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RESEARCH

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Open 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-everything (V2X) and machine-type communication in future cellular networks. D2D communication is envisaged to be the enabler to accomplish the requirements for the applications as mentioned earlier. Due to the scarcity of radio resources, a 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 underutilized radio resources from D2D communication to device-to-infrastructure communication, which are moving in a dynamic environment. The sub-granting assignment problem is cast as a maximization problem of the uplink cell throughput. Firstly, we evaluate the sub-granting signaling overhead due to mobility in a centralized sub-granting resource algorithm, dedicated sub-granting radio resource (DSGRR), and then a distributed heuristics algorithm, open sub-granting radio resource (OSGRR), is proposed and compared with the DSGRR algorithm and no sub-granting case. Simulation results show improved cell throughput for the OSGRR compared with other algorithms. Besides, it is observed that the overhead incurred by the OSGRR is less than the DSGRR while the achieved cell throughput is yet close to the maximum achievable uplink cell throughput.

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

1 Introduction

Capacity, reliability, and latency are the major requirements of applications for future wireless communications. Device-to-device (D2D) communication is foreseen as the first realization for the new emerging applications, e.g., vehicle to everything and machine-type communication [1]. 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, radio resources dedicated to a D2I are shared with D2D users. This approach increases spectral efficiency; however, it may cause 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 fully used by D2D users. To address this problem, authors in [2] proposed a new resource allocation technique based on energy sensing and mode selection, in which every user measures received signal strength of configured radio resources. After that, the cellular user performs a D2I/ D2D mode selection based on the measured received signal strength in a distributed manner. In [3], further study was taken on both centralized and distributed radio resource allocation techniques. 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. Authors in [4] suggest a reservation mechanism for autonomous resource selection algorithm in cellular V2X communication. In the proposed algorithm, each vehicle announces its reservation information for the second next re-selection. The results show some improvements in the face of congestion and the fringe of the communication range.

Authors in [5] studied a joint power and radio resource allocation problem. First, a factor graph is proposed to address the problem. Then, a belief propagation algorithm based on the real-time message received from other nearby vehicles is applied. After that, Lagrange decomposition is used to allocate the power to every vehicular user aiming to maximize the overall sum rate. The results show a significant improvement in terms of throughput and spectral utilization. However, the authors do not consider a processing delay and overhead due to the cooperative message exchange in the algorithm. In [6], the authors propose a centralized cluster-based resource allocation, called maximum inter-centroids reuse distance (MIRD), by which the same radio resources are scheduled between different clusters considering the quality service requirements of the application. The results show an improvement in spectral efficiency compared with the baseline scenario. However, the different traffic models in dynamic traffic were not considered.

As mentioned earlier, typically, many new applications are characterized by small payloads, and thus current subframe granularity in long-term evolution (LTE) is too coarse for the traffic payloads in such applications. As a result, a part of allocated resources is wasted, especially for the overlay radio resource allocation. For the first time, in [7], the 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 [8, 9] to evaluate the efficiency of the sub-granting scheme. In [8], the sub-granting and shortening transmission 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 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 [9] is proposed by which better results in terms of overhead, uplink cell throughput, and latency can be achieved.

The previous works assumed that a nearby beneficiary user with the highest modulation scheme is always available to utilize the sub-granting resources. However, 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, to the best of our knowledge, for the first time, a new DSGRR algorithm is proposed in [10] to resolve the beneficiary user selection problem in the sub-granting scheme. 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 indicates the unused resources information along with the selected beneficiary user identity through sub-granting signaling. 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 [10], 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., position information 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 cannot be performed centrally.

In this paper, we propose a novel distributed algorithm, i.e., OSGRR, 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 cooperatively. This way, the beneficiary user selection is decided in a distributed manner, whereby the overhead on the network due to measurement in a dynamic scenario can be reduced. With best of our knowledge, the proposed distributed beneficiary selection is discussed for the first time in this paper to address the problem of the beneficiary user selection of the sub-granting scheme.

The main contributions of this study are summarized as follows:

- We formulate the beneficiary user selection problem for the sub-granting scheme as a resource assignment optimization problem. The optimization problem aims to select the beneficiary users subject to some constraints in order to maximize the uplink cell throughput.
- A new distributed algorithm OSGRR is proposed and compared with the baseline algorithm DSGRR and when the no sub-granting case is applied in terms of uplink cell throughput, the number of selected beneficiary users, and sub-granting errors considering different measurement transmission interval in a dynamic environment.
- The overhead is formulated for both algorithms. We calculate the overhead of DSGRR and OSGRR algorithms, taking into account position information CSI measurements, sub-granting signaling, bidding information.

The remainder of this article is organized as follows. In Sect. 1, the system model is described. We explain the problem formulation in Sect. 2. In Sect. 3, the operational functionality of the sub-grant provider D2D and the beneficiary user D2I for

both algorithms is briefly described, and then both centralized DSGRR and distributed OSGRR algorithms are explained. The results are discussed in Sect. 4. Finally, in Sect. 6, some concluding remarks are presented.

2 Scenarios and system model

2.1 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 evolved Node B (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 overheads 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 un-utilized 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.

Table 1 Different scenarios of the sub-granting scheme

Sub-grant provider	Beneficiary user	Use cases
D2D or D2I	D2D or D2I	V2V, V2I, MTC, P2I

2.2 System model

We consider a single-cell environment with M D2I users (D2I-UEs) and N D2D users (D2D-UEs) denoted by sets $C = \{1, \dots, M\}$ and $D = \{1, \dots, N\}$, 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 Blocks (RBs) 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 schedules orthogonal uplink radio resources for D2I users at every scheduling time by any reasonable scheduling scheme. To avoid scheduling delays, the eNB assigns one Resource Block (RB) to every D2D-UEs for a specific time (see Label (1) in Fig. 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 Fig. 1), to the all nearby D2I-UEs, i.e., beneficiary user (see Label (3) in Fig. 1). Also, the D2I-UEs are a side-link capable user who can communicate with other users in proximity through the side-link communication [11].

Further assumptions in this study are made as follows:

- All D2I-UEs are full buffer users with best-effort traffic payload.
- 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:

$$G = cr^{-\alpha}|\mu|, \tag{1}$$

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.

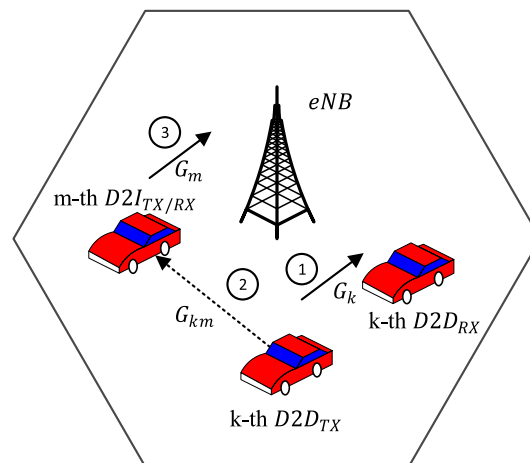


Fig. 1 A typical network is consisting of one eNB, one D2D-UE, and one D2I-UE. The $k - th$ D2D user sub-grants the un-used radio resources to the $m - th$ D2I user, when channel gain G_{km} between $k - th$ D2D user and $m - th$ D2I user is above a certain threshold

- All users are equipped with a Global Positioning System (GPS), and assists the eNB with the position information.
- The notations used in this study are summarized in Table 2.

3 Problem formulation

In [10], it is proposed to decompose the uplink cell throughput into the aggregated throughput of the D2I and D2D users within the cell. Then, a scenario with stationary users was studied. In such a scenario, 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 position transmission, was ignored. In this study, we consider a scenario where 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 transmission overhead, the uplink cell throughput stated in [10] could be reformulated as:

Table 2 List of notations

Notation	Interpretation
D	Set of D2D users where $d_k \in D$ for $k = 1, \dots, N$
C	Set of D2I users where $c_m \in C$ for $m = 1, \dots, M$
L	Set of allocated RBs to D2D communication
F	Set of available RBs on eNB
B_W	Allocated bandwidth
b	Number of allocated RBs to every entities where $b = 1, \dots, F$
\mathbb{X}	Sub-granting allocation indicator
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, $m = 1, \dots, M$
P_{MAX}^C	Power threshold limit for D2I transmitter
P_k	Transmission power of D2D transmitter, $k = 1, \dots, N$
q	Modulation and coding scheme of every entities
ϵ	General term for BLER
ϵ_{th}^D	Minimum BLER threshold for D2D communication
ϵ_{th}^{sg}	Minimum BLER threshold for sub-granting
ϵ_{mk}	Measured BLER between D2D and D2I users
T	Subframe transmission time
τ	Data transmission duration
T_{me}	Channel state information transmission interval
T_{pos}	Position information transmission interval
T_{br}	Bids transmission interval
S_{Min}	Sub-granting signaling processing time
\mathcal{U}	Unique number of a cellular user in network

$$R_{cell}(\epsilon, \tau) = \sum_{m=1}^M (R_m(\epsilon, \tau) - \bar{h}_m(\tau)) + \sum_{k=1}^N (R_k(\epsilon, \tau) - \bar{h}_k(\tau)), \quad (2)$$

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 [12]:

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

where G is the radio channel gain that is calculated from (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, $\Gamma = \frac{-\ln(\epsilon)}{1.5}$ [12]. In case of $D2D$ users with small traffic payloads, the equation in (3) is not accurate enough, and thus the achievable throughput R_k for $D2D$ user is reformulated as follows [13]:

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

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

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

In (2), \bar{h}_k and \bar{h}_m are the overhead due to the sub-granting signaling, the position information and radio link measurement reports transmitted by the $D2I$ and $D2D$ users. In [10], 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:

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

where S_{Min} is a processing time of a UE that depends on the hardware and the number of allocated resources in time and frequency domain [14]. We now rewrite (2) for the dedicating and open sub-granting considering the $D2I$ and $D2D$ overhead as follows:

$$\begin{aligned}
R_{cell}(\epsilon, \tau) &= \sum_{m=1}^M (R_m(\epsilon, \tau) - \bar{h}_m(\tau)) \\
&+ \sum_{m=1}^M \sum_{k=1}^N \mathbb{X}_{mk} R_{mk}(\epsilon, T - \tau_k) \\
&+ \sum_{k=1}^N (R_k(\epsilon, \tau) - \bar{h}_k(\tau)).
\end{aligned} \tag{7}$$

The equation in (7) considers the case where the D2D users have ultra-reliable and low-latency communication 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 [12] to calculate the upper bound bit error rate (ϵ) between D2D and D2I users as follows:

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

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:

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

subject to

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

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

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

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

where (9b) is constraint showing errors limit for the D2D sub-granting signaling. Constraint (9c) denotes that the available resources for sub-granting should be greater than the processing time at 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 [15]. 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 (9) aims to find a list of beneficiary users that maximizes the cell throughput. This problem can be defined as a Maximum Weighted Matching (MWM) problem in bipartite graphs with some non-linear constraints. When a large number of D2I and D2D users exist in a dynamic environment, an exhaustive search becomes intractable due to its high computational complexity. To avoid the drawbacks in using an exhaustive search solution, in the following sections, we explain a centralized algorithm considering the overhead due to the user mobility. A new distributed algorithm is suggested and compared with the centralized approach to address the beneficiary user selection problem in the sub-granting scheme.

4 Sub-granting radio resource algorithms

This section briefly explains the beneficiary users' operational functionality and the sub-grant provider user in the DSGRR algorithm and the new proposed OSGRR algorithm. Then, some basics in the bipartite graph are described and explained how the maximum weighted matching is fitted to the beneficiary user selection problem in the sub-granting scheme to solve the problem. Finally, DSGRR algorithm in [10] and the new OSGRR algorithm are explained considering the overhead due to the user mobility.

Figure 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 eNB with their actual position information and CSI towards the eNB in every time interval. Afterwards, the eNB considers a hypothetical geographical area around every sub-grant provider users and seeks a beneficiary user within this area, aiming at increasing the overall cell throughput. Every selected beneficiary user is informed about the paired sub-grant provider users and monitors the sub-granting signaling at every time interval to utilize the sub-granting resources.

In a dynamic scenario with mobile users, the position and CSI information need to be updated more frequently, resulting in a high overhead on the cellular network.

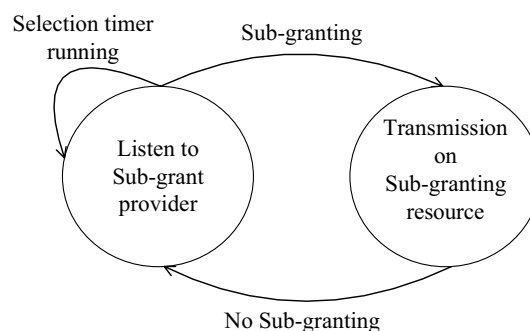


Fig. 2 State-machine diagram of a beneficiary user functionality on the dedicated sub-granting algorithm

To reduce the overhead arising from the position 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 this algorithm, the beneficiary user measures the received signal strength of the nearby sub-grant provider users and the eNB. Then, a bid value associated with every sub-grant provider user is computed based on these measurements. The bid value and the sub-grant provider identity are exchanged between nearby beneficiary users. The beneficiary user with the highest bid value can transmit on the sub-granting resource for a time interval.

In both algorithms, the sub-grant provider only informs the nearby beneficiary users about the unused resources and has not an impact in the beneficiary user selection process. Figure 4 depicts the functionality of the sub-grant provider in the dedicated and open sub-granting algorithms. In the dedicated sub-granting algorithm, the selected beneficiary user identity and the number of free symbols are indicated by the sub-granting signaling. In contrast, in the open sub-granting algorithm, only the number of free symbols and the sub-grant provider identity is transmitted.

Many problems can be cast as matching problem in a bipartite graph. The radio resource assignment problem can generally be modeled by a bipartite graph [16]. In this study, the relation between the sub-grant provider users and the beneficiary users is first modeled by a time-varying bipartite graph. The edge of the graph is weighted by 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.

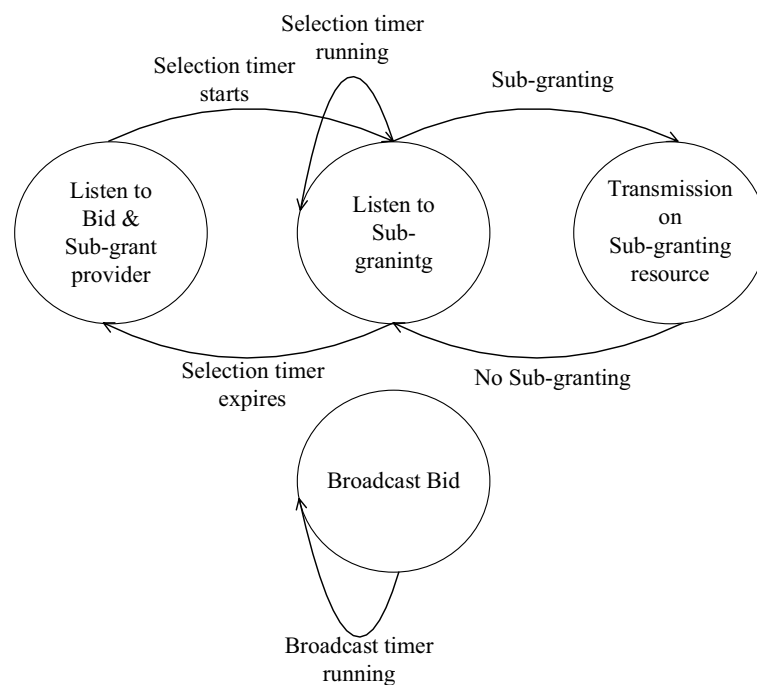


Fig. 3 State-machine diagram of a beneficiary user functionality on the open sub-granting algorithm

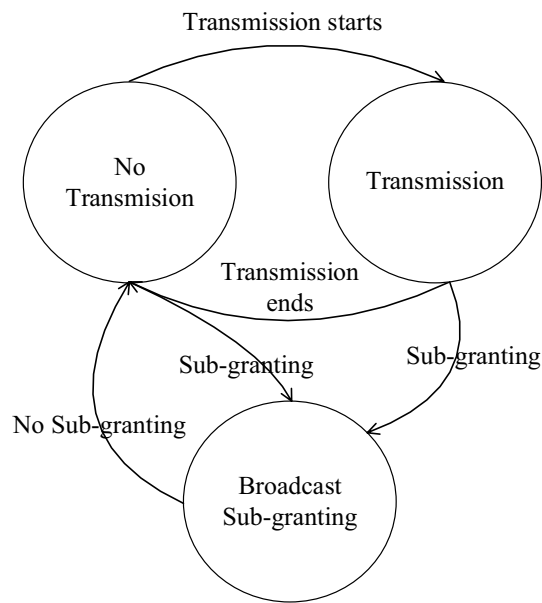


Fig. 4 State-machine diagram of sub-grant provider functionality

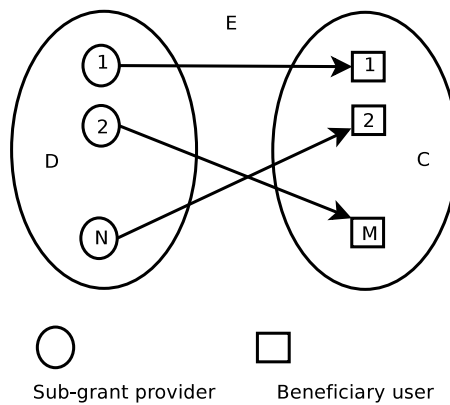


Fig. 5 An illustrative example of graph model

Definition 3.1 *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 $G = (U, V, E)$.*

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 of the graph. Every user in D is connected to the users in C .

Definition 3.2 *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.*

General background on maximum weighted matching and bipartite graphs can be found in [17].

4.1 Dedicated sub-granting radio resource (DSGRR) algorithm

The centralized dedicated sub-granting radio resource algorithm was initially proposed in [10] in a scenario where all users are stationary, and no overhead was taken into consideration. Here, we investigate the overhead due to user mobility and apply the algorithm to address the beneficiary user selection problem of the sub-granting scheme in (9). The DSGRR algorithm acts to solve the optimization problem in two stages. In the first stage, a hypothetical geographical area, an error-limited area, wherein the sub-granting signaling can be reliably received, for every sub-grant provider is calculated. In the second stage, a bipartite graph, as explained earlier, is constructed where the edges of the constructed bipartite graph are weighted by the beneficiary user data rate and updated in every beneficiary user selection time interval. The beneficiary selection problem is then solved applying the procedure explained in the algorithm to achieve the highest cell throughput.

4.1.1 Error-limited area (eLA)

As previously discussed, CSI 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 (1) and the channel model parameters for D2D communication in [18], the eLA (r_{eLA}) is bounded as:

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

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} .

Algorithm 1 Dedicated Sub-Granting Radio Resource

```

1: procedure BENEFICIARY USER SELECTION
   Input:  $d_k \in D^{1 \times N}, c_m \in C^{1 \times M}, e_{th}^{sg}$ 
   Initialization:
2:   Calculate error limited area radius for
    $d_k \in D, k = 1, \dots, N$  (Equation (10))
3:    $E \leftarrow \phi$ 
4:   for  $d_k \in D$  do
5:     for  $c_m \in C$  do
6:       if  $(c_m \in eLA_k) \& (\text{Constraint (9e)})$  then
7:          $e_{mk} = q_m, b_k$ 
8:          $E \leftarrow (E \cup e_{mk})$ 
9:       endif
10:    endfor
11:  endfor
   Repeat:
12:   $\mathbb{X} \leftarrow \phi$ 
13:  for  $d_k \in D$  do
14:    Find  $c_m \in C$  with Maximum  $e_{mk}$ 
15:     $\mathbb{X}_{mk} = 1$  &  $\mathbb{X} \leftarrow \mathbb{X} \cup \mathbb{X}_{mk}$ 
16:     $E \leftarrow E - \cup_{k=1}^N e_{mk}$ 
17:  endfor
   Output: Transmit  $\mathbb{X}_{mk}$  to every  $d_k$ 

```

4.1.2 Overhead

Due to the mobility of all users, the position information and channel state measurement information of users should be transmitted, which results in the overhead. The beneficiary user overhead \tilde{h}_m is given by:

$$\tilde{h}_m(\tau) = \frac{\mathbb{X}_m^{me} \times O_{me} + \mathbb{X}_m^{pos} \times O_{pos}}{\tau_m}, \quad (11)$$

where O_{me} and O_{pos} are the overhead values due to the channel state measurement and position information. The values \mathbb{X}_m^{me} and \mathbb{X}_m^{pos} are set at the measurement time interval T_{me} and position information time interval T_{pos} . The value τ_m stands for the data transmission time.

The overhead \tilde{h}_k on the sub-granting provider mainly arises from transmitting the position information to the eNB and indicating the unused radio resources to the beneficiary users and given by:

$$\tilde{h}_k(\tau) = \frac{\sum_{m=1}^M \mathbb{X}_{mk} \times O_{sg} + \mathbb{X}_k^{pos} \times O_{pos}}{\tau_k}, \quad (12)$$

where O_{sg} is the overhead values due to the sub-granting signaling overhead, when the assignment value \mathbb{X}_{mk} is set. Moreover, \mathbb{X}_k^{pos} is set when the position information is transmitted to the eNB at the transmission time interval T_{pos} , and τ_k is the data transmission time.

4.1.3 Computational 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 \mathcal{O} ($N \times M$) operations to complete the beneficiary users' selection process.

4.2 Open sub-granting radio resource (OSGRR) algorithm

The auction theory, which initially developed in the economy, is also 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 [19], 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 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 price 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 [19], the strategy function in every beneficiary users s_{mk} yields:

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

where q_m and q_{mk} are modulation and coding scheme of m – th beneficiary user towards the eNB and the sub-grant provider user, which are normalized by 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 eNB. 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. This way, the probability of the sub-granting errors is reduced, when the time interval of beneficiary user selection increases.

Note that if two beneficiary users have the same transmission parameters, e.g., q_m and q_{mk} , 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 unique value of γ_m is added to the first

term of bidding strategy function. This value can be the reverse of a unique cellular user-specific number \mathcal{L}_m , e.g., temporary mobile subscriber identity (TMSI) [20].

Figure 6 shows an illustrative example of the equilibrium bidding value of the strategy function in (13), considering a specific unique value TMSI for every beneficiary user. In the figure, β value of 0.9 is considered and q_m and q_{mk} values are normalized by the maximum value q_{MAX} in [21].

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

A 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 Fig. 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. To resolve the problem, a heuristic algorithm, i.e., open sub-granting radio resource, is applied.

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 eNB. 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 (13) considering the bit errors rate and power head room stated in constraints (9b) and (9e) in (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

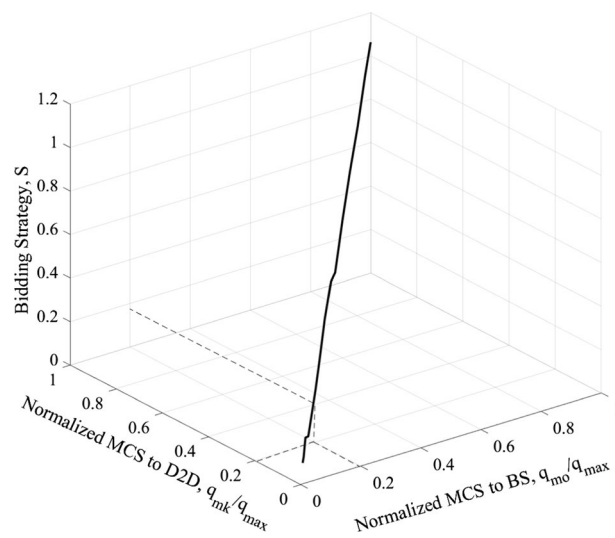


Fig. 6 An illustrative example of bidding strategy function

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 – 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 with the biggest bid value on the list is allowed to transmit on the sub-granting radio resources for a time interval configured by the eNB (see Lines (16 – 20) in Algorithm 2.

Algorithm 2 Open Sub-Granting Radio Resource

```

1: procedure BENEFICIARY USER SELECTION
   Input: Configure  $\beta$  value used in Equation (13)
   Initialization:
2:   Calculate  $\gamma_m = \frac{1}{z_m}$ ,  $m = 1, \dots, M$ 
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,  $E \leftarrow (E \cup s_{m-1,k})$ 
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: Matching List  $\mathbb{X}$ 

```

4.2.1 Overhead

The overhead in the open sub-granting algorithm is mainly due to the bidding and the sub-granting signaling messages exchanged between the beneficiary users. This way, the overhead on the beneficiary users \tilde{h}_m is given by:

$$\tilde{h}_m(\tau) = \frac{\mathbb{X}_m^{br} \times O_{br}}{\tau_m}, \quad (14)$$

where O_{br} stands for the overhead value owing to bidding message exchanged between the beneficiary users. The value \mathbb{X}_m^{br} is set when the bidding message is triggered at every broadcast time interval T_{obr} .

In the open sub-granting scheme, the sub-grant provider does not need to transmit the position information to the eNB, and thus the overhead h_k , in (12) is rewritten as follows:

$$\tilde{h}_k(\tau) = \frac{\sum_{m=1}^M \mathbb{X}_{mk} \times O_{sg}}{\tau_k}, \quad (15)$$

4.2.2 Computational 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 $O(N + M)$ to find a match list. For $N \gg M$ or $M \gg N$, the complexity is simply $O(N)$ or $O(M)$, respectively.

5 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 with a constant speed. At the cell borders, the UEs select a random direction towards inside the cell and continue moving inside the cell. The channel models in [18] 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 [18]. Besides, we consider the Rayleigh and Rician fading models to capture the small-scale fading effects. Without loss of generality, it is assumed that the channel conditions do not vary during the beneficiary user selection process. For both D2D and D2I communications, LTE open-loop power control is assumed [15]. The transmission power distribution of D2I users is shown in Fig. 8. In this paper, a traffic model based on the requirements given in [22] is considered (see Table 3). Figure 7 illustrates the distribution of traffic payload generated by D2D users during the simulation run.

To avoid any nonuniformity 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 4000 ms, and then the average of the results is considered. Simulation parameters are summarized in Table 3.

In this article, the following metrics are considered to evaluate the performance of the studied algorithms:

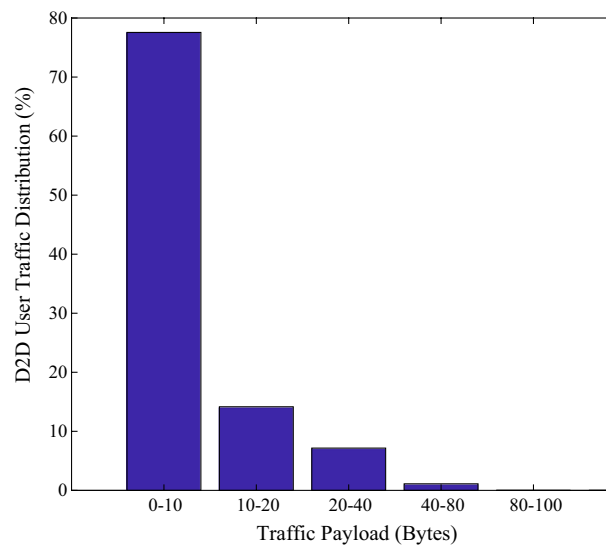
- Uplink cell throughput.
- Average throughput of beneficiary user.
- Number of selected beneficiary users.
- Sub-granting signaling errors.
- Overhead.

6 Results and discussion

The first time, a new DSGRR algorithm is proposed in [10] to resolve the beneficiary user selection problem in the sub-granting scheme. 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. This way, the measurement transmission to eNB, which is needed for the beneficiary resource selection, is avoided. Figure 9 shows the relationship between the *eLA* and desired received power, P_0 , in the open-loop

Table 3 Network parameters used in the simulator

Parameter	Value
Frequency, f_c 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 [18]	UMi-NLOS α_c : 3.67 μ_c : $\sigma = 4$ dB, Rayleigh InH-NLOS α_d : 4.33 μ_d : $\sigma = 4$ dB, Rician, K=20 dB
User velocity	30Kmph
Traffic model	Packet size=10B, $\lambda=1$ ms, $\epsilon_{th}^D=10^{-5}$ [1]
Power control	Open-loop power control [15] D2D ($P_0 = -90$ dBm/RB) D2I ($P_0 = -107$ 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 (l)	4000
T_{me}, T_{pos}, T_{br}	480 ms
β	0.9

**Fig. 7** D2D traffic distribution

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 P_0). Despite the circular eLA shape shown in Fig. 9, the actual geometry eLA is irregular and thus far from being circular. The reason is because of large-scale fading phenomena, i.e.,

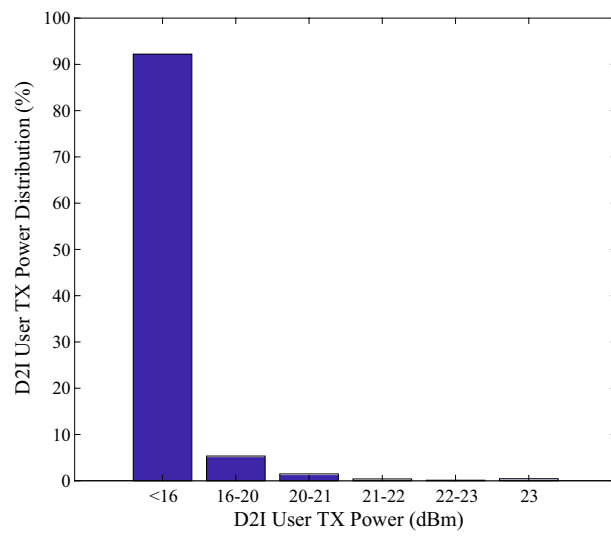


Fig. 8 D21 transmit power distribution

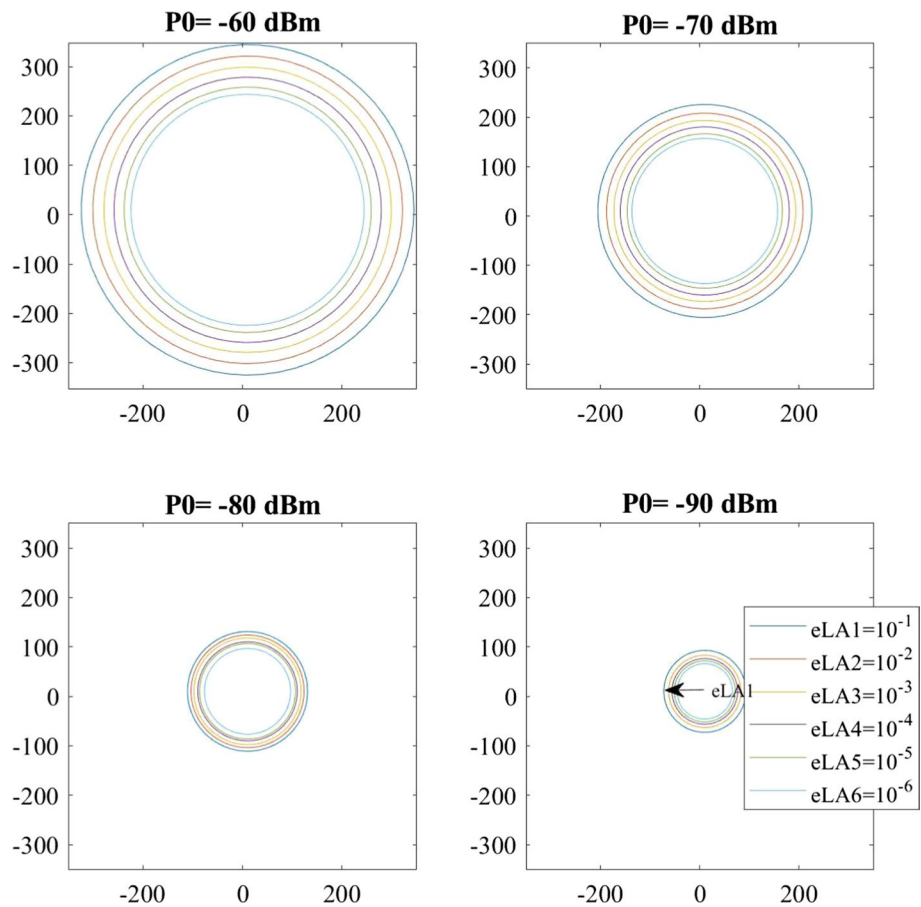


Fig. 9 Impact of P_0 on the error-limited area, eLA, where eLA is an area that sub-granting signaling is received reliably. P_0 is the desired received signal in the open-loop power control equation [15]

shadowing, employed in (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 modulation coding scheme value towards the BS are selected. Although the difference between the achieved throughput with β values of 0.9 and 0.5 is marginal in the studied scenario, the results show a slightly higher uplink throughput when β value is set to 0.9.

Although using a centralized approach could achieve an optimal solution for the beneficiary users' selection problem, it will increase the burden of overhead arising from the measurement. Therefore, an eLA based beneficiary selection algorithm, i.e., DSGRR, was proposed in [10] whereby 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 measured received strength signal from the sub-grant provider users. Due to the small-scale fading in the OSGRR, the probability of receiving a signal from the sub-grant provider is higher. As a result, the average coverage radius of a sub-grant provider becomes bigger in the OSGRR than the eLA area, estimated in the DSGRR. Figure 11 shows an illustrative example of a coverage area that is considered by the OSGRR and DSGRR algorithms for the beneficiary user selection.

Considering the above explanation, more beneficiary users receive the sub-granting signaling in the OSGRR, which the chance of the sub-granting resources being used by the beneficiary users increases.

To prove this, the number of the candidate beneficiary users of every sub-grant provider for both algorithms is investigated. As shown in Fig. 12, the number of the

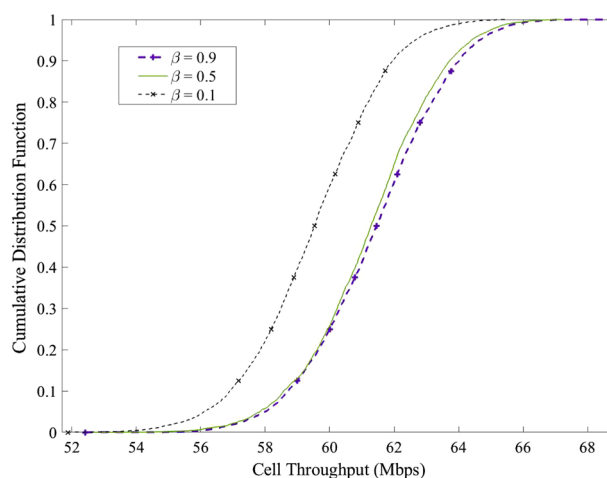


Fig. 10 Impact of beta value on cell throughput for the OSGRR. The highest cell throughput is achieved at a value of β 0.9

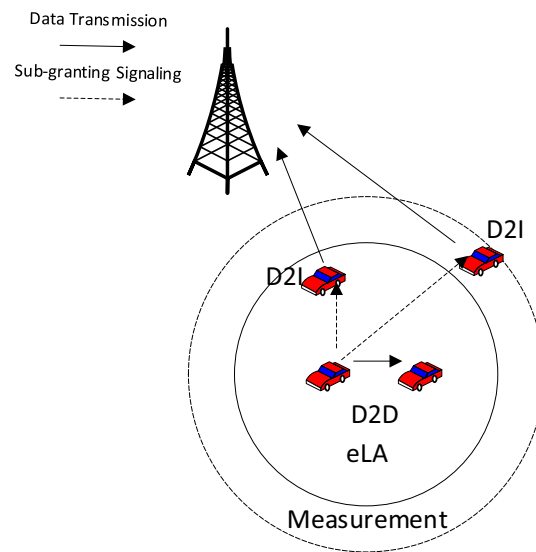


Fig. 11 An illustrative example of the sub-grant provider coverage area for measurement-based and eLA-based approaches

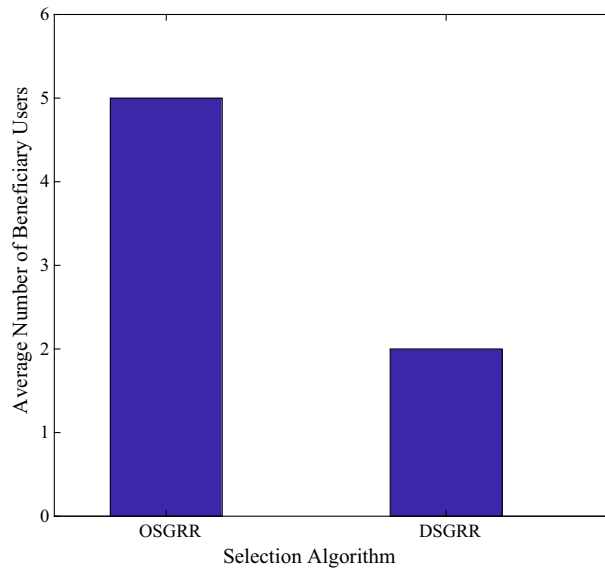


Fig. 12 An illustrative example of the average number of candidate beneficiary users of every sub-grant provider

candidate beneficiary users is higher in the OSGRR compared with the DSGRR. The reason is that the measurement-based method, i.e., OSGRR, will increase the probability of receiving the sub-granting signaling. It is worth noting that the uniform large-scale fading assumption in the eLA computation causes to have a lower number of the candidate beneficiary users of ever sub-grant provider in the DSGRR, resulted in further performance degradation in the DSGRR algorithm.

Further, an observation is undertaken to indicate the impact of measurement information between beneficiary user and the sub-granting provider and to validate the implementation of both algorithms in the simulation study. For this purpose, the small-scale fading effect and overhead are not considered for both algorithms. It is observed that both algorithms achieve almost the same uplink cell throughput (see Fig. 13). Note that the marginal difference is due to the stochastic essence of the large-scale fading in both algorithms, whereby a different number of beneficiary users may be selected.

In the dedicated sub-granting algorithm, i.e., DSGRR, every entity transmits CSI measurement and position information to the eNB at a time interval of 480 ms. Then, the eNB informs the sub-grant provider user about the beneficiary user identity through control information. These measurements and control information is conveyed by the uplink/downlink LTE physical layer control channels. This study assumes the bandwidth of one resource block and modulation coding scheme of QPSK-1/2 to carry the control information and measurement information in both downlink and uplink, respectively. The overhead due to the uplink measurement is calculated by $(\text{sub-carrier}) \times (\text{OFDMA symbols}) \times (\text{modulation order}) \times (\text{code rate}) = \frac{12 \times 14 \times 2 \times 1/2}{8} = 21$ bytes and considering 3 bytes for cyclic redundancy check (CRC), total overhead has amounted to 24 bytes [15].

In the downlink, the overhead is $\frac{12 \times 3 \times 2 \times (1/2)}{8} = 5$ bytes, and 3 bytes is added as CRC resulted in 8 bytes overhead for the beneficiary user selection indication.

Also, given that every cellular user is equipped with a global positioning system (GPS), every user caters for the cellular network location information (e.g., location estimate, pseudo-range, velocity). Considering the uplink user-assisted information in [23], the overhead due to position information, the MAC layer information, and physical layer information, is about 40 bytes. In this study, it is assumed that the network

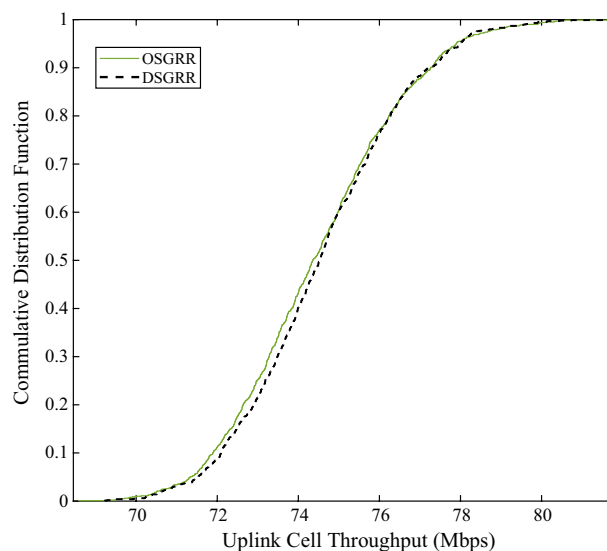


Fig. 13 An illustrative example of comparison of the uplink cell throughput for both algorithms in a scenario with stationary users where the overhead and small-scale fading are not considered

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

Selection algorithm	Overhead components	Size (Byte)
DSGRR	Position information	40
	Measurement information (e.g., buffer status, power head room)	24
	Beneficiary user selection signaling	8
	Sub-grant signaling	1
OSGRR	Bidding information	11
	Sub-grant signaling	1

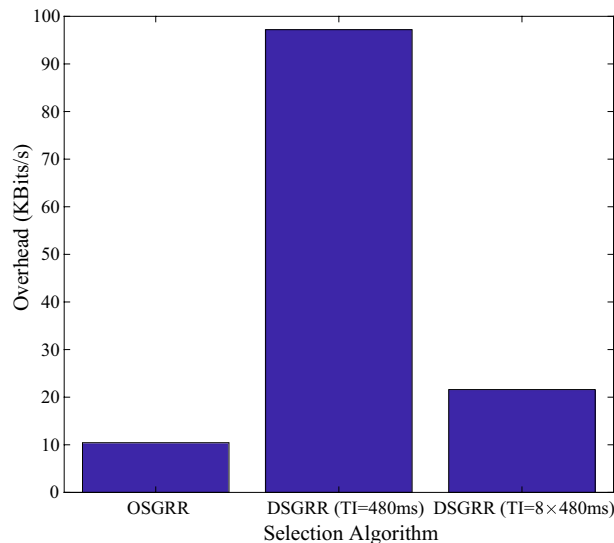


Fig. 14 Overhead comparison between open sub-granting and dedicated sub-granting algorithms. The impact of different position information and measurement transmission interval for the dedicated sub-granting algorithm is shown

can obtain a sufficiently accurate position of every user employing user-assisted information.

In the open sub-granting algorithm, i.e., OSGRR, every beneficiary user offers a bid value on the sub-granting resources, and a beneficiary user offering the highest value can utilize the sub-granting resource for a specific transmission interval time, e.g., 480 ms. In (13), one byte is required to indicate the CQI values, and 4 bytes are used to show the beneficiary user's unique number γ_m . Considering overhead of MAC and physical layers, i.e., 6 bytes, [15], the OSGRR imposes 11 bytes overhead to indicate the bid value. Note that the sub-granting signaling imposes 1 byte overhead on both algorithms [7]. Table 4 illustrates components and size of the overhead for both algorithms.

Figure 14 compares the overall overhead of the OSGRR and the DSGRR algorithms when the bidding transmission interval and position and measurement information transmission interval are the same for both algorithms. Also, the impact of CSI measurement and position transmission interval on the DSGRR algorithm is examined. It can be seen that the overhead on the DSGRR algorithm is higher than the OSGRR algorithm. The reason is that in the beneficiary user selection process, the volume of measurement and position information that are transmitted to the eNB in

the DSGRR algorithm is higher than the bidding information exchanged between users in the OSGRR algorithm.

The overhead on the DSGRR is reduced when the measurement transmission interval increases from 480 ms to 8×480 ms; however, the result still shows less overhead in favour of the OSGRR algorithm. The reason is that the OSGRR needs a few bytes to broadcast the bids and does not impose any CSI and position information transmission overhead on the eNB. Although in the DSGRR, the overhead can be further reduced by the increment of the 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, in the OSGRR, a beneficiary user has a higher chance of receiving the sub-granting signalling than 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 only selected by one of the sub-grant provider users. In contrast, in the OSGRR, farther beneficiary users may receive sub-granting signaling from a sub-grant provider user not assigned to any beneficiary user, resulted in increasing the number of selected beneficiary users. 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 errors for the OSGRR and DSGRR algorithms for different position information and measurement transmission interval.

The DSGRR shows a lower error rate compared with the OSGRR considering the same transmission interval for position information, CSI, and bid information. The reason is that in the OSGRR, farther beneficiary users are selected, which increases

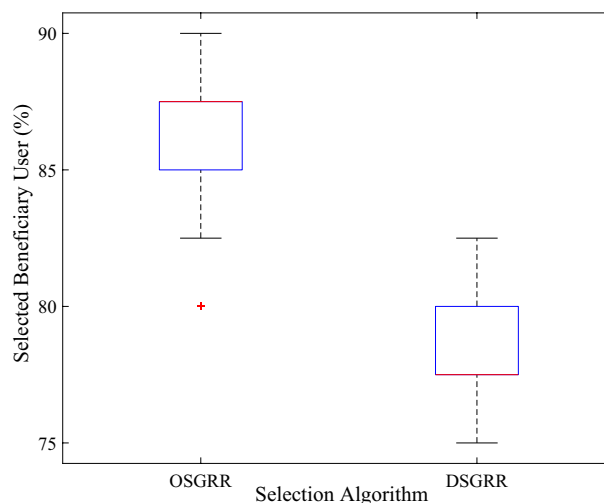


Fig. 15 Comparison of the average number of selected beneficiary users between the DSGRR and OSGRR algorithms

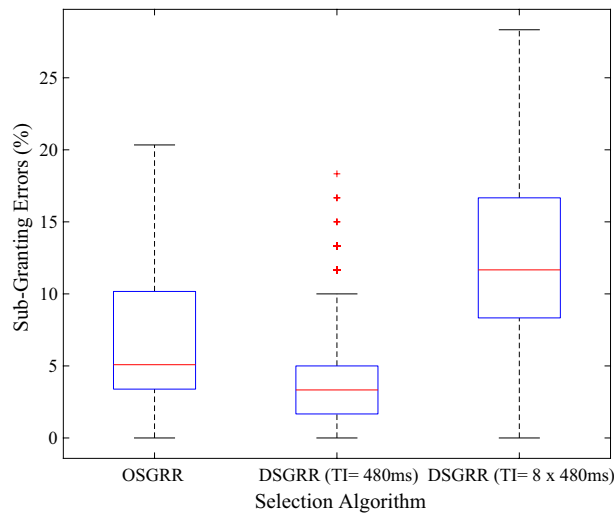


Fig. 16 Sub-granting errors comparison between the DSGRR and OSGRR algorithms

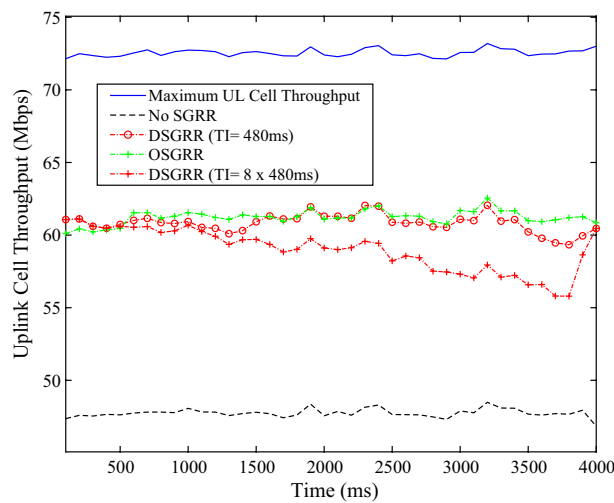


Fig. 17 Performance of different approaches in terms of cell throughput. The impact of measurement and position information transmission interval for the dedicated algorithm is shown

the probability of not decoding the sub-granting signaling owing to the fading between the sub-grant provider and the beneficiary user. In the DSGRR, when CSI and position information transmission interval increases by eight times, the sub-granting signaling errors increase by more than two times due to using the outdated eLA information during the beneficiary selection process.

Figure 17 shows the impact of the CSI and position information transmission 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 mainly contribute to the cell throughput degradation in the DSGRR compared with the OSGRR. As indicated in Fig. 14, the overhead contributes only to about 5% of the cell throughput reduction in the DSGRR. Another factor in the cell throughput reduction is that having a lower number of selected beneficiary users in the DSGRR, resulted in a higher throughput in favor of the OSGRR.

When the transmission interval increases by eight times, the cell throughput in the DSGRR gradually decreases during simulation runs. The results show about a 10% reduction in the cell throughput than the cell throughput with a shorter transmission 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 finding a beneficiary user with the highest MCS. It is noteworthy to mention that 35% of the allocated radio resources are wasted w/o sub-granting scheme (see Fig. 17).

Figure 18 depicts the beneficiary user's average throughput for both algorithms, considering the exact measurement, position, and bidding transmission interval. Both algorithms show about a 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 Fig. 16), the average beneficiary user throughput is slightly higher than the one 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.

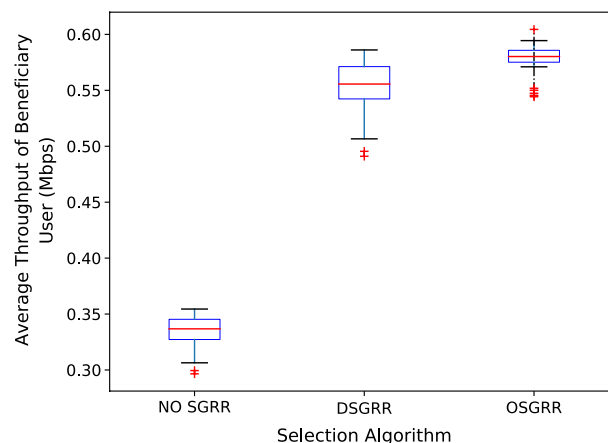


Fig. 18 Comparison of the average uplink throughput of beneficiary user for different approaches

7 Conclusions

This paper investigates the beneficiary user selection problem in the sub-granting of unused radio resources of the sub-grant provider to the beneficiary users [7].

The beneficiary user selection problem in the sub-granting scheme is formulated as a maximum weighted matching in a bipartite graph. Then, inspired by the auction theory, a novel distributed algorithm, i.e., Open sub-granting radio resource (OSGRR), is proposed to resolve the assignment problem. The proposed algorithm is compared with the centralized algorithm, i.e., dedicated sub-granting radio resource (DSGRR) [10], and no sub-granting fashion, in a scenario with a dynamic environment. The overhead of both algorithms is formulated and computed considering the channel state information, position information, bidding information, and sub-granting signaling, exchanged among different entities at different transmission intervals. Moreover, both OSGRR and DSGRR algorithms are evaluated in terms of cell throughput, user throughput and sub-granting signaling errors. Finally, the uplink cell throughput for both algorithms is compared to the maximum achievable uplink cell throughput.

Both OSGRR and DSGRR algorithms achieve the same uplink cell throughput, which is 85% of the network's maximum achievable uplink cell throughput. However, the OSGRR algorithm imposes less overhead on the network than the DSGRR algorithm. Furthermore, it is observed that both the OSGRR and DSGRR algorithms improve the uplink cell throughput by almost 20% compared with the case no sub-granting scheme is applied.

Considering the beam steering, the applicability of the beam steering on both DSGRR and OSGRR algorithms is worth investigating further in the future for a scenario when multiple re-uses of sub-granting resources are allowed. This way, the same sub-granting resource is allocated to different beneficiary users considering the geographical and mobility direction of the users while maintaining the interference below a certain threshold.

8 Methods/experimental

The purpose of this study was to develop a distributed radio resource allocation algorithm to assign the underutilized radio resources from D2D user to D2I user, i.e., sub-granting scheme, in a distributed fashion. The system consists of a single cell where D2D and D2I users are distributed uniformly within the cell. The channels are assumed to be time-variant, complying with the 3GPP channel model, and open-loop power control is applied to all users. Per-cell and per-user uplink throughput and overhead were optimized applying the proposed algorithm. Furthermore, the proposed distributed algorithm is compared with a centralized algorithm, no sub-granting fashion, and the maximum achievable uplink cell throughput.

Abbreviations

BS	Base station
GPS	Global positioning system
LTE	Long term evolution
UE	User equipment
MTC	Machine-type communication
D2D	Device-to-device
D2I	Device-to-infrastructure
CSI	Channel state information

V2X	Vehicle-to-everything
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
TTI	Transmission time interval
MCS	Modulation and coding scheme
M2M	Machine-to-machine
P2I	Pedestrian to infrastructure
eNB	Evolved node B
RB	Resource block
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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Authors contributions

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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.

Declarations**Competing interests**

The authors declare that they have no competing interests.

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