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Interference Aware Channel Assignment Algorithm for D2D Multicast Underlying Cellular Networks

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Abstract

Abstract: Device-to-device (D2D) multicast has become a promising technology to provide specific services within a small geographical region with a high data rate, low delay and low energy consumption. However, D2D multicast communications are allowed to reuse the same channels with cellular uplinks and result in mutual interference in a cell. In this paper, an intelligent channel assignment algorithm is designed in D2D underlaid cellular networks with the target of maximizing network throughput. We first model the channel assignment problem to be a throughput maximizing problem which is NP-hard. To solve the problem in a feasible way, a novel channel assignment algorithm is proposed. The key idea is to find the appropriate cellular communications and D2D multicast groups to share a channel without causing critical interference, i.e., finding a channel for a D2D multicast group which generates the least interference to network based on current channel assignment status. In order to show the efficacy and effectiveness of our proposed algorithm, a novel search algorithm is proposed to find the near-optimal solution as the baseline for comparisons. Simulation results show that the proposed algorithm improves the network throughput.

Keywords: Cellular Networks, D2D, Interference, Multicast Communication, Resource Management

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1. Introduction

Recently, content sharing based services, such as live streaming, weather forecasting, multi-player online games, file distribution, which broadcasting the same information to multiple proximate devices or user equipments (UEs) have been increasing rapidly. D2D multicast in cellular networks has received widely attention in future 5G networks, since it provides direct communications among multiple users in a small geographical region [1, 2]. In D2D multicast cellular networks, the same packets are sent from a D2D transmitter to multiple nearby D2D receivers directly without forwarding to base station (BS). This allows us to save a considerable amount of channel resource in comparison to a dedicated channel to every device.

Based on spectrum utilization, D2D communications in cellular networks can be divided into two categories: in-band D2D and out-band D2D [3]. For in-band D2D, D2D communications use the licensed spectrum of cellular network, which improves spectrum efficiency. However, new interference is generated within a cell [4]. Further, in-band D2D can work in underlay mode if D2D communications reuse the same channels as cellular communications or in overlay mode if D2D communications and cellular communications use different fractions of system channels. Although the spectrum efficient of underlaid D2D is higher than overlay D2D, the serious interferences generated from D2D devices to cellular devices and the cellular communication may be deteriorated. When compared to underlaid D2D, the interference scenario in overlaid cellular networks is simpler, since there is no interference exists between cellular devices and D2D devices and the interferences among D2D devices are relatively lower due to the limited transmit power. For out-band D2D, D2D communications utilize the unlicensed spectrum of other network, such as WiFi or Bluetooth and result in uncontrollable interference [5]. Moreover, D2D multicast in cellular networks can also be divided into categories: single-rate and multi-rate [6]. For single-rate multicast, a D2D transmitter sends packets to all D2D receivers at a uniform rate [7, 8]. In the case of multi-rate multicast, the D2D receivers in a D2D multicast group (DMG) can receive packets from the D2D transmitter in different rates according to their channel conditions [9]. Although multi-rate multicast is more efficient, it is too complex and costly to implement in current cellular networks.

Underlaid D2D is popular and has been researched by many scholars, since the network performance can be significantly improved when interference-aware channel assignment algorithm is proposed. By adopting underlaid D2D multicast in cellular networks, DMGs are allowed to reuse the same channels as traditional cellular user equipments (CUE). It provides direct communication among devices within a reasonable distance, which can effectively improve the network performance, reduce energy consumption, relieve the traffic load of BSs and decrease end-to-end latency of D2D user equipments (DUEs) [10, 11]. Unfortunately, channel sharing among DMGs and cellular uplinks results in critical interferences in a cell and deteriorates QoS (Quality-of-Service) requirement of Apps [12]. BS and D2D devices may suffer critical interferences from nearby DUEs which even stronger than the desired signal. The mutual interferences among devices may decrease or even outweigh the benefits of D2D communications.

In order to improve the network throughput as well as the communication reliability, QoS and energy saving, etc. A lot of research works have been carried out on resource management schemes in the past few years. Many interference mitigation approaches in D2D unicast cellular network have been proposed, such as exploiting graph theory [13, 14], fraction frequency reuse (FFR) [15], machine learning [16], stackelberg game [17], interference alignment [18], etc.

However, interference mitigation in D2D multicast network is more complex than in D2D unicast network [19]. For example, due to the varying communication distance and complicated radio environment, link conditions are significantly different in each D2D link in a DMG. As **Fig. 1** shows, D2D transmitter sends packets to all D2D receivers at a uniform rate which is the smallest rate of D2D link in the DMG, i.e., the transmission rate of a DMG is severely limited by the worst link. Therefore, providing the optimal channel assignment in the presence of interference is still a challenge work.

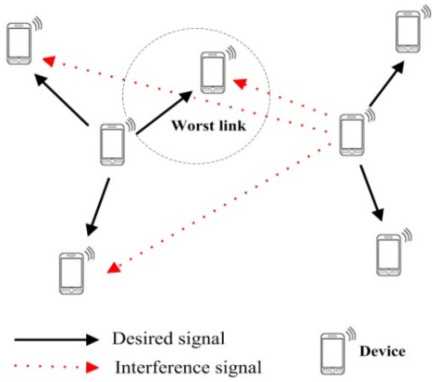

Fig. 1. The worst link in a DMG

In recent year, many works treat the interference problem in D2D multicast cellular networks. However, they designed with different objectives or had some drawbacks. Authors in [20] use Poisson point process (PPP) model to analyze D2D multicast cellular network performance. In their work, both device mobility and network assistance features are considered to improve network throughput by selecting an appropriate rate for D2D links. However, it is not related to the channel quality of each of the links for multicast. The most straightforward solution to address the interference problem is power control. In [21], particle-swarm optimization technique is utilized to allocate appropriate transmit power to MSGs. In [22], a game theory based power control algorithm is proposed to achieve higher sum-rates at the cost of a higher amount of expended downlink power. Although power control based algorithms provide an efficient way to reduce the interference among UEs, the communication distances between DUEs are also reduced due to lower transmit power. Authors in [23] proposed a stackelberg game based algorithm which combines power control and channel assignment. In the algorithm, the BS is modeled as the seller and DUE is modeled as the buyer. The algorithm groups BSs and DUEs to form the seller-to-buyer pairs and leads to an equilibrium. The simulation results show that the proposed algorithm made a reasonable tradeoff between D2D link rate and network throughput. However, they assume that only one DMG is allowed to share channel with a CUE. A group based utility improvement scheme is proposed for e-MBMS based multicast service in [24]. They have analyzed the utility and achieved a trade-off between the unicast and multicast users group size and throughput. In [25] and [26], social information is utilized to form DMGs. In [25], the authors integrate Software Defined Network (SDN) and millimeter wave into cellular networks. After that, a clustering algorithm for D2D multicast group is proposed to handle the massive traffic load in the cellular network. In [26], the authors first utilize social information to select D2D cluster head.

Then a D2D assisted caching strategy is proposed to share spectrum between DMGs in dense D2D cellular network. However, the proposed strategy cannot be applied to current networks directly, since network architecture need changes. In [27], a novel resource allocation scheme is proposed to maximize the satisfied user throughput and to maximize the number of satisfied users when the resources in the network are limited. In [28], a maximum weight bipartite matching algorithm is proposed to improve network throughput with low complex. Unfortunately, the algorithm only mitigates the intra-cell interferences, the inter-cell interference is overlooked. It cannot be applied in the network, since the number of DMGs is larger than CUEs. Authors in [29] propose a joint power and channel allocation algorithm which utilized location information of all devices. However, the locations of devices cannot be accurately measured in some spaces.

In this work, a novel channel assignment algorithm with low computational complexity is proposed. Different from previous works, our objective is to mitigate the interference between communications with low computation complexity. The proposed algorithm can be applid to cellular networks with an arbitrary number of CUEs, channels and DMGs. In the proposed algorithm, we try to maximize the throughput on each channel, i.e., appropriate CUE and DMGs are selected to share a channel without causing critical interference among UEs. The main contributions of this paper are summarized as follows:

1) The channel assignment problem is modelled to be a throughput maximizing problem which is NP-hard.

2) A novel channel assignment algorithm is proposed to mitigate interference and maximize the system throughput with low overhead and computational complexity. The key idea is finding an appropriate channel for a D2D multicast group which generates the least interference to the current network.

3) To show the efficacy and effectiveness of our proposed algorithm and solve the throughput maximizing problem in an easy way, an exhaustive search algorithm is proposed to find the near-optimal solution as the baseline for comparisons.

The remainder of the paper is organized as follows. Section 2 introduces the system model of D2D multicast cellular network. In Section 3, we convert the throughput maximizing problem to be a channel assignment problem. The proposed channel assignment algorithm is presented in detail in Section 4. Section 5 introduces an exhaustive search algorithm to find the near-optimal solution of the throughput maximizing problem. In Section 6, the simulation results is presented. Concludes is given at last.

2. System model

A cell of D2D multicast cellular network is considered in this paper. As **Fig. 2** shows, D2D multicast communication links and cellular uplinks are allowed to use the same channels at the same time. On one hand, the more channels are unoccupied in cellular uplink when compared to cellular downlink. On the other hand, critical interference could be generated by BS due to the high transmit power of BS when DMGs share the same channels with cellular downlinks. A DMG contains one D2D transmitter and K D2D receivers, namely, the transmitter broadcasts the same packets to D2D receivers on a typical channel on the condition that D2D devices are close enough to meet distance constraint of D2D communication. The notations used in our model are summarized as shown in **Table 1**.

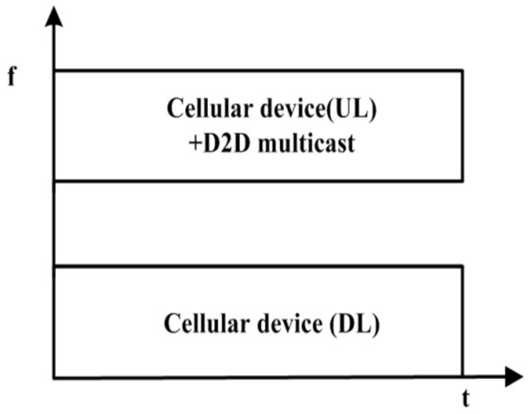

Fig. 2. Frame structure

Table 1. Notation summary of system model

Notation	Description
C; C_i	Set of the CUE; *i*th CUE, $i=(1,2,3,\ldots,C)$
D ; D_j	Set of the D2D DMG; *j*th D2D DMG, $j=(1,2,3,\ldots,D)$
D_j^T ; $D_{j,k}^R$	The transmitter of D2D DMG D_j ; the *k*th receiver of D2D DMG D_j , $k=(1,2,3,\ldots,K)$
P_C	The transmit power of cellular device
P_D	The transmit power of D2D transmitter
$G_{C_i,BS}$	Gain between C_i and the BS
$G_{D_j^T BS}$	Gain between D_j^T and the BS
G_{C_i,D_j^R}	Gain between C_i and D_j^R
$G_{D_j^T,D_j^R}$	Gain between D_j^T to $D_{j,k}^R$
$G_{D_j^T,D_{j'}^R}$	Gain between D_j^T to $D_{j',k}^R$ $(j\neq j')$
σ^2	The power of thermal noise
N ;*n*	Set of the channels; *n*th channel, $n=(1,2,3,\ldots,N)$

Two binary variables are utilized to denote occupation status on each channels, where $x_{i,n}=1$ indicates that C_i occupies channel *n* and $x_{j,n}=1$ indicates that DMG D_j occupies channel *n*; $x_{i,n}=0$ and $x_{j,n}=0$ for otherwise. Without loss of generality, we claim that one cellular link and more than one DMGs can reuse a same channel. As depicted in **Fig. 3**, there are three categories of co-channel interference in our model: C2D interference, D2C interference and D2D interference.

1) **C2D interference:** the interference at a DMG receiver caused by CUE.

2) **D2C interference:** the interference at the BS caused by DMG transmitter.

3) **D2D interference:** the interference at a DMG receiver caused by another DMG transmitter.

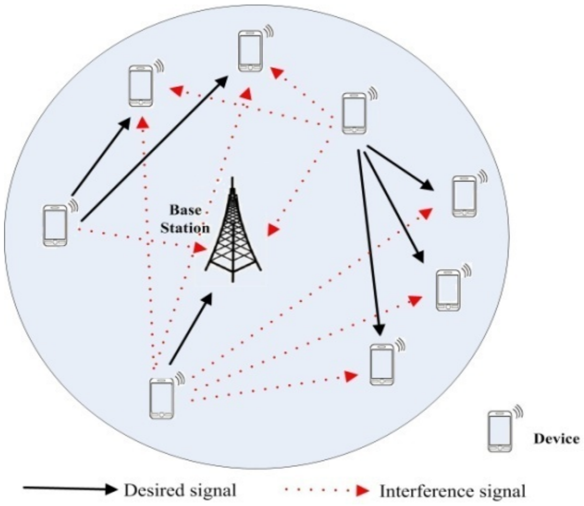

Fig. 3. Network model

It is further assumed that non-frequency-selective channel is used. Therefore, different channels with same bandwidth supply a constant data rate. If channel *n* is assigned to C_i, the signal to interference plus noise ratio (SINR) is given by

$$SINR_{C_i} = \frac{P_C G_{C_i,BS}}{\sum_{D_j \in \mathrm{D}} \sum_{n \in N} x_{i,n} x_{j,n} P_D G_{D_j^T BS} + \sigma^2} \tag{1}$$

where the suffered co-channel interference comes from DMG transmitters which reuse channel *n*. The suffered co-channel interference at a typical DMG receiver is generated by two parts: the interference from cellular devices and the interference from other DMG transmitters. The SINR at $D_{j,k}^R$ on channel *n* is given by

$$SINR_{D_{j,k}} = \frac{P_D G_{D_j^T, D_j^R}}{\sum_{D_j \in \mathrm{D}, j \neq j'} \sum_{n \in N} x_{j,n} x_{j',n} P_D G_{D_{j'}^T, D_{j,k}^R} + \sum_{C_i \in \mathrm{C}} \sum_{n \in N} x_{i,n} x_{j,n} P_C G_{C_i, D_{j,k}^R} + \sigma^2} \tag{2}$$

Once the SINR is known, the transmission rate can be calculated by the Shannon capacity formula.

3. Problem formulation

For the *j*th DMG, the achievable throughput is determined by the worst user who is far away from DMG transmitter or suffers critical interferences from near devices. Then, the SINR of *j*th DMG can be defined as:

$$SINR_{D_j} = \min \left\{ SINR_{D_{j,k}} \right\} \quad (k = 1, 2, \dots, K) \tag{3}$$

Based on the system model and Shannon capacity formula, the throughput of *i*th CUE is $\log_2(1 + SINR_{C_i})$ and the throughput of *j*th DMG is $K \log_2(1 + SINR_{D_j})$. Our aim is to maximize the system throughput which is the sum of the throughput of cellular communication and D2D communications. Therefore, the system throughput maximization problem can be formulated as follows:

$$max\, f(\boldsymbol{x}_c, \boldsymbol{x}_d) = \sum_{n \in \mathrm{N}} \left[\sum_{C_i \in \mathrm{C}} \log_2(1+SINR_{C_i}) x_{i,n} + \sum_{D_j \in \mathrm{D}} K \log_2(1+SINR_{D_j}) x_{j,n} \right] \tag{4}$$

s.t.

$$\text{C1:} \quad \sum_{\forall n \in \mathrm{N}} x_{i,n} = 1 \qquad \forall \mathrm{C}_i \in \boldsymbol{C} \tag{5}$$

$$\text{C2:} \quad \sum_{\forall n \in \mathrm{N}} x_{j,n} = 1 \qquad \forall D_j \in \boldsymbol{D} \tag{6}$$

$$\text{C3:} \quad \sum_{\forall n \in \mathrm{N}} \sum_{C_i \in \mathrm{C}} x_{i,n} = 1 \quad \forall \mathrm{C}_i \in \boldsymbol{C} \tag{7}$$

$$\text{C4:} \quad \boldsymbol{x}_c \in \{0,1\}^{|C| \times K} \tag{8}$$

$$\text{C5:} \quad \boldsymbol{x}_d \in \{0,1\}^{|D| \times K} \tag{9}$$

where $\boldsymbol{x}_c$, $\boldsymbol{x}_d$ are the feasible solution of problem (4) and $x_{i,n}$, $x_{j,n}$ are elements of them. The constraints C1 and C2 indicate that each CUE and DMG must occupy one channel. Constraints C3 indicate that CUEs cannot share any channels. Our objective is maximizing the network throughput which is the sum throughput on each channel. Unfortunately, the problem is a mixed integer problem which has been proven to be NP-hard [30]. It is hard to get the optimal solution in real time. In order to solve the problem in an easier way, a novel channel assignment algorithm is proposed to make a proper trade-off between computational complexity and network performance.

4. Proposed channel assignment algorithm

Here, the proposed channel assignment algorithm is presented, which can be used in the general case, i.e., more than one DMGs can share a channel with a CUE and more than one DMGs can share a channel. Without loss of generality, as the number of CUEs, DMGs and channels changes, there are three cases of channel sharing:

Case1: $|\mathrm{C}| + |\mathrm{D}| \leq |\mathrm{N}|$

In this case, each CUE and DMG occupies different channels and no interference exists among devices. Note that uplinks in a cell cannot share any channels. This is because a BS cannot distinguish multiple signals on a channel simultaneously. $|\mathrm{N}| \geq |\mathrm{C}|$ always hold, since admission control algorithm will reject admission requests of CUEs when channels are used up.

Case 2: $|\mathrm{N}| < |\mathrm{C}| + |\mathrm{D}|$

In this case, at least one DMG reuses a channel with CUE or with other DMG. Appropriate pair of communication links need to be selected to share a channel.

Case 3: $2|\mathrm{N}| < |\mathrm{C}| + |\mathrm{D}|$

In this case, more than one DMGs share the same channel with one CUE or share channel with other DMGs. For each channel, appropriate CUE and DMGs need to be selected to share a channel.

4.1 Channel assignment algorithm

In order to solve the throughput maximization problem which is defined in (4) in an easy way, an alternative idea is maximizing the throughput on each channel. For this purpose, appropriate CUE and DMGs need to be selected to share a channel and mitigate the interferences among communications. S_n is used to denote the set of communications that share channel *n* for data transmission. The throughput of S_n can be calculated as

$$T_{S_n} = \sum_{C_i \in S_n} \log_2(1+SINR_{C_i}) + K \sum_{D_j \in S_n} \log_2(1+SINR_{D_j}) \tag{10}$$

where the first and the second term represent the throughput of CUE uplink and DMGs respectively. In order to minimize the interference among communications in set S_n, firstly, the mutual interference is defined to characterize the interference relationship between two elements in S_n. The mutual interference between C_i and DMG D_j is the sum of interference from D_j^T to BS and the strongest interference from C_i to $D_{j,k}^R$, which can be expressed as

$$I_{i,j} = P_D G_{D_j^T BS} + \max\ P_C G_{C_i D_{j,k}^R} \quad (k = 1,2,3,...,K) \tag{11}$$

The mutual interference between two different DMGs D_j and $D_{j'}$ is the sum of strongest interference from D_j^T to $D_{j',k}^R$ and the strongest interference from $D_{j'}^T$ to $D_{j,k}^R (k \in 1,2,3,...,K)$, that is

$$I_{j,j'} = \max P_D G_{D_j^T, D_{j',k'}^R} + \max P_D G_{D_{j'}^T, D_{j,k}^R} \quad (k, k' = 1,2,3,...,K) \tag{12}$$

Note that $I_{i,j} = I_{j,i}$, $I_{j,j'} = I_{j',j}$. Thus, the sum interference suffered at *j*th DMG can be calculated as

$$I_{D_j} = \sum_{C_i \in S_n} I_{i,j} + \sum_{D_{j'} \in S_n, j \neq j'} I_{j,j'} \tag{13}$$

where the first and the second term represent the interference from CUE and the sum interference from other D2D transmitters.

If a new DMG $D_{j'}$ is added to S_n, the generated interference $I_{S_n,D_{j'}}$ comes from two parts: the mutual interference between $C_i (C_i \in S_n)$ and $D_{j'}$. The mutual interference between $D_j (D_j \in S_n)$ and $D_{j'}$, this can be expressed as

$$I_{S_n,D_{j'}} = I_{i,j'} + \sum_{D_j \in S_n} I_{j,j'} \quad (C_i \in S_n) \tag{14}$$

The details of the proposed algorithm are shown in Algorithm 1. Since CUEs cannot share any channels, the proposed algorithm assigns channels to CUEs and DMGs separately. In the first step, different channels are assigned to cellular uplinks such that CUEs occupy different channels. The second step is assigning channels to DMGs one by one in the order that the suffered interferences from highest to lowest. For a typical DMG $D_{j'}$, the best channel n'' is the channel which generates the least interference $I_{S_n,D_{j'}}$ to network according to current channel assignment status. If $|\mathsf{N}| > |\mathsf{C}|$, there are $|\mathsf{N}| - |\mathsf{C}|$ unoccupied channels after the first step. After that, the algorithm will assign the unoccupied channels to DMGs until each DMG occupies a channel (for *case 1*) or no unoccupied channels left (for *case 2* and *case 3*). This is because the

UEs suffer critical mutual interference always in the dense area or near to the BS, if they occupied the same channel with other devices, it will make critical interference and degenerate the system throughput. The algorithm is terminated until each DMG occupies a channel. In the proposed algorithm, the channel to a DMG which generates the least interference is assigned according to current channel assignment status, so that local optimality can be guaranteed in each step.

Algorithm 1 Channel assignment algorithm

```
Initialization: Channel Gains, $S_n = \varnothing, \forall n \in \mathcal{N}$, $\mathbf{x}_c, \mathbf{x}_d = \mathbf{0}$, Calculate $I_{D_j} (\forall D_j \in \mathcal{D})$.
Output: $\mathbf{x}_c, \mathbf{x}_d$
while $\mathcal{C}$ is not empty do
        Random select a CUE $C_{i'}$ from set $\mathcal{C}$
        Random select a channel $n'$ from set $\mathcal{N}$
        $x_{i,n'} = 1$
        $\mathcal{C} = \mathcal{C} \setminus \{C_{i'}\}$
        $S_{n'} = S_{n'} \cup \{C_{i'}\}$
        $\mathcal{N} = \mathcal{N} \setminus \{n'\}$.  //assign different channels to cellular devices
end while
while $\mathcal{D}$ is not empty do
    Select a DMG $D_{j'}$ from set $\mathcal{D}$ where
    $D_{j'} = \arg\max_{D_j} I_{D_j}$.  //according to (13)
    For all $S_n$
        Calculate $I_{S_n, D_{j'}}$.  //according to (14)
    End for
    Find the smallest $n''$ which $n'' = \arg\min_{n} I_{S_n, D_{j'}}$
    $x_{j',n''} = 1$
    $S_{n''} = S_{n''} \cup \{D_{j'}\}$
    $\mathcal{D} = \mathcal{D} \setminus \{D_{j'}\}$.
end while
```

4.2 Realization and computational complexity analysis

In our work, the proposed algorithm is executed by BS, which works as a centralized scheduler. Before executing channel assignment algorithm, the BS should collect the channel gains between CUE and BS, between two DUEs and between a CUE and a DUE. This mechanism is somewhat more demanding than that in traditional cellular networks and has been widely applied in the literature of D2D communications [31, 32]. For the proposed algorithm, the complexity of computing I_{D_j} is $O(|\mathcal{D}|(|\mathcal{C}|+|\mathcal{D}|)K)$, the channel assignment for cellular uplink is $O(|\mathcal{C}|)$ and the complexity of selecting an appropriate channel to a DMG is $O(|\mathcal{N}||\mathcal{D}|K)$. Thus, the overall computational complexity of the proposed algorithm is $O(|\mathcal{N}||\mathcal{D}|^2 K)$ when $|\mathcal{C}|+|\mathcal{D}| \le |\mathcal{N}||\mathcal{D}|$ (including *case 1*) and $O(|\mathcal{D}|(|\mathcal{C}|+|\mathcal{D}|)K)$ when $|\mathcal{C}|+|\mathcal{D}| > |\mathcal{N}||\mathcal{D}|$.

5. Exhaustive search algorithm and near-optimal solution

To evaluate the efficiency of the proposed channel assignment algorithm, an exhaustive search algorithm is presented to find a near-optimal solution of the throughput maximization problem which has been described in (4). Due to the NP-hard property, it is difficult to find a global optimal solution in real time, since it involves exponential computational complexity. To reduce the computational complexity, an alternative method is searching a finite number of different UE and DMGs combinations that share a channel with the objective of finding a near-optimal solution.

In our search algorithm, an initial solution is generated at first. Then, the solution is iteratively improved by finding better neighboring solutions until a near-optimal solution is obtained. The initial solution and neighboring solution are defined as follows:

1) Initial solution: the initial solution is obtained from random channel assignment algorithm, i.e., network first randomly assigning different channels to cellular communication links and DMGs until channels are used up. Then, channels are assigned to the remain DMGs randomly.

2) Neighboring solution: based on solution $\boldsymbol{x}$, a variant is operated as follows, which is called channel reassigning. We first randomly select a DMG D_j in $\mathcal{D}$ and a channel n in $\mathcal{N}$ on the condition that $x_{j,n}=0$. Then, the operator changes solution $\boldsymbol{x}$ by reassigning channel n to D_j, i.e., $x_{j,n}=1$ and $x_{j,n'}=0\ (n'\neq n)$. Then a new solution $\boldsymbol{x}(D_j,n)$ is obtained. If $f(\boldsymbol{x}(D_j,n))>f(\boldsymbol{x})$, $\boldsymbol{x}(D_j,n)$ can be a neighboring solution of $\boldsymbol{x}$. The essence of finding neighboring solution is assigning an appropriate channel to a communication link only if it has ability to further improve network throughput.

To avoid generating repeated solutions and directing the search to new different solution, two search labels are defined as follows:

1) *EI*: an one-dimensional array, its element *EI*[D_j] records the earliest iteration that a new channel is assigned to DMG D_j $(D_j\in\mathcal{D})$.

2) *EIC*: a two-dimensional array, its element *EIC*[D_j,n] records the earliest iteration that channel n is assigned to DMG D_j $(D_j\in\mathcal{D})$.

A new solution is generated if and only if the number of iterations larger than *EI*[D_j] and *EIC*[D_j,n]. When the algorithm finds a neighboring solution, the two search labels are updated by adding variables T and TC, respectively.

The details of the search algorithm are presented in Algorithm 2. The search algorithm starts from an initial solution which is generated by random assignment algorithm. At each iteration, the new solution which generated by channel reassigning is evaluated according to the criterion of maximizing the objective function in (4). If the new generated solution is a neighboring solution, it will be the starting solution in the next iteration. Otherwise, another new solution is generated. The algorithm is over when the number of iterations equals to *tMax*. Obviously, as the number of iterations increase, the overall interference decreases by finding neighboring solutions. At last, the neighbor solution converges to a near-optimal solution.

The computational complexity of obtaining near-optimal solution increases exponentially with increasing in number of UEs and channels. Since a DMG can select any channel n in $\mathcal{N}$, the overall search space is $|\mathcal{D}|^{|\mathcal{N}|}$.The complexity of finding a new solution is $O(1)$. The complexity of computing $f(\boldsymbol{x}(D_j,n))$ for a new solution $\boldsymbol{x}(D_j,n)$ is $O(|\mathcal{D}||\mathcal{N}|)$. Therefore, the computational complexity of the proposed search algorithm is $O(tMax|\mathcal{D}||\mathcal{N}|)$.

Algorithm 2 Exhaustive search algorithm

```
Initialization: $EI[D_j]$ and $EIC[D_j,n]$ to be zero for all $D_j \in \mathcal{D}$, $n \in \mathrm{N}$, $\boldsymbol{x}_c, \boldsymbol{x}_d = \boldsymbol{0}$.
Output: $\boldsymbol{x}_c, \boldsymbol{x}_d$

Assign different channels to cellular devices one by one get $\boldsymbol{x}_c$.
An initial solution $\boldsymbol{x}_d$ is generated by random channel assignment algorithm. // Get initial solution
for $t$=1 to $tMax$ do
    Random select $D_j$ in $\mathcal{D}$ and randomly select a channel $n'$ from $\mathrm{N}$, when $t > EI[D_j]$, $t > EIC[D_j, n]$ and $x_{j,n'} = 0$.
    get a new solution $\boldsymbol{x}(D_j, n')$: $x_{j,n'} = 1$, and $x_{j,n} = 0$.
    if $f(\boldsymbol{x}(D_j, n')) > f(\boldsymbol{x})$
        Replace $\boldsymbol{x}$ with $\boldsymbol{x}(D_j, n')$
        $EI[D_j] = t+T$, $EIC[D_j,n] = t+TC$    //update labels
    end if
end for
```

6. Simulation results and discussions

In this section, simulation results and comparisons with other algorithms are presented. In our simulation setup, all CUEs and D2D transmitters are randomly distributed in a cell. The detailed simulation settings are summarized in **Table 2**. Moreover, the proposed algorithm is compared to three other algorithms: random channel assignment algorithm (denoted as Random), the proposed algorithm with random sequence with DMG (denoted as RS), exhaustive search algorithm (ES). The RS algorithm is the same to the proposed algorithm, the only difference is that RS assigns channels to DMGs in a random order of DMGs. Since the search space is $|\mathrm{D}|^{|N|}$, the number of iterations in ES algorithm must be large enough to get a near-optimal solution. Therefore, the computational complexity of ES is larger than our proposed algorithm. Both our proposed algorithm and RS have the same computational complexity.

The fairness of rates is also compared by adopting Jain's fairness index. The fairness can be calculated as

$$fairness = \frac{\left(\sum_{C_i \in \mathrm{C}} \log_2(1+SINR_{C_i}) + \sum_{D_j \in \mathcal{D}} \log_2(1+SINR_{D_j})\right)^2}{(C+D)\left(\sum_{C_i \in \mathrm{C}} (\log_2(1+SINR_{C_i}))^2 + \sum_{D_j \in \mathrm{D}} (\log_2(1+SINR_{D_j}))^2\right)} \tag{15}$$

Table 2. Simulation parameters

Parameter	**Value**
Path loss model	140.7+37.6log$_{10}$(R) dB, R in *km*
Number of cellular devices (C)	10
Penetration loss	10dB
Shadow fading	Log-normal distribution with 0 mean and 8 dB of standard deviation
D2D communication distance	uniform distribution on interval (10, 20) in m
Radius of cell coverage	200 m
D2D transmitter power (P_D)	8 dBm
Cellular device power (P_C)	8 dBm
Noise Figure	5 dB
Noise Power Spectral Density	-174 dBm
Traffic Model for devices	Best effort Traffic
tMax	100 000
T	uniform distribution on intervals [1,6)
TC	uniform distribution on intervals [3,6)

Fig. 4 shows the system capacity that is achieved by adopting the ES algorithm with varying *tMax* when $|C|=10$, $|D|=30$ and $|\mathrm{N}|=15$. It is obvious that the value of *tMax* has a considerable effect on the system throughput. As *tMax* increases, the cell throughput increases at first, then becomes more stable, and finally converges to a near-optimal value. When $tMax = |\mathrm{D}|^{|N|}$, all solution space is completely searched and we get the optimal solution.

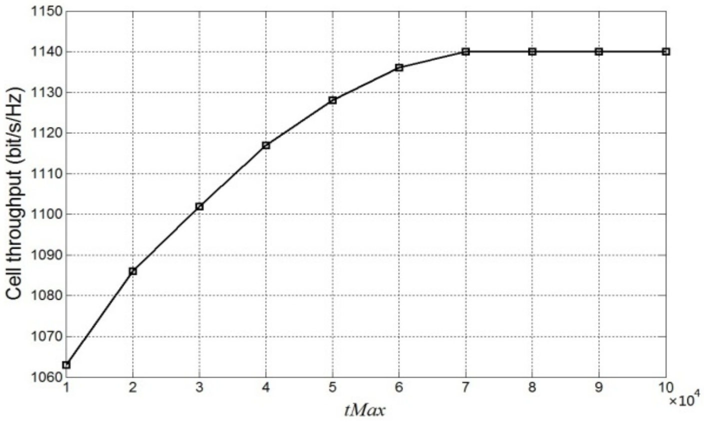

Fig. 4. Cell throughput with increasing number of *tMax*.

Fig. 5 shows the cell throughput with varying number of channels under different algorithms when $|C|=10$ and $|D|=30$. It can be observed that as the number of channels increase, cell throughput increases with all algorithms but different in rate. This is because the probability of CUEs and DMGs sharing a channel is decreased when the number of channels increase. Then, the interferences between UEs can be reduced. It is also observed that the ES algorithm is better than the proposed algorithm and RS algorithm in terms of cell throughput. This is because the ES algorithm obtains a global near-optimal solution, while the proposed algorithm only guarantees local optimality in each step. Note that, although the ES algorithm is better than the proposed algorithm in cell throughput, it cannot apply to current systems due to unacceptable computational complexity.

Random algorithm has the lowest throughput due to critical interferences. Note that, the same throughput is achieved under four different algorithms when $|N|=40$. Since each CUE and DMG occupies distinct channels and there is no interference exists in a cell.

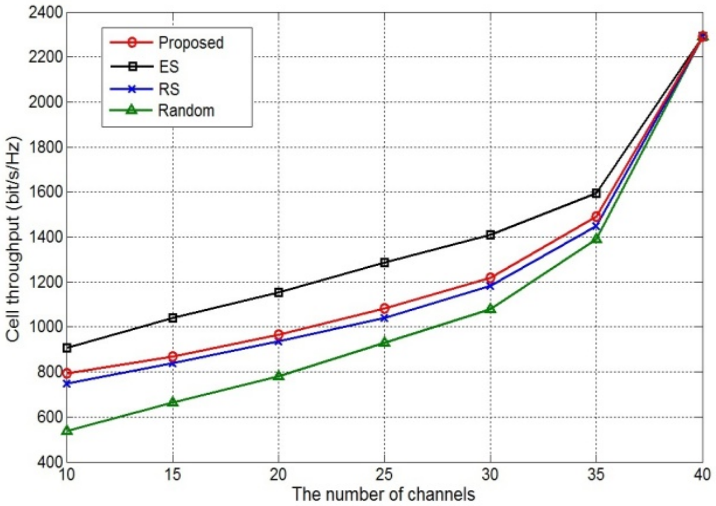

Fig. 5. Cell throughput with varying number of channels

Fig. 6 shows the cell throughput with variable number of DMGs when $|C|=10$ and $|N|=15$. The result shows that when the number of DMGs increases, the cell throughput increases, but the rates of increment decrease. The reason is that with the number of DMG increases, more communication links will reuse a channel and bring new interferences in a cell on the condition that the number of channels is fixed. Moreover, the ES algorithm achieves the best cell throughput, since it obtains a near-optimal by exhaustive search. The proposed algorithm outperforms the RS algorithm, because the proposed algorithm forbids the DMGs which are near the BS to share a channel with cellular communications, then the D2C interference is smaller than RS algorithm. This demonstrates that the channel assignment priority of DMGs is important in our proposed algorithm. Since the random assignment algorithm does not consider interferences between UEs, the throughput is low.

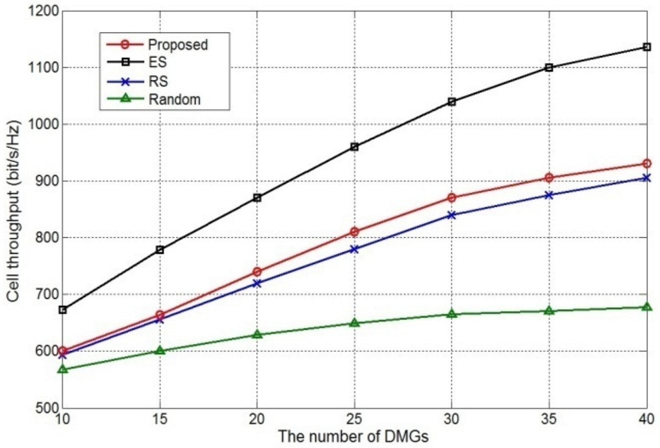

Fig. 6. Cell throughput with varying number of DMGs.

Fig. 7 presents the Cumulative Distribution Function (CDF) of the rate of CUEs and DMGs when $|C|=10$, $|D|=30$ and $|N|=15$, which represents the ability of interference mitigation. Obviously, the ES algorithm achieves the best rate distribution. This is because ES algorithm obtains near-optimal solution by searching the solution space, the interferences between UEs can be minimized. The proposed algorithm tries to minimize the interferences between devices when they share the same channels, i.e., the DMGs always select a channel in the case that least interference is generated according to the current channel assignment status. Thus, the rate of UEs under our proposed algorithm is lower than ES. At last, random assignment algorithm causes critical interferences in a cell, the rate is relatively lower than other algorithms.

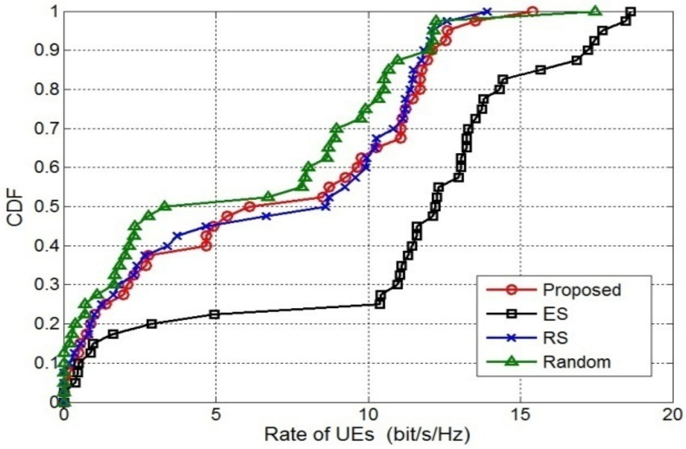

Fig. 7. CDF of UEs.

In **Fig. 8**, the fairness of the four different channel sharing algorithms is compared. The ES algorithm achieves the best fairness among links, since the strong interferences among devices are mitigated. The fairness of the proposed algorithm is lower than ES algorithm and is better than random algorithm. This is because our proposed algorithm avoids to generate critical interferences between UEs according to the current channel assignment status. For random algorithm, some links may suffer strong interference from near UEs and the rates varied vastly among UEs, leading to worst fairness.

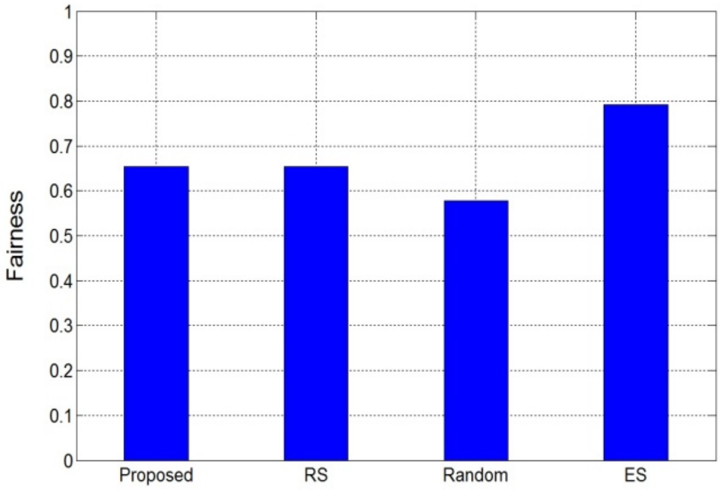

Fig. 8. Fairness for different algorithms

7. Conclusion

In this paper, we research the channel assignment problem in D2D multicast cellular networks. A novel channel assignment algorithm is proposed to improve the system throughput and mitigate the interference between communication links. The proposed algorithm finds appropriate CUE and DMGs to share a channel without causing critical interference among UEs, i.e., selecting a channel to a D2D multicast group which generates the least interference according to the current channel assignment status. It is also demonstrated that the priority of DMGs is important in our proposed channel assignment algorithm. Moreover, a novel exhaustive search algorithm is proposed to show the efficacy and effectiveness of our proposed algorithm by searching the different UE and DMGs combinations that share a channel. Simulation results show that the proposed algorithm can improve the cell throughput.

References

[1] M. Sun, X. Xu, X. Tao, P. Zhang and V. C. M. Leung, “NOMA-based D2D-enabled traffic offloading for 5G and beyond networks employing licensed and unlicensed access,” *IEEE Trans. Wirel. Commun.*, vol. 19, no. 6, pp. 4109-4124, 2020. Article (CrossRef Link)

[2] F. Qamar, K. Dimyati, M. N. Hindia, K. A. Noordin and I. S. Amiri, “A stochastically geometrical poisson point process approach for the future 5G D2D enabled cooperative cellular network,” *IEEE Access*, vol. 7, pp. 60465-60485, 2019. Article (CrossRef Link)

[3] Y. Zhang, Y. Shen, X. Jiang and S. Kasahara, “Mode selection and spectrum partition for D2D inband communications: a physical layer security perspective, ” *IEEE Trans. Commun.*, vol. 67, no. 1, pp. 623-638, 2019. Article (CrossRef Link)

[4] M. Pavel, B. Zdenek, V. Tomas, “In-band device-to-device communication in OFDMA cellular networks: A survey and challenges,” *IEEE Commun. Surveys Tuts.*, vol. 17, no 4, pp. 1885-1922, 2015. Article (CrossRef Link)

[5] S. Andreev, O. Galinina, A. Pyattaev, K. Johnsson, Y. Koucheryavy, "Analyzing assisted offloading of cellular user sessions onto D2D Links in unlicensed bands," *IEEE J. Sel. Areas Commun.*, vol 33, no 1, pp. 67-80, 2015. Article (CrossRef Link)

[6] A. Richard O., D. Aresh, K. Kiseon, "Multicast scheduling and resource allocation algorithms for OFDMA-based systems: A survey," *IEEE Commun. Surveys Tuts.*, vol 15, no 1, pp. 240-254, 2013. Article (CrossRef Link)

[7] J, Xu., S.-J. Lee, W.-S. Kang, J.-S. Seo, "Adaptive resource allocation for MIMO-OFDM based wireless multicast systems," *IEEE Trans. Broadcast.*, vol 56, no 1, pp. 98-102, 2010. Article (CrossRef Link)

[8] H. Won, H. Cai, D.Y. Eun, K. Guo, A. Netravali, I. Rhee, K. Sabnani, "Multicast scheduling in cellular data networks," *IEEE Trans. Wireless Commun.*, vol 8, no 9, pp. 4540-4549, 2009. Article (CrossRef Link)

[9] M. Shao, S. Dumitrescu, X. Wu, "Layered multicast with inter-layer network coding for multimedia streaming," *IEEE Trans. Multimedia*, vol 13, no 2, pp. 353-365, 2011. Article (CrossRef Link)

[10] X. Cheng, L. Yang, X. Shen, "D2D for intelligent transportation systems: A feasibility study," *IEEE Trans. Intell. Transp. Syst.*, vol 16, no 4, pp. 1784-1793, 2015. Article (CrossRef Link)

[11] P. Phunchongharn, E. Hossain, D. I. Kim, "Resource allocation for device-to-device communications underlaying LTE-advanced networks," *IEEE Trans. Wireless Commun.*, vol 20, no 4, pp. 91-100, 2013. Article (CrossRef Link)

[12] Y. Xiao, K. Chen, C. Yuen, L. A. DaSilva, "Spectrum sharing for device-to-device communications in cellular networks: A game theoretic approach,"*in Proc. of the IEEE International Symposium on Dynamic Spectrum Access Networks (DYSPAN)*, 2014 McLean, VA, USA, pp. 60-71, 2014. Article (CrossRef Link)

[13] L. Zhao, H. Wang, X. Zhong, "Interference graph based channel assignment algorithm for D2D cellular networks," *IEEE ACCESS*, vol 6, pp.3270-3279, 2018. Article (CrossRef Link)

[14] T. Yang, R. Zhang, X. Cheng, L. Yang, "Graph coloring based resource sharing (GCRS) scheme for D2D communications underlaying full-duplex cellular networks," *IEEE Trans. Veh. Technol.*, vol 66, no 8, pp.7506-7517, 2017. Article (CrossRef Link)

[15] L. Eslami, G. Mirjalily, T. N. Davidson, "Spectrum-efficient QoS-aware resource assignment for FFR-based D2D-enabled heterogeneous networks," *IEEE Access*, vol. 8, pp. 218186-218198, 2020. Article (CrossRef Link)

[16] F. Jiang, L. Zhang, C. Sun, Z. Yuan, "Clustering and resource allocation strategy for D2D multicast networks with machine learning approaches," *China Communications*, vol. 18, no. 1, pp. 196-211, 2021. Article (CrossRef Link)

[17] J. Wang, Y. Sun, B. Wang, B. Wang, A. Wang, S. Li, Z. Sun, "Resource allocation for D2D video multicast using multi-leader multi-follower stackelberg game with personalized incentives," *IEEE Access*, vol. 7, pp. 117019-117028, 2019. Article (CrossRef Link)

[18] W. Li, M. Zhang, B. Bai, "Power threshold based interference alignment in hybrid D2D & cellular uplink transmissions," in *Proc. of the IEEE VTC*, Sydney, NSW, Australia, pp.1-5, 2017. Article (CrossRef Link)

[19] Y. Xu, X. Li, J. Zhang, "Device-to-device content delivery in cellular networks: multicast or unicast," *IEEE Trans. Veh. Technol.*, vol 67, no 5, pp.4401-4414, 2018. Article (CrossRef Link)

[20] F. Qamar, K. Dimyati, M. N. Hindia, K. A. Noordin, I. S. Amiri, "A stochastically geometrical poisson point process approach for the future 5G D2D enabled cooperative cellular network," *IEEE Access*, vol. 7, pp. 60465-60485, 2019. Article (CrossRef Link)

[21] W. Gong, X. Wang, "Particle swarm optimization based power allocation schemes of device-to-device multicast communication," *Wireless Personal Commun.*, vol 85, no 3, pp. 1261-1277, 2015. Article (CrossRef Link)

[22] L. Song, D. Niyato, Z. Han, E. Hossain, "Game-theoretic resource allocation methods for device-to-device (D2D) communication," *Wireless Commun.*, vol 21, no 3, pp. 136-144, 2014. Article (CrossRef Link)

[23] C. Xia, S. Xu, K. S. Kwak, "Resource allocation for device-to-device communication in LTE-A network: A stackelberg game approach," in *Proc. of the IEEE VTC*, Vancouver, BC, Canada, pp. 1-5, 2014. Article (CrossRef Link)

[24] J. Chen, M. Chiang, J. Erman, G. Li, K. K. Ramakrishnan, R. K. Sinha, "Fair and optimal resource allocation for LTE multi-cast (eMBMS): Group partitioning and dynamics," in *Proc. of the IEEE Conference on Computer Communications (INFOCOM)*, Hong Kong, China, pp. 1266-1274, 2015. Article (CrossRef Link)

[25] P. Rahimi, C. Chrysostomou, V. Vassiliou, "Social-aware clustering for D2D multicast content sharing in 5G networks," in *Proc. of the Global Information Infrastructure and Networking Symposium (GIIS)*, Tunis, Tunisia, pp. 1-8, 2020. Article (CrossRef Link)

[26] N.-S. Vo, T.-M. Phan, M.-P. Bui, X.-K. Dang, N. T. Viet, C. Yin, "Social-aware spectrum sharing and caching helper selection strategy optimized multicast video streaming in dense D2D 5G networks," *IEEE Systems Journal*, vol. 15, no. 3, pp. 3480-3491, 2021. Article (CrossRef Link)

[27] R. Jagadeesha, J. -P. Sheu and Wing-Kai Hon, "User satisfaction based resource allocation schemes for multicast in D2D networks," in *Proc. of European Conf. on Netw. and Commun. (EuCNC)*, Oulu, Finland, pp.1-5, 2017. Article (CrossRef Link)

[28] D. D. Ningombam, J. Pyun, S. Hwang, S. Shin, "Bipartite matching mechanism for fractional frequency reuse-based D2D multicast communications," in *Proc. of the 53rd Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, USA, pp. 286-290, 2019. Article (CrossRef Link)

[29] J.-H. Kim, J. Joung, J. W. Lee, "Resource allocation for multiple device-to-device cluster multicast communications underlay cellular networks," *IEEE Commun. Lett.*, vol 22, no 2, pp. 412-415, 2018. Article (CrossRef Link)

[30] Z.-Q. Luo, S. Zhang, "Dynamic spectrum management: complexity and duality," *IEEE J. Sel. Topics Signal Process.*, vol 2, no 1, pp.57-73, 2008. Article (CrossRef Link)

[31] W. Wang, F. Zhang, V. K. N. Lau, "Dynamic power control for delay-aware device-to-device communications," *IEEE J. Sel. Areas Commun.*, vol 33, no 1, pp. 14-27, 2015. Article (CrossRef Link)

[32] H.-B. Jeon, B.-H. Koo, S.-H. Park, J. Park, C.-B. Chae, "Graph-theory-based resource allocation and mode selection in D2D communication systems: the role of full-duplex," *IEEE Wireless Communications Letters*, vol. 10, no. 2, pp. 236-240, 2021. Article (CrossRef Link)

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