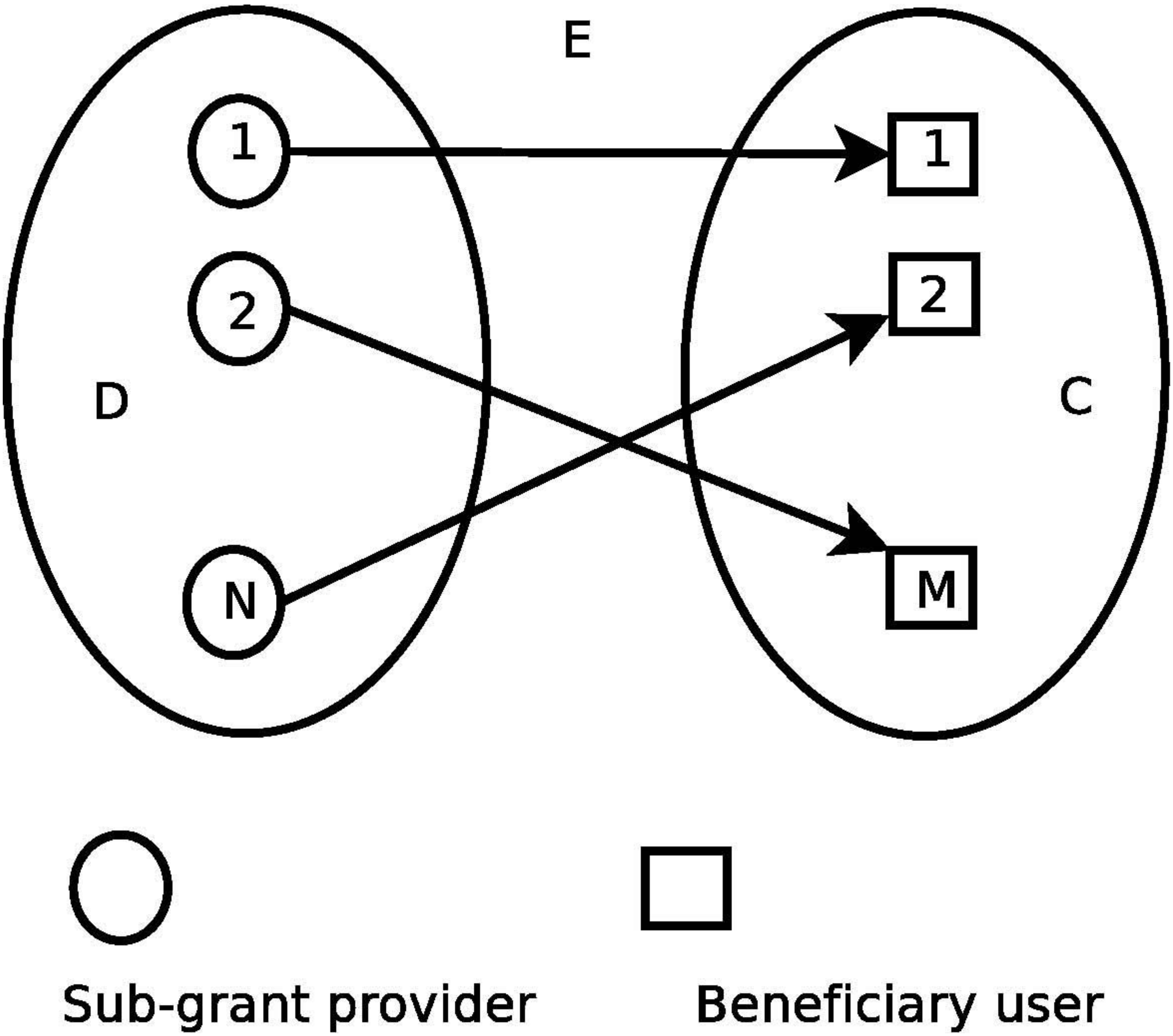


Figure 4

State-machine diagram of sub-grant provider functionality.



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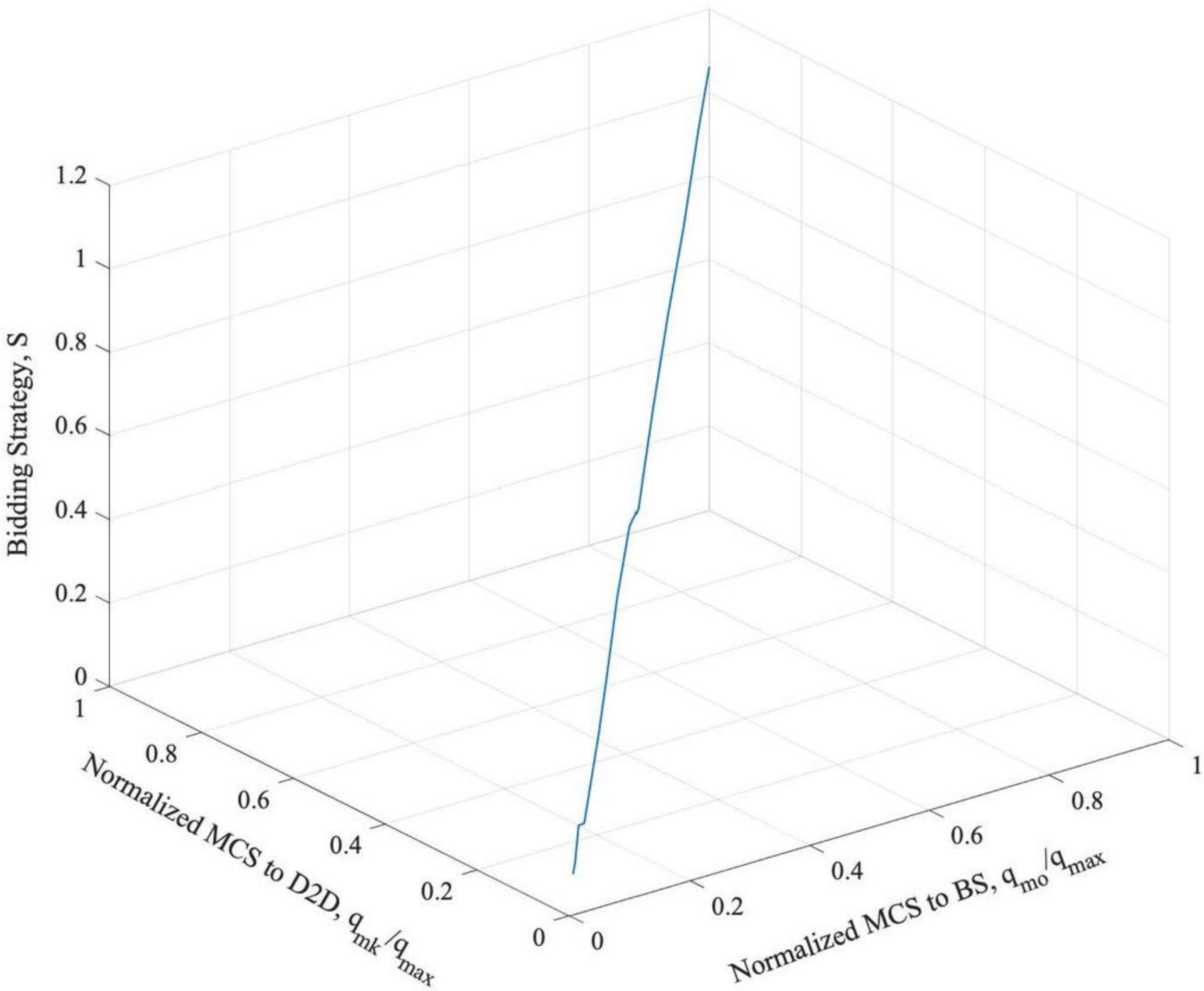

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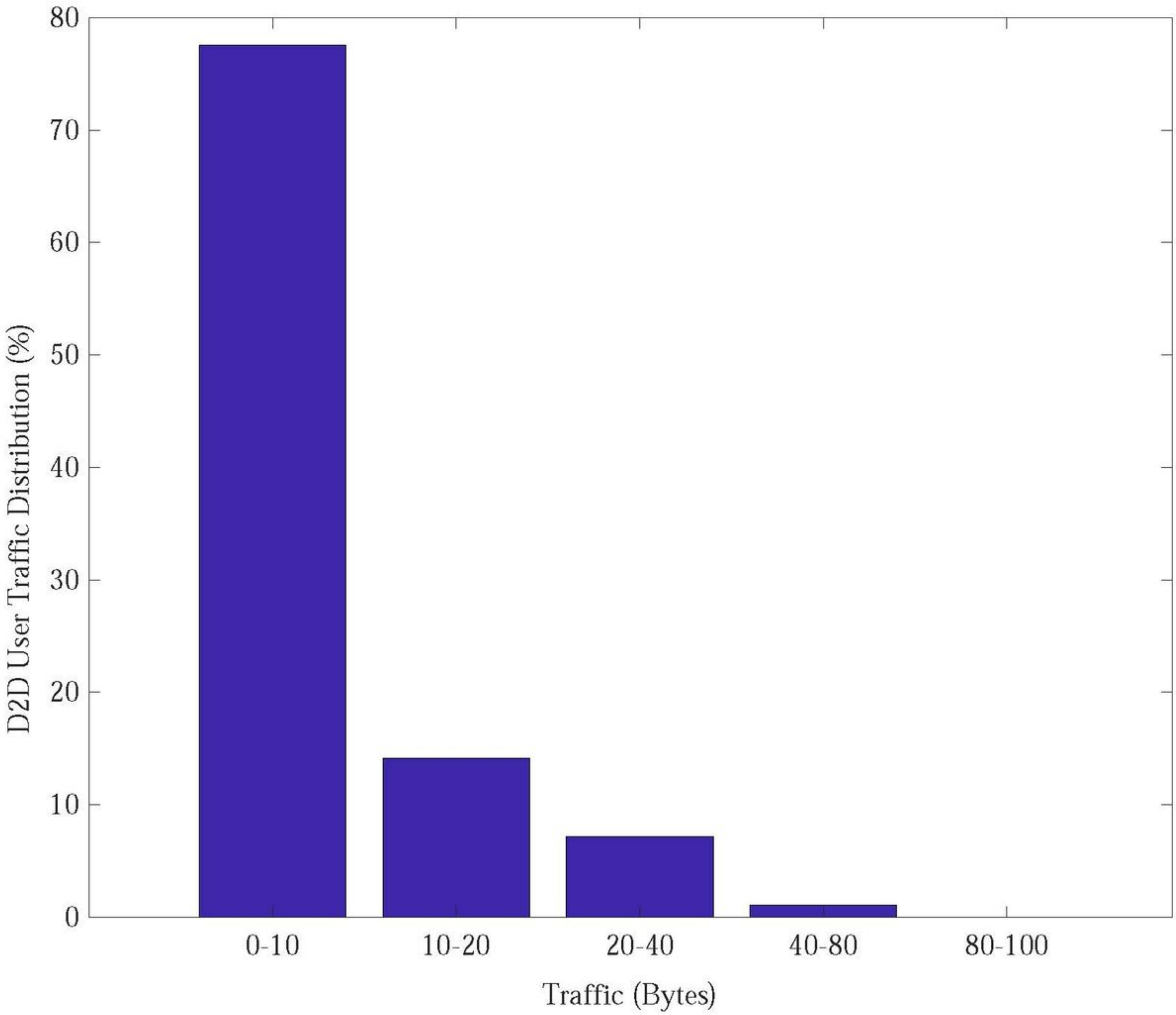

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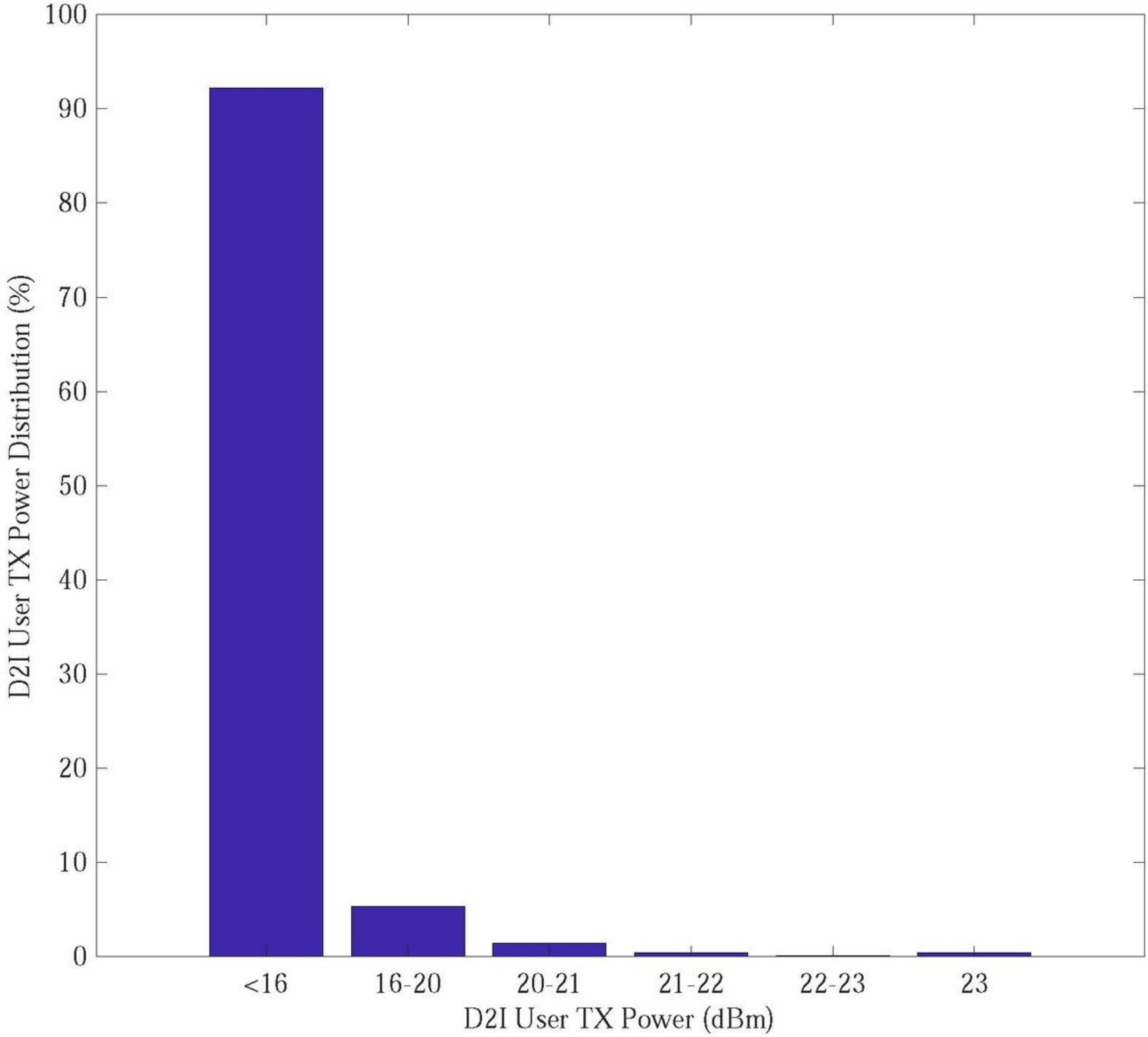

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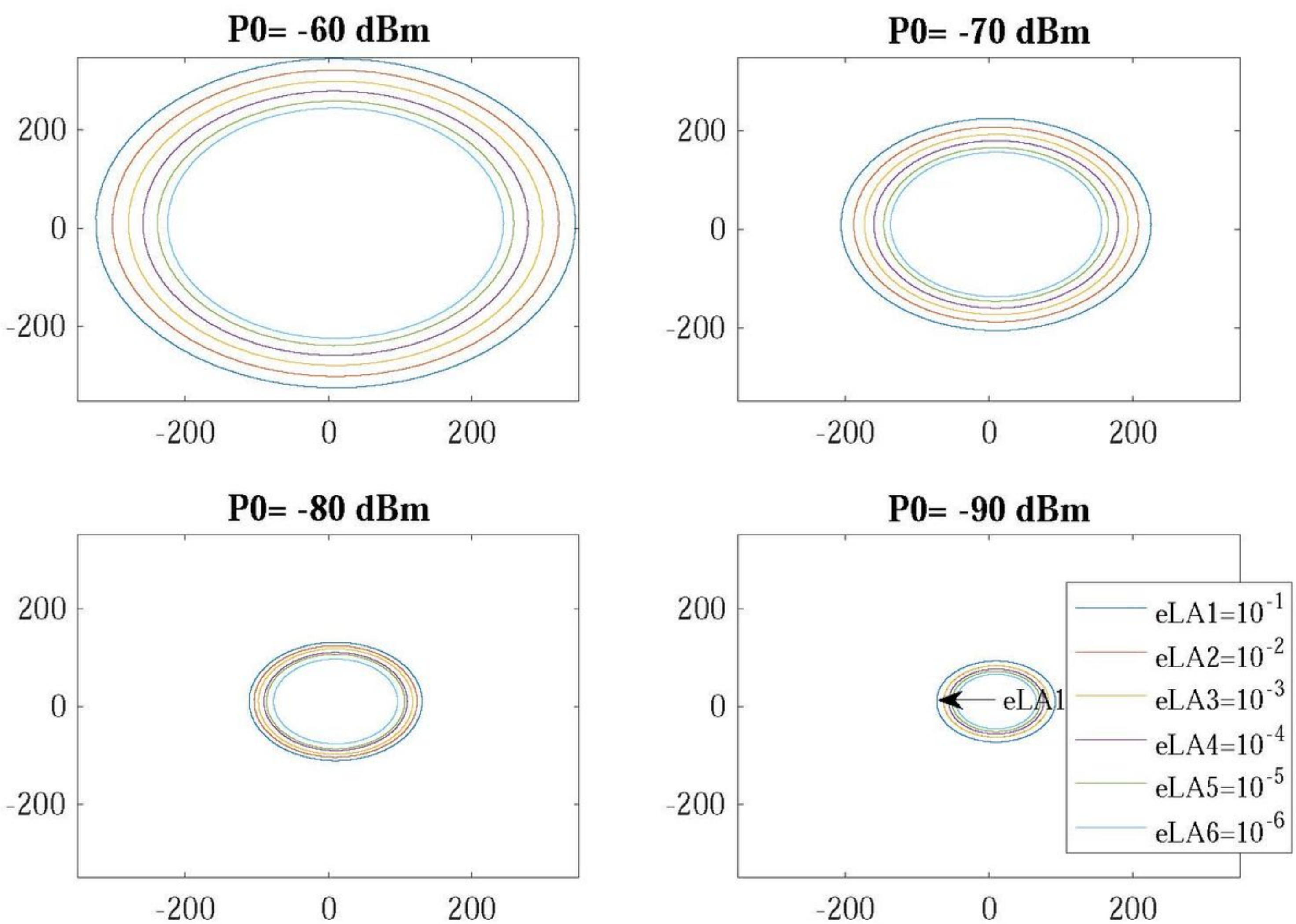

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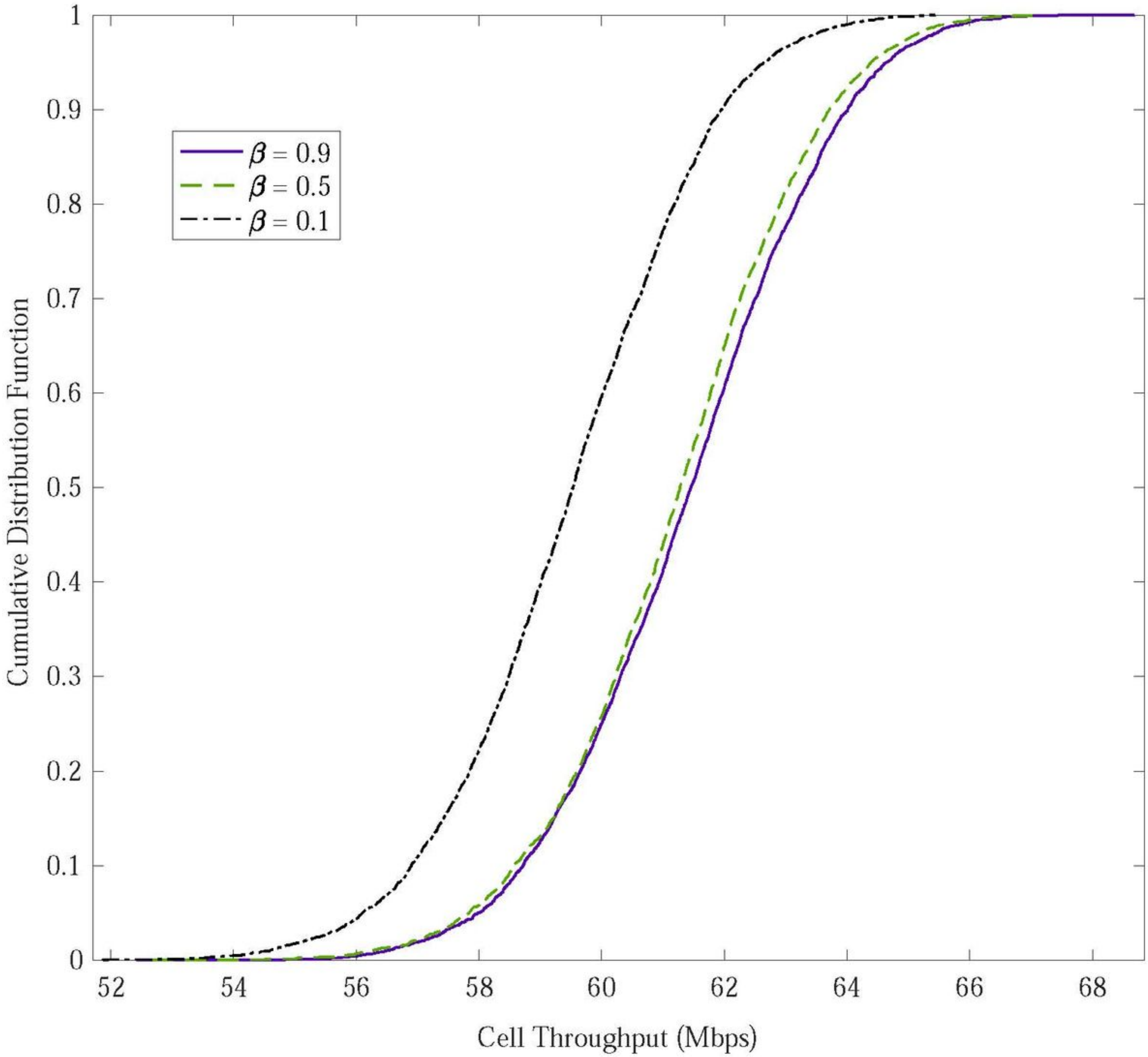

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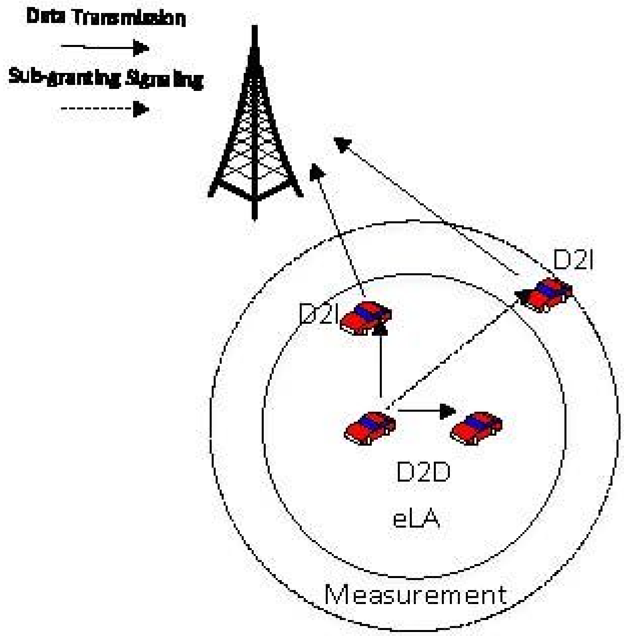

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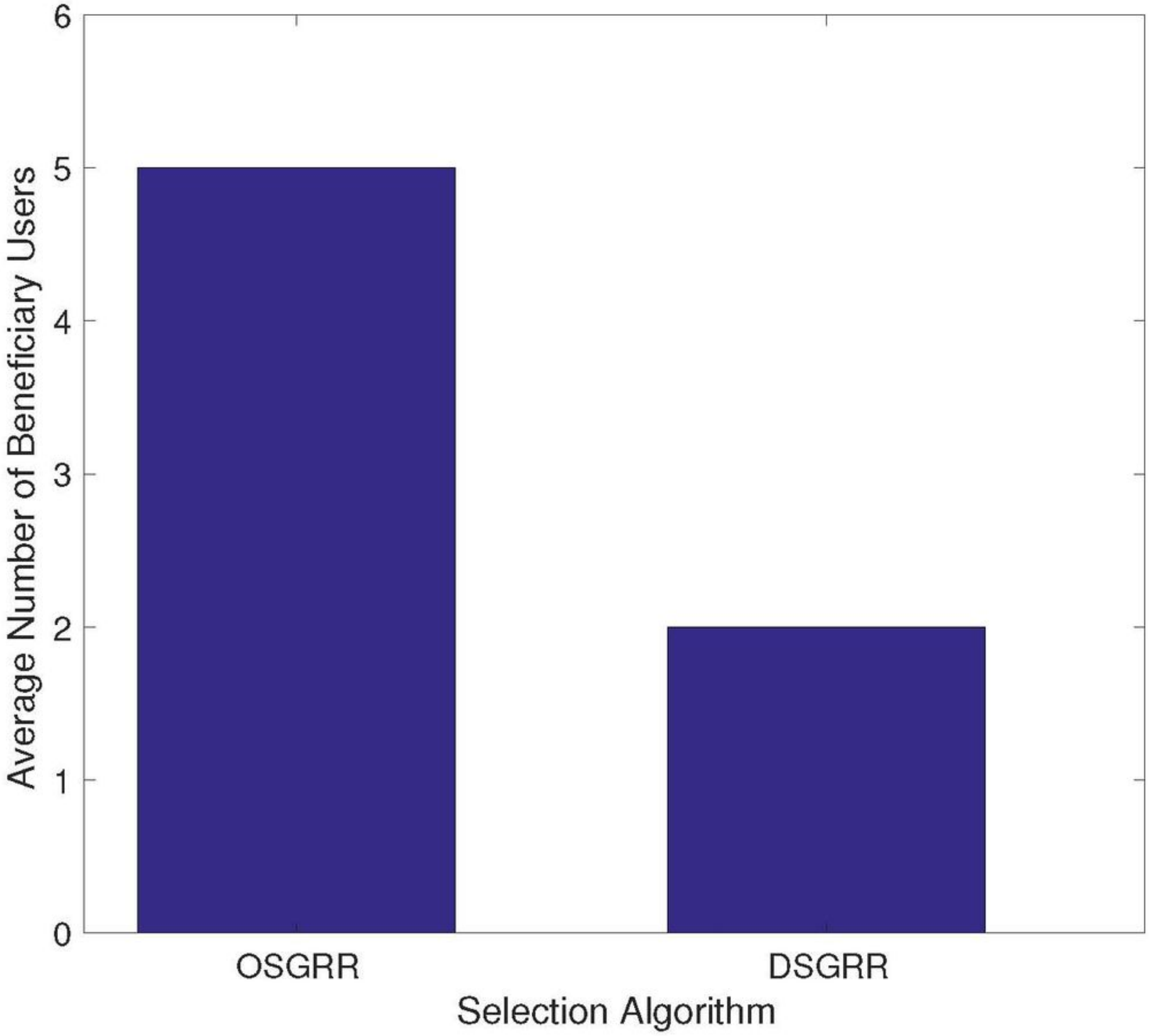

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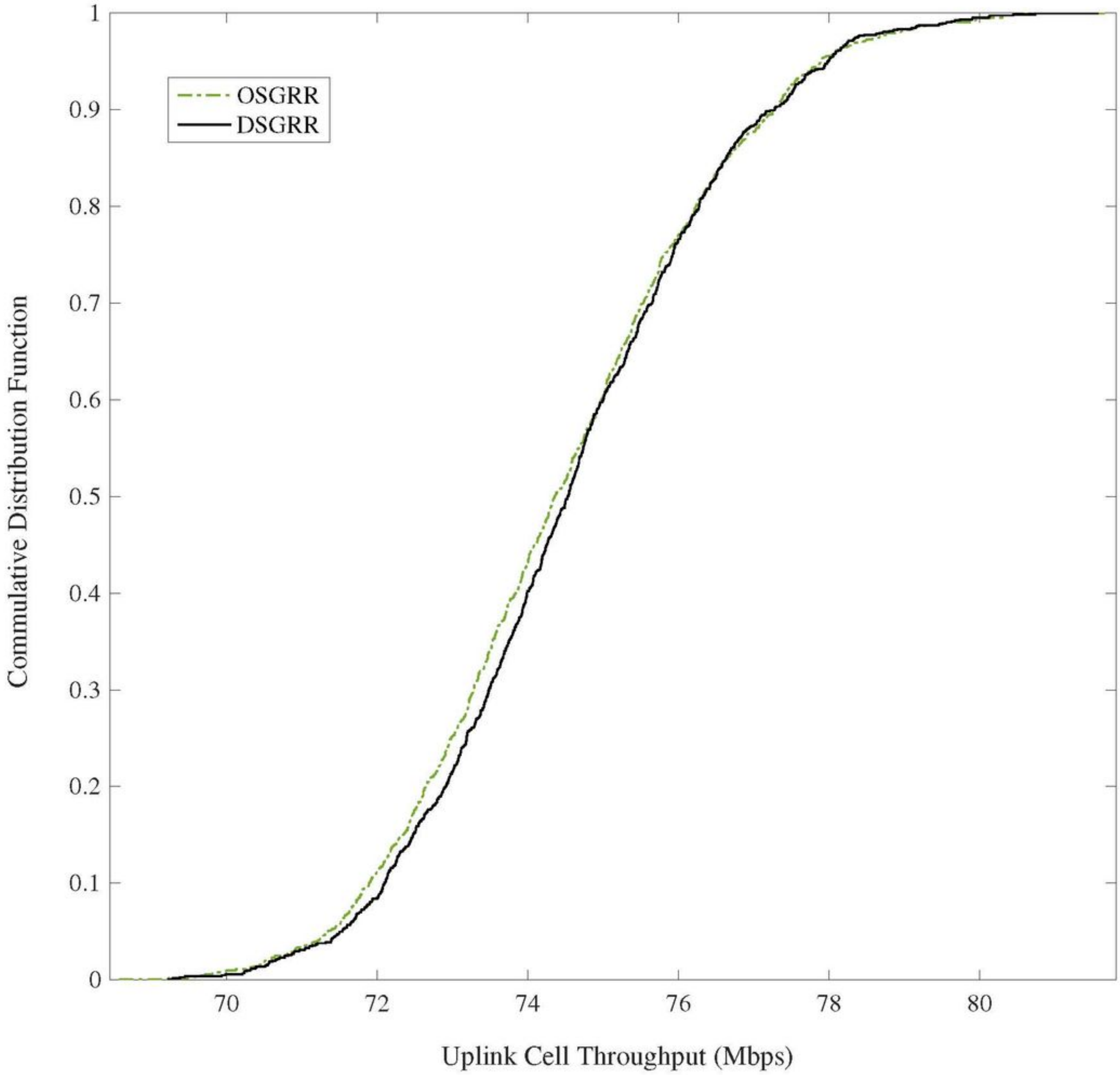

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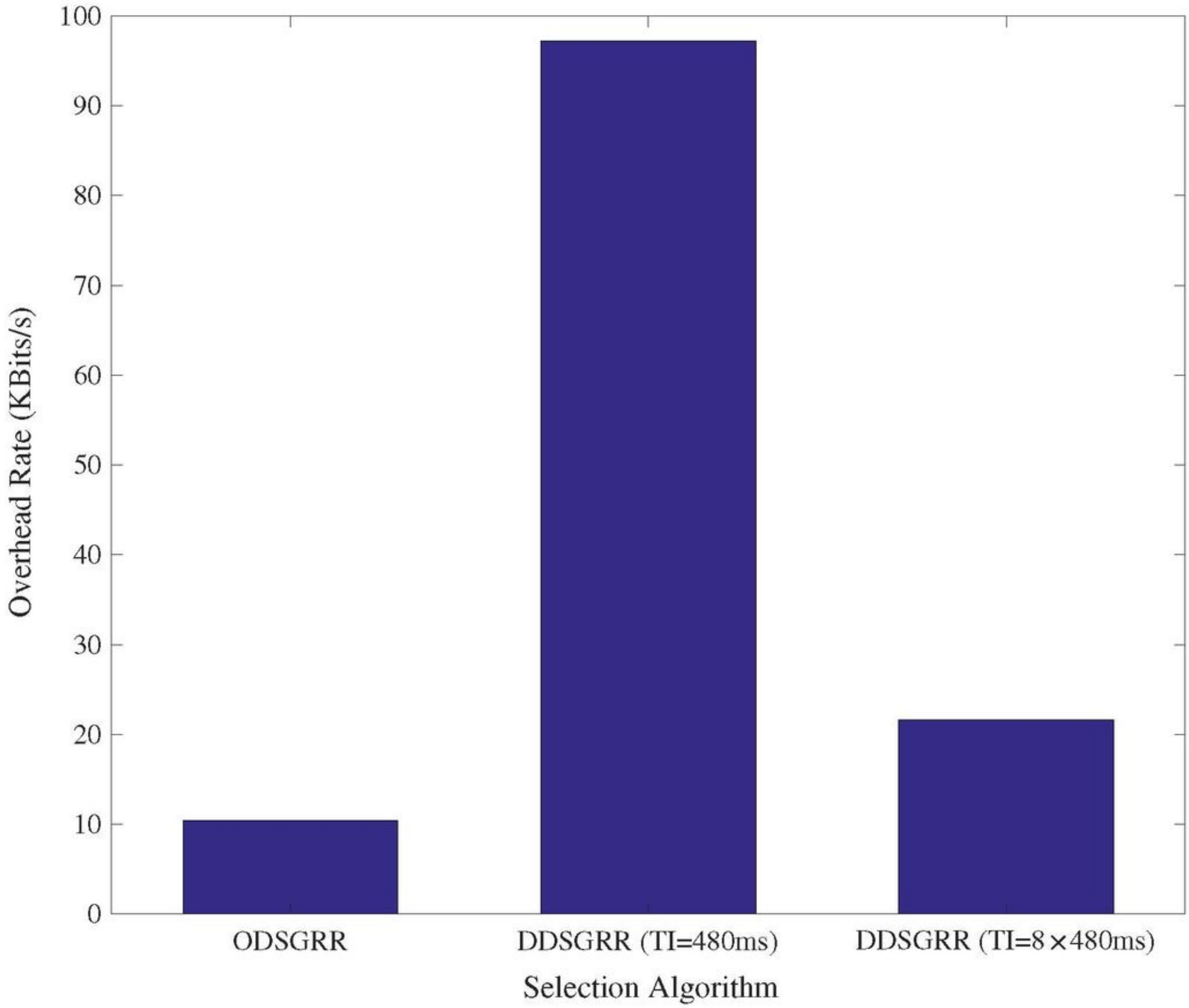

Figure 14

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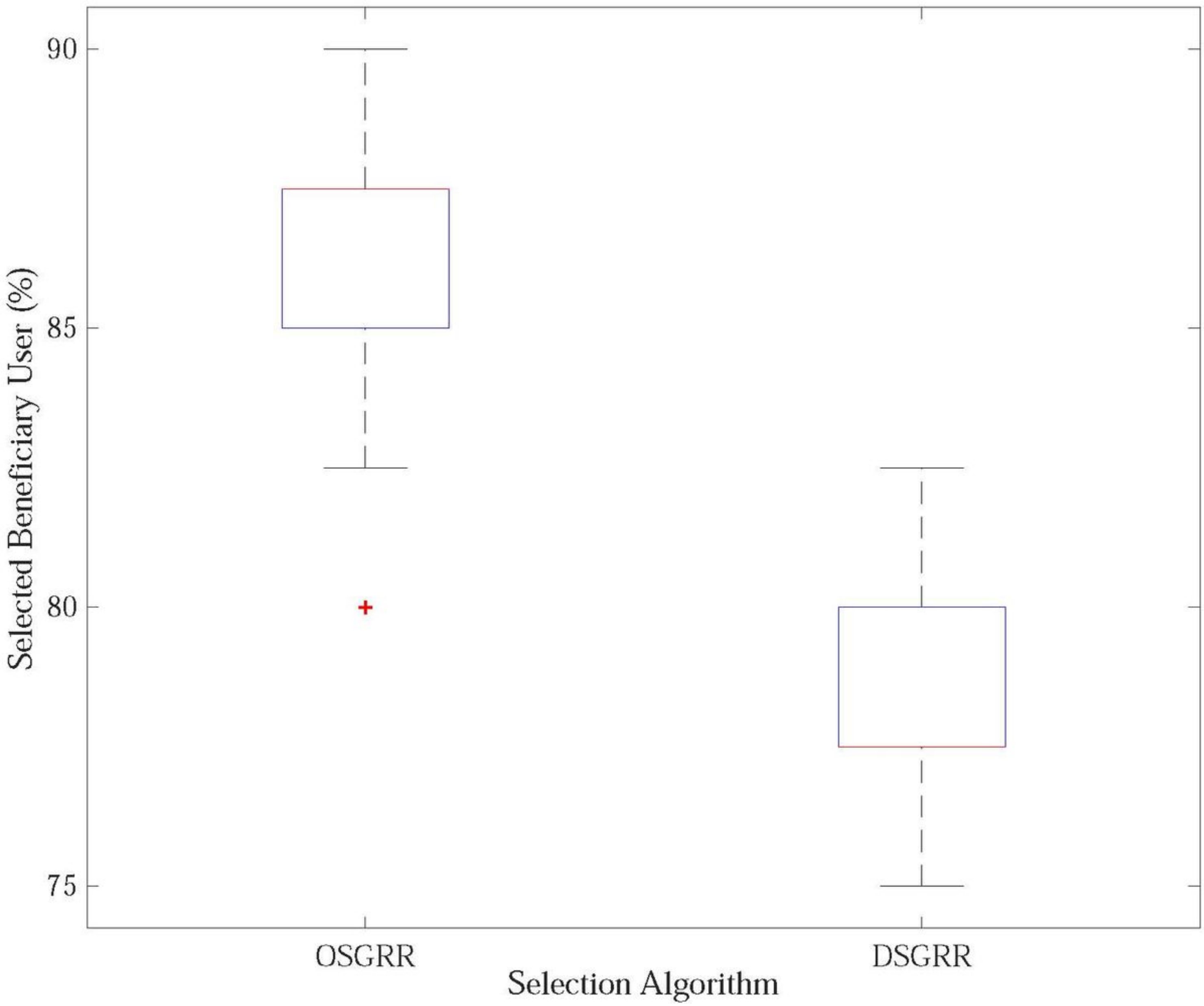

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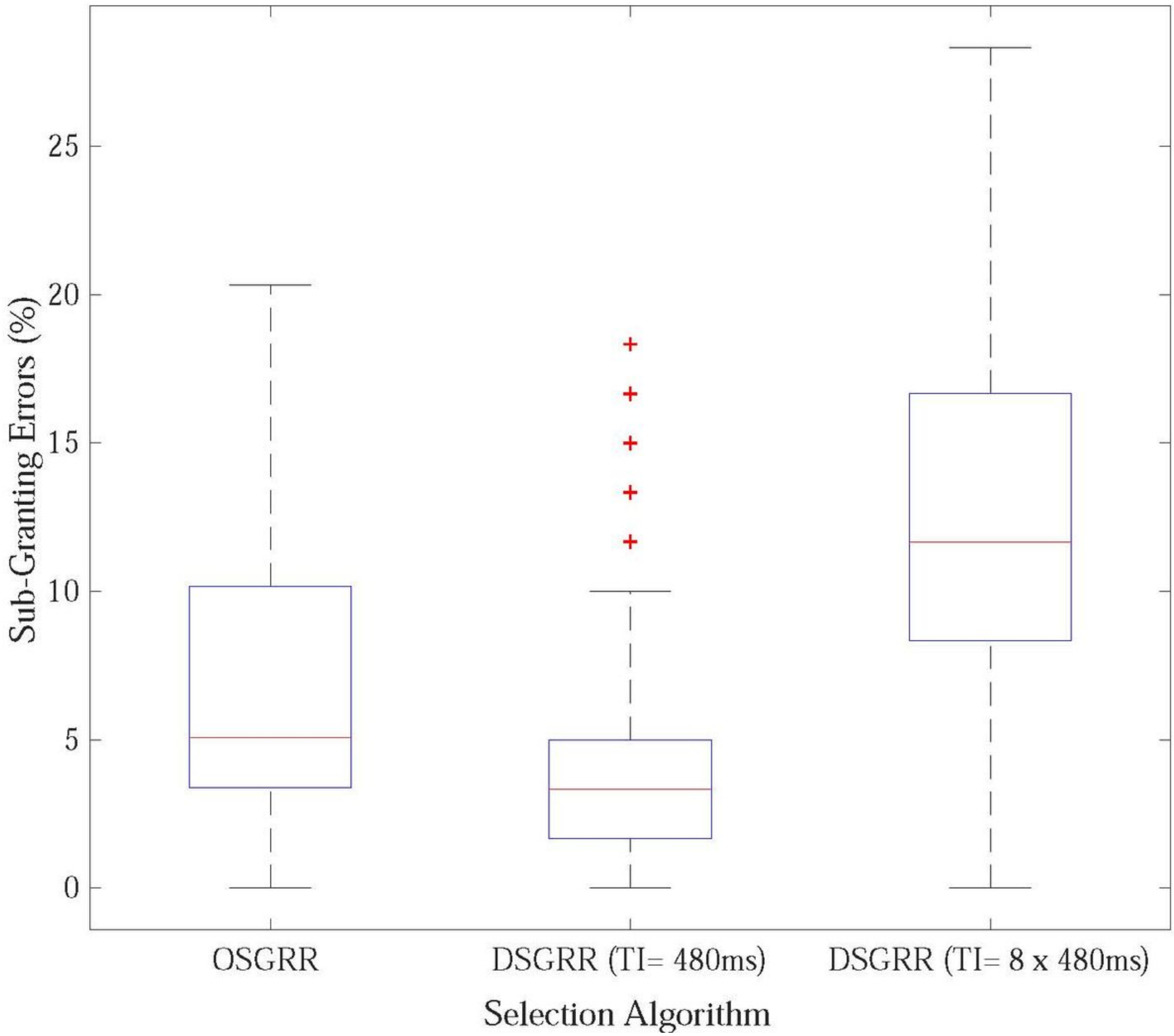
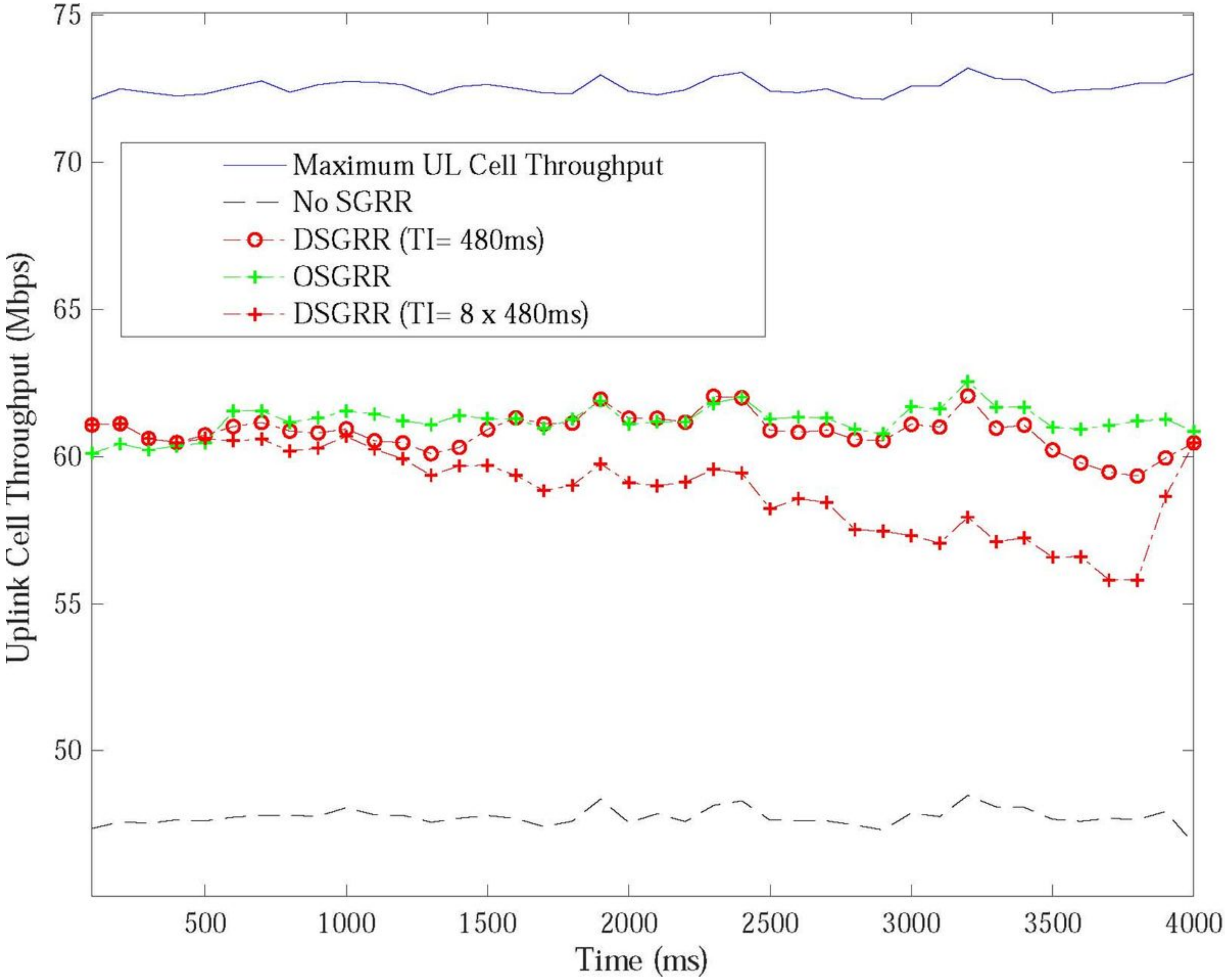


Figure 16

Sub-granting errors rate comparison between the DSGRR and OSGRR algorithms.



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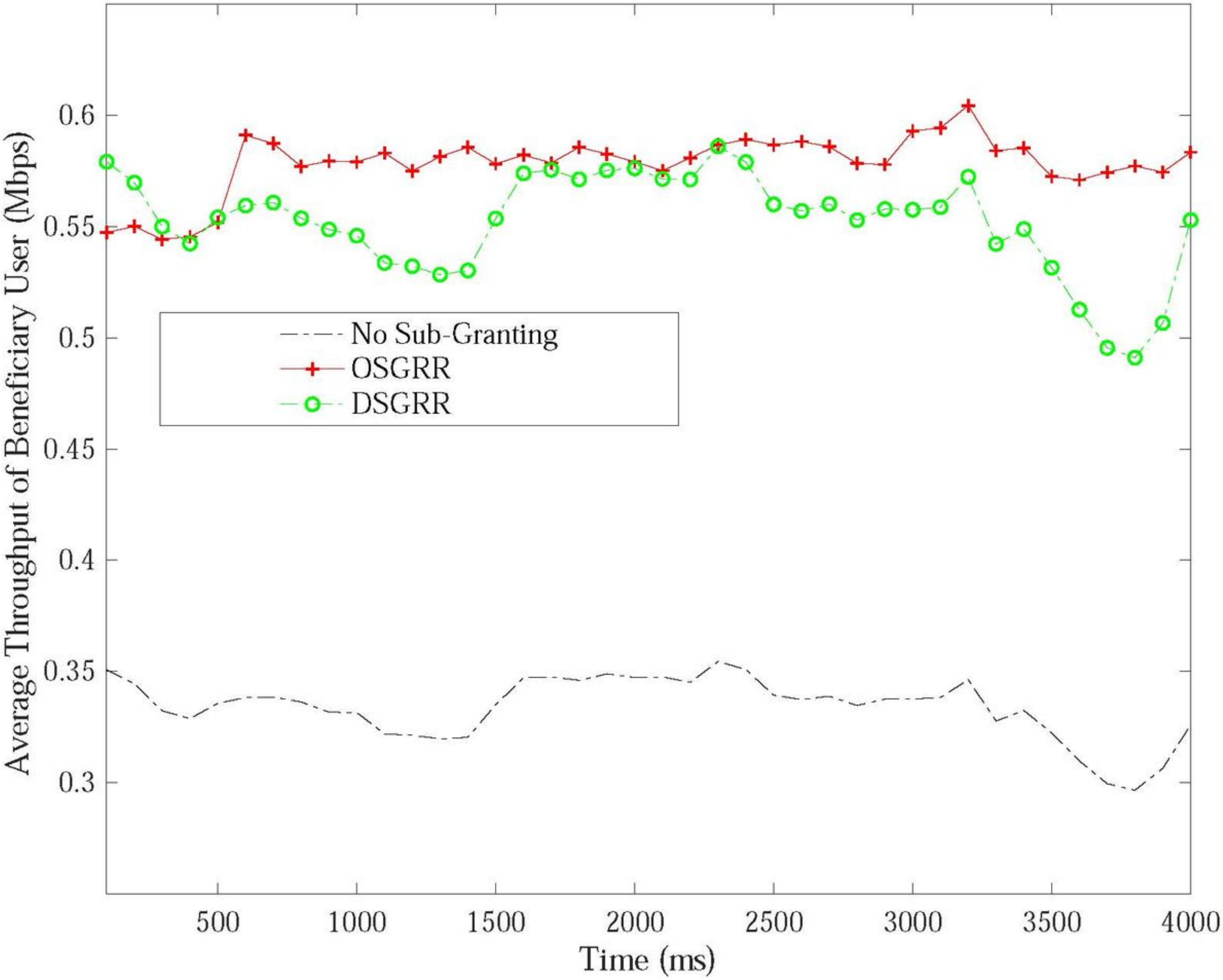

Figure 18

Comparison of the average uplink throughput of a beneficiary user.

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