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# Autonomous Interface Selection for Multi-Radio D2D Communication

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**ABSTRACT** Device-to-device communications are considered as a key feature to enhance the performance of the fifth generation (5G) wireless networks. Several radio access technologies such as LTE Direct, Bluetooth, Wi-Fi, and ZigBee are expected to provide the opportunity of D2D communications. Therefore, it is possible to choose any of them autonomously to establish a D2D link. The primary focus of this work is to investigate the *radio interface selection*, where end users select an interface opportunistically among different available radio interfaces to establish outband D2D connectivity against interference. We model a non-cooperative game to select a radio interface for D2D users to minimize their communication cost. We have investigated Nash equilibrium in the game and argue that without any co-operation users can achieve a balanced strategy. In our model, each pair selects a radio interface based on a utility function that associates communication performance and cost. Finally, we propose three heuristic algorithms: *Social*, *Greedy*, and *Local*, that achieve Nash equilibrium with different information. Event-driven simulation experiments are then conducted to evaluate the utility and cost of the equilibrium strategy. Our results confirm that the proposed schemes can increase the utility, lower the cost, and lead to higher efficiency in terms of achievable throughput per consumed energy.

**INDEX TERMS** D2D communications, game theory, multiple radio interfaces, Nash equilibrium.

## I. INTRODUCTION

Wireless communications have boosted the opportunity for smart devices with a number of standards and technologies. Smart devices are now the most important computing and communication platform. In previous years wireless connectivity was only possible with a single operator/technology. However, these days smart devices are capable of multiple wireless opportunities. These end users are often equipped with multiple radio interfaces (i.e., 3G/LTE, Bluetooth, Zigbee, and Wi-Fi), which complements their cellular communication capabilities. According to a recent market research report, 70% of the mobile phones have Bluetooth interface, while 80% are enabled WiFi [1].

The proliferation of smart devices and exponential demand of bandwidth have created spacious performance requirement on the future wireless networks [2]. Device-to-device communication (D2D) [3] is considered one of the major technology to enhance the boosting demand [4] of users. Motivated by the performance gain, many telecommunication companies have performed experiments on D2D using some preliminary prototypes. 3GPP has already joined this front by announcing D2D communications (so-called LTE Direct) for the public safety feature in the LTE-A [5], [6]. These actions from different academic, industries, and standardization bodies indicate the impact of D2D in next-generation wireless networks. However, there are still a lot of challenges to be addressed in different fields. For example signaling architecture requires to support resource allocation in network side; an appropriate technique to support user discovery and opportunity to connect based on quality (i.e., throughput, delay, interference) in the user side.

D2D communication is mainly classified as inband D2D (i.e., cellular spectrum) and outband D2D (i.e., unlicensed spectrum). However, the rapid expansion of D2D communication has shaped the technologies for both short-range and long-range communication. In this view, many low-power wide-range[1] (LPWA) technologies based on cellular design have arisen in both licensed and unlicensed market. The high

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[1]Long-range (LoRA) [7], narrowband (NB) IoT [8], SigFox [9], [10] are the major technologies

demand for connectivity in close proximity has motivated the researchers to propose some short-range communication technologies [11] which include RuBEE, Z-WAVE, ANT, Insteon, and RFID. Among them Z-Wave, ANT, and Insteon are proprietary and the others provide a very low data-rate [11]. Compared to these, Bluetooth [12], Wi-Fi direct [13], LTE direct [5], [6], and ZigBee [14] are relatively well-established standards for distributed short-range data transfer. The availability of these different technologies introduces the opportunity of selecting the best connection to enable D2D. In [15], D2D is compared via LTE direct and Wi-Fi direct by assuming different application requirements and load of network. It reflects that when the number of users is relatively high LTE direct technology provides the most energy efficiency. However, Wi-Fi direct outperforms LTE direct in case of small amount of data. The results motivate to focus on multiple D2D radio technologies available and select the most suitable one for communication.

We define this problem as *radio interface selection* (hereafter, simply expressed as *interface selection*). This is different from the classic access network selection; best known as network selection [16]–[22]. In heterogeneous networks (HetNet) where macro, micro, pico, and femtocell coexist, the best network is selected based on the physical layer parameter [18]. Oftentimes, the users connect with the ''best received'' base station, i.e., the one with the highest receive power or data rate. Similarly, the channel selection problem [20] defines opportunistic selection of vacant cellular channels for D2D users (i.e., inband) considering a cellular radio interface. Most of the previous works [19], [21] are focused on maximizing the overall sum rate while maintaining the QoS of both D2D and cellular users. In addition, *the mode selection problem,ref10,ref11,ref12* targets to choose a communication mode for a given spectrum resource. Interestingly many researchers consider D2D communication on the cellular spectrum, however, the standard has a more flexible view. Unlicensed spectrum can be used for outband D2D communication which will reduce the interference with cellular users and increase network throughput [26], [27]. Therefore, we have considered outband D2D for further exploration.

Our focus in this work is to ensure the best D2D connection among multiple radio interfaces (i.e., Bluetooth, Wi-Fi, ZigBee, and LTE) in a device to enable outband D2D communication. However, none of those D2D radio technologies can guarantee efficient and non-interference communication to support the required QoS [15], [28]. In summary, existing works on D2D communications have generally considered mode selection, resource allocation, and power control. These multiple radio interfaces consume different amounts of energy during communication and therefore spawn distinct interference to neighbor users. As a consequence, interface selection is also an issue that needs to be resolved.

In this paper, a D2D pair is defined as a combination of two rendezvoused nodes [29], in the same collision domain. D2D pairs will select an interface to improve the overall network throughput and resource efficiency. We investigate the *interface selection* as a strategic game in the non-cooperative multi-channel wireless network. In order to design a protocol for *interface selection*, we first analyze the cost and utility function for our model. Later, we explore the possibility of Nash equilibrium (NE), that the system could achieve. We obtain quantified cost efficiency of these NEs. We have also shown that these NEs have a very desirable property, i.e., Pareto optimality. So, without these NEs there are no better states for the D2D pairs to achieve more payoffs without decreasing others' payoffs. Sequential, greedy and distributed are three algorithms based on global coordination, perfect information, and local information accordingly. Finally, we evaluate our work through simulation which verifies that the proposed scheme performs much better in utility that is a function of energy, compared to legacy transmissions.

The remainder of this paper is organized as follows. Section II describes the system model and game formulation. In section III we analyze the cost function and explain the Nash equilibrium for this game. Later in section V we propose three heuristic algorithms to achieve an equilibrium state. We exhibit extensive simulation results in section VI and conclude in section VII.

## II. SYSTEM MODEL AND GAME FORMULATION

### A. NETWORK MODEL

In our model, we consider multiple D2D pairs are randomly distributed in a geographical area. Each pair represents an undirected link $l_j$ between two rendezvoused nodes. Available links are presented as a set $\mathbb{L} = \{l_1, l_2, \ldots, l_j, \ldots\}$. Since links are undirected, two D2D pairs can select the same channels for communication from the available $M_r$ channels. Each node has multiple radio interface/transceivers to use and they are denoted as $\mathbb{R} \in \{1, 2, 3, \ldots, r, \ldots\}$. We assume that wireless transceivers have different transmission power.

To communicate, we assume two nodes of a link select one of their radio interfaces to the same channel. Each channel for at most one D2D pair is proved to a be the elementary condition to escalate the link throughput [31], [32]. Fig. 1a depicts the general network model where the range of interference changes based on the selected interface $r$. Fig. 1b shows an example of interface selection where $r_1$ is selected although the other two interfaces $r_2$ and $r_3$ are also available to establish a link between the two nodes.

### B. INTERFERENCE MODEL

Wireless transmission of D2D pairs (i.e., two links) with different transceivers can create co-channel interference if they are within the transmission range. This is a well-known channel allocation problem in non-cooperative wireless networks [31], [32]. Again, the power of the wireless transmission degrades exponentially if the distance from the transmitter increases. Therefore, the signal power of a D2D pair from a distance, if not negligible enough, can prevent the communication of another D2D pair. The primary interference model [33], the protocol interference model [30],

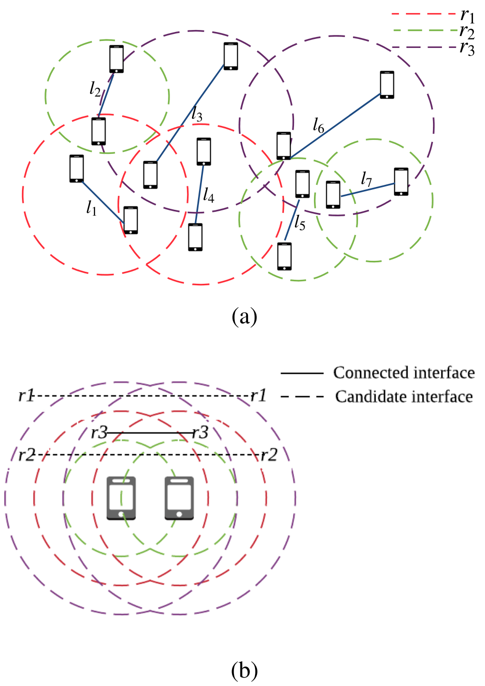


**FIGURE 1.** **(a) A network with multi-interfaced D2D links; (b) Interface selection.**

and the physical interference model [30] are three major models to characterize a network with multiple collision domains.

In our network architecture, we adopt the protocol interference model because of its acceptance in most of the works of channel allocation [34], [35]. The interference range of each D2D pair is at least equal to the transmission range. Any node $i \in l_j$ will interfere with node $i' \in l'_j$ if $i$ is within $i'$'s interference range. Every $l_j$ forms an interference range that combines the interference range of both users in that link. $l_j$ will interfere with pair $l'_j$ if and only if $i$ and $i'$ in those pairs have one communication channel common between them.

### C. GAME THEORY CONCEPT IN A NUTSHELL

The process of game theory is to model a scenario where an individual can decide an action with mutual interest or conflict with others. In game theory, the concept of Nash Equilibrium is significant to understand the strategy among D2D pairs. Some basic definitions from game theory are reused, to analyze the interface selection game. We include the definitions below (definitions can refer to, e.g., [36] for further discussion).

A game consists of players denoted as $\mathcal{P} = P_1, P_2, \ldots, P_n$ (i.e., in our model each player represents a D2D pair). Each player $\mathbb{P} \in P_i$ contains a non-empty strategy set $\mathbb{S}$. Let us assume that $P_i$ selects a strategy $s_i$. A strategy profile is also a set of strategies, i.e., $s = (s_1, s_2, \ldots, s_n)$. Let us assume that $s_{-i}$ denotes the strategy profile of player $i$ excluding $s_i$. Therefore, we have $(s_i, s_{-i})$ according to the convention of the game theory. Any player $P_i$ decides its strategy profile $s$ and measures the utility (or payoff) function $u_i(s)$.

*Definition 1 (Nash Equilibrium (NE)):* Let us consider a game of $\mathcal{P}$ players with $(\mathbb{S}, \mathbb{U})$, where $\mathbb{S} = (s_1, s_2, \ldots, s_{|\mathcal{P}|})$ is the set of strategy profiles and $\mathbb{U} = (u_1(s), u_2(s), \ldots, u_{|\mathcal{P}|}(s))$ is the utility function for $s \in \mathbb{S}$. For every player $i$, the strategy $s^*$is an Nash equilibrium point if we have

$$u_i(s_i^*, s_{-i}^*) \geq (u_i(s_i, s_{-i}^*) \quad (1)$$

for all strategies $s^* = \{s_1^*, s_2^*, \ldots, s_{|\mathcal{P}|}^*\}$.

The system is stable if none of the players have an incentive if they leave the current strategy. Therefore, a stable strategy is called NE. Usually, the system aims to converge to an NE and stays at the decision permanently. Consequently, NEs should gain valuable properties such as network throughput.

*Definition 2 (Pareto Optimality):* Let us consider a game of $\mathcal{P}$ players with $(\mathbb{S}, \mathbb{U})$, where $\mathbb{S} = (s_1, s_2, \ldots, s_{|\mathcal{P}|})$ is the set of strategy profiles and $\mathbb{U} = (u_1(s), u_2(s), \ldots, u_{|\mathcal{P}|}(s))$ is the utility function for $s \in \mathbb{S}$. For any player $i$, the strategy $s^{po}$ is Pareto-optimal if the following conditions satisfy.

$$u_i(s^{po}) < u_i(s),$$

there must exist another player $j' \in \mathcal{P}$,

$$u_j(s^{po}) < u_{j'}(s).$$

Intuitively, a state is Pareto-optimal if it cannot achieve a better payoff without hurting the other players. It is worth noting that all NEs are not Pareto-optimal.

### D. PROPOSED GAME THEORETIC MODEL

We formulate the interface selection problem in a non-cooperative game simply with two interfaces and multiple channels. In this game, each pair (i.e., link) is considered as a player and their action is the selection of a radio interface between the available ones. Hereafter, we will use the terms, link, and pair interchangeably. A pair is determined by the user's position and the available channel between them. For data communication, one node can select any radio interface considering the transmission range, energy consumption, and the required data rate. In this model, each interface has a compatible target area of coverage. We have depicted the scenario in Fig. 1a where many D2D pairs are connected via different interfaces.

The interface selection on a channel is defined to be a vector $s_i = \{z_1^1, z_2^1, \ldots, z_M^1, z_1^2, z_2^2, \ldots, z_M^2, \ldots, z_M^r, \ldots\}$, where $z_m^r = 1$ if user $i$ is active on channel $m \in M$ using radio interface $r \in \{1, 2, \ldots, n\}$. The strategy profile $s$ is then an $M \times \mid \mathbb{N} \mid$ matrix defined by all players' strategies, $s = \{s_1, s_2, \ldots, s_{|\mathbb{N}|}\}$. Formally, we present as

$$z_m^r = \begin{cases} 1 & \text{if interface } r \text{ is used on channel } m, \\ 0 & \text{if interface } r \text{ is unused on channel } m. \end{cases}$$

Each D2D pair pays cost $C_{l_j}$ that depends on the interference level perceived by the receiver on link $l_j$. Cost increases proportionately with the number of users on channel $l_j$. The effect of D2D pairs are irrespective of their selected interface for communication, i.e., different links on the same channel will interfere on each other.

The primary goal of a D2D pair is to maximize the utility and minimize the cost. The strategy of each pair is to decide

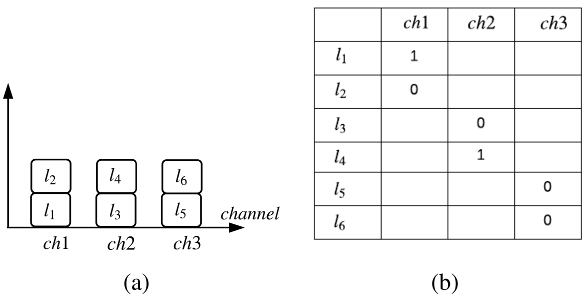


**FIGURE 2.** **(a) Active link (D2D) profile on different channels; (b) Active interfaces on those links.**

whether to use its radio interface and which channel to put the radio on.

Fig. 2a depicts the active links on different channels, and Fig. 2b presents active interfaces on those channels. Here $K_{l_j}$ presents the set of pairs who have an active link $l'_j$ using the same frequency $m$ and interfere with pair $i$ on link $l_j$. In this paper, we derive a utility function as a parameter to extend the interface selection. More specifically, the utility function $U_{l_j}$ of each pair depends on the transmit power of the selected interface and delay on the specific link. In the next section, we will discuss details to formulate the utility function.

## III. UTILITY FUNCTION

We define three different attributes which approximate the actual utility function for provided radio interfaces. A pair must choose the interface wisely such that expected bandwidth (i.e., data rate) requirement is satisfied. For instance, an interface with higher transmission power will increase the interference for surrounding neighbors whereas a low transmission power with a different interface may fail to satisfy the capacity. The relation among users' energy cost, capacity, and waiting time has to be resolved as a form of a game. We formulate the utility function for each pair based on the following network factors: transmit power, expected capacity, average waiting time before transmission, and cost involved for transferring a file. In the following subsections, we will discuss these factors to finally derive the utility function.

### A. CAPACITY

In D2D networks, each pair obtains their quality of service based on the perceived actual throughput. Since multiple D2D pairs share a limited bandwidth, the quality/cost perceived by a pair depends on the interfering pairs who are sharing the same channel. Total interference ($\sum_{K_{l_j}} I_{l_j}$) will affect on the expected SINR. Therefore, we consider the cost function considering the capacity of a channel. According to Fig. 1a, the signal-to-noise ratio (SINR) for D2D pair $l_j$ is given as

$$SINR_{l_j} = \frac{P_i^r \alpha_i^r g_i^r}{\sigma^2 + \sum_{\substack{i \neq i' \\ i,i' \in \mathbb{N}}}^{K_{l_j}} P_{i'}^r \alpha_{i'}^r}, \quad (2)$$

**TABLE 1.** **List of notations.**

| | |
|---|---|
| $\mathbb{L}$ | Set of undirected links |
| $\mathbb{N}$ | Set of D2D pairs |
| $\mathbb{R}$ | Set of transceivers |
| $s_i$ | Strategy of user $i$ |
| $M_r$ | Number of channels for interface $r$ |
| $C_{l_j}$ | Cost function of link $l_j$ |
| $U_{l_j}$ | Utility function of link $l_j$ |
| $W_r$ | Bandwidth of interface $r$ |
| $K_{l_j}$ | Number of interfering pairs on $l_j$ |
| $P_i^r$ | Transmit power of user $i$ on interface $r$ |
| $\mathbb{E}[C_{l_j}]$ | Expected capacity of link $l_j$ |
| $L$ | Normalized load for each pair |
| $\mathbb{E}[T_{l_j}^{wait}]$ | Expected waiting time on $l_j$ |
| $\mathbb{E}[T_{l_j}^{tx}]$ | Expected transmission time on $l_j$ |

where $P_i^r$ and $P_{i'}^r$ are the transmission power of $i \in l_j$ and $i' \in l_{j'}$ D2D pairs, respectively. Here $\alpha_i^r$ is a link gain, $\sigma^2$ is the additive white Gaussian noise, and $g_i^r$ is the processing gain of link $i$ on interface $r$. The capacity of each D2D link is given by

$$\mathbb{E}[C_{l_j}] = W_r \log_2(1 + SINR_{l_j}), \quad (3)$$

where $W_r$ is the bandwidth given for radio $r$.

### B. WAITING TIME

We have analyzed a general probabilistic delay model for our approach. Since connections are established in an ad-hoc manner, a variable number of D2D pairs may coexist in the same channel/area. Each D2D pair is independent and wish to communicate using the channel they have established. We suppose each channel is accessible in terms of time slots that are opportunistically used by D2D pairs.

Let us consider that $L$ is the normalized load over every D2D pair. A D2D pair transmits in a slot of a particular channel and the number of channel is $M_r$. The users hop on $M_r$ channel to achieve rendezvous and the rendezvoused D2D pair transmits on that channel [29]. The probability of collision for a D2D pair, who transmits in a slot of a particular channel is $\frac{L}{M_r}$, that is, the probability of a transmission attempt occurs in another D2D pair on the same channel. Therefore, $1 - \frac{L}{M_r}$ is the probability that a collision does not occur. Finally, the probability of successful transmission can be expressed as below.

$$Prob(l_j) = \left(1 - \frac{L}{M_r}\right)^{K_{l_j}}. \quad (4)$$

The time slot has three states: no transmission attempts, collision, and successful transmission. Each wasted slot (i.e., collision in the slot) is a Bernoulli trial with the probability of success $Prob(l_j)$. According to the Geometric distribution, the mean of the wasted slots is $\frac{1-Prob(l_j)}{Prob(l_j)}$.

We have analyzed the probability of successful transmission as a function of the new transmission attempts. Therefore we can calculate the expected mean delay of a transmitted packet. Let us consider that other D2D pairs transmit in an alternate slot and mean delay combines the successful slot. Therefore, the mean delay is

$$\mathbb{E}[T_{l_j}^{wait}] = 2\left(\frac{1 - Prob(l_j)}{Prob(l_j)}\right) + 1. \quad (5)$$

In communication, delay also induces energy consumption. Here, we assume that each user has a minimum energy consumption for each slot before transmission. For mean delay $\mathbb{E}[T^{wait}]$, energy consumption is presented as $E_{l_j}^{wait} = P_{slot} \times \mathbb{E}[T_{l_j}^{wait}]$, where $P_{slot}$ presents energy per slot.

### C. COST FUNCTION

Let us consider that, user $i$ transfers a file of size $L$ (i.e., load) via the selected interface $r$ on link $l_j$. The size of the packet is $B$ bytes and a user can send $N_p$, where $N_p > 0$. With any interface $r$, the file transfer time is inversely proportional to the expected link capacity $\mathbb{E}[C_{l_j}]$ and link capacity is directly proportional to energy consumption $P_i^r$. Therefore, the link with low capacity will cause more delay, i.e., the transmit energy is low. The estimated duration to transmit a single packet to the destination is $\frac{B}{\mathbb{E}[C_{l_j}]}$. The average delivery time $\mathbb{E}[T_{l_j}^{tx}]$ of a user to transfer $N_p$ packets on link $l_j$ can be expressed as

$$\mathbb{E}[T_{l_j}^{tx}] = \sum_{l_j \in \mathcal{L}} \frac{N_p B}{\mathbb{E}[C_{l_j}]}. \quad (6)$$

Note that interfaces have competitive performance but the energy consumption is different in distinct interfaces [37], [38]. The cost includes the number of bytes a user transmits and the transmission time. Each user $i$ transmits $N_p B$ bytes of data with interface $r$. Hence, the cost function can be expressed as

$$C_{l_j} = P_i^r \mathbb{E}[T_{l_j}^{tx}] + E_{l_j}^{wait}. \quad (7)$$

### D. UTILITY FUNCTION

In formulating the overall utility expression, each pair always aims to find a strategy that can provide better link capacity, with minimum energy cost. The utility can be calculated considering how much energy the adopted strategy can save for each pair. To model our utility function, we have to calculate the maximum achievable data rate where $(\sum_{K_{l_j}} I_{l_j}) = 0$. Considering equation (7), we can calculate maximum cost $C_{l_j}^{max}$. The utility function after reducing the energy cost for a selected interface can be expressed as

$$U_{l_j} = \frac{1}{1 + e^{C_{l_j} - C_{l_j}^{max}}}. \quad (8)$$

## IV. FINDING NASH EQUILIBRIUM

The primary goal of this work is to estimate the NE in the game. Therefore, we consider first to prove the existence of NE. In a non-cooperative game, there are two types of NE [36] : pure strategy NE and mixed strategy NE. Since the interface selection problem is critical to understand with the mixed strategy, the target is to realize the pure strategy NE.

*Assumption 1:* A pair $i$ is a neighbor of another pair $i'$ if the location of $i$ is within the interference range of $i'$ and visa versa.

*Assumption 2:* Nodes $x$ and $y$ form D2D pair $i$, which means they have at least one common channel between them for communication. And that channel can be reused by any other pair $i'$ around it.

Assumption 1 indicates that $i$, $i' \in \mathbb{N}$ are two D2D pairs and they are neighbors when these pairs are in transmission range. Fig. 1a depicts the D2D pairs and their range of transmission. Assumption 2 mentioned above renders that each D2D pair has a communication channel and any other neighbor node pair can transmit on that channel. Time division multiple access (TDMA) can provide such a transmission opportunity. We assume that each node has the same interference range and symmetric property. This means if $i$ is a neighbor of $i'$, $i'$ is also a neighbor of $i$. The assumption is realistic since the transmission range of radio interfaces may differ. All the pairs will pose the same payoff function that depends on the channel selection of other pairs. We first characterize the properties of NE in the interface selection game by providing significant and satisfactory conditions to become NEs.

*Theorem 1: 1 $s_i$ is NE if the following three conditions are satisfied.*

*(1) $\forall l_j$ if $s_i = 0$, then $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 1$*

*(2) $\forall l_j$ if $s_i = 1$, then $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 0$*

*(3) $\forall l_j$, there does not exist player $i$, s.t. $s_i = 0$, then $\prod_{i' \in \mathbb{N}} s_{i'} = 1$.*

*Lemma 1:* 1 $s_i$ is NE, then $\forall l_j$, if $s_i = 0$, we have $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 1$.

*Proof 1:* We prove the lemma by contradiction. Suppose $\exists i, l_j$ s.t., $s_i = 0$ and $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 0$. We consider another strategy for $i$, $s_i'$ which equals $s_i$. Then we compare the utilities of player $i$ taking strategies $s_i$ and $s_i'$ where the strategies of player $i$ remain the same.

$$\begin{aligned} &U(s_i', s_{-i}) - U(s_i, s_{-i}) \\ &= \frac{1}{1 + e^{C(s_i', s_{-i})}} - \frac{1}{1 + e^{C_{max}(s_i', s_{-i})}} \\ &\quad - \frac{1}{1 + e^{C(s_i, s_{-i})}} + \frac{1}{1 + e^{C_{max}(s_i, s_{-i})}} \\ &= \frac{1}{1 + e^{C(s_i', s_{-i})}} - \frac{1}{1 + e^{C(s_i, s_{-i})}} > 0 \end{aligned} \quad (9)$$

This contradicts with the fact that $s_i$ is a NE.

*Lemma 2:* 2 $s_i$ is NE, then $\forall l_j$, if $s_i = 1$, we have $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 0$.

*Proof 2:* This is also proved by contradiction. As it is methodically similar, we skip the proof to avoid redundancy.

Another certain condition is that pairs will choose the channel with less interference to achieve NEs. On that channel, a user will achieve his required data rate with the selected interface. Formally it is expressed as the following lemma.

| | | $i$ | |
|---|---|---|---|
| | | B | W |
| $i'$ | B | $(U_i, U_{i'})$ | $(U_i + \theta, U_{i'} - \theta')$ |
| | W | $(U_i - \theta, U_{i'} + \theta')$ | $(U_i, U_{i'})$ |

**FIGURE 3.** A utility profile for two pairs.

*Lemma 3:* 3 $s_i$ is NE, there is no D2D pair $i$ s.t., $\forall l_j$, $s_i = 0$ and $\prod_{i' \in \mathbb{N}} s_{i'} = 1$.

Proof of Theorem 1.

*Proof 3:* Through Lemma 1, Lemma 2, and Lemma 3, we have to justify that $s$ is an NE if all these three conditions are true.

Suppose that a D2D pair $i$ can change the strategy to $s_i'$, therefore, change the utility. We explain two possible measures to do so.

(i) changing strategy $s_i$ from 0 to 1.

If $s_i = 0$, according to the theorem $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 1$. In this case $U(s_i', s_{-i}) - U(s_i, s_{-i}) \leq 0$. Therefore, by changing strategy $s_i$ from 0 to 1,utility of $i$ cannot be improved.

(ii) changing strategy $s_i$ from 1 to 0.

If $s_i = 1$, according to the theorem $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 0$. Therefore, $i$ will reduce the utility if and only if the strategy changes to 0.

Therefore, $i$ cannot increase the utility with other strategies being equal. Hence, $s_i$ is an NE.

In this section, we have explained the properties of NE. If a pair achieves NE but not Pareto optimal, then a possibility remains to increase the utility without hurting other D2D pairs. Therefore, we should verify whether all NEs are Pareto optimal in this game.

Here we present a simple matrix of utility profile between two pairs of a D2D link, based on their interface selection. $\theta$ and $\theta'$ are simple parameters to present the utility increase or decrease due to the change of strategy. We can define it as $-1 \leq (\theta, \theta') \leq 1$. D2D pairs $i$ and $i'$ can choose strategy $B$ or $W$. Here, $B$ stands for Bluetooth and $W$ stands for Wi-Fi, respectively. From the simple definition of game $(B, B)$ is an NE as given in Lemma 1. Here, $(B, B)$ is also Pareto optimal. If pair $i$ moves the interface to $W$, it imposes interference on the other pair. In this way, pair $i$ can increase his utility but decrease the utility of pair $i'$, which implies that this strategy is Pareto optimal. This specification is legitimate for the other pair $i'$.

This example of a non-cooperative game explains the strategy points that are Pareto optimal and NE. If the strategy of neighbors induces low interference, compared to the interference on current channels there can be NEs that are Pareto optimal.

*Example 1:* Consider a network with two D2D pairs $i$, $i'$ and a single channel. Each player has two interfaces. Fig. 3 presents an intuitive utility profile.

*Proposition 1:* For $I_{l_j} \leq I_{l_j'}$, if the strategy is NE, is also Pareto optimal.

*Proof 4:*

If $I_{l_j} \leq I_{l_j'}$, suppose a strategy exists that is NE but not Pareto optimal. Let us consider that D2D pair $i$ can change the strategy from $s_i$ to $s_i'$ without decreasing the utility of other D2D pairs.

$\exists l_j$, s.t., $s_i = \emptyset$ and $\exists l_j'$, s.t., $s_i' = 1$ or $s_i' = 0$.

Since there is no empty channel we can assume that $\exists l_j'$, s.t., $s_i \neq \emptyset$, $s_{i'} = 1$ or $s_{i'} = 0$.

Hence, the pair has no interface on a channel and the strategy is $\emptyset$. Now we show four cases regarding $s_i$ and $s_{i'}$

*Case 1:* $\forall l_j$, $s_i = 0$ and $\forall l_j'$, $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 1$. Now pair $i$ meets the same situation with user $j$ on channel $l_j'$ as give in Lemma 1. This is a contradiction with the condition because utility will not increase.

*Case 2:* $\forall l_j$, $s_i = 1$ and $\forall l_j'$, $\prod_{i' \in \mathbb{N}}(1 - s) = 1$. Here, pair $i$ changes the strategy but it will increase the interference for strategy $s_{i'} = 0$ and thus will reduce the utility. .

*Case 3:* $s_i = 0$ and $\prod_{i' \in \mathbb{N}}(1 - s_{i'}) = 0$, then $\forall s_{i'} = 1$. It contradicts with Theorem 1.

*Case 4:* $s_i = 1$ and $\prod_{i \in \mathbb{N}}(1 - s_{i'}) = 0$. This conceives as given in Lemma 2, thus yielding a contradiction for Pareto improvement.

Therefore, if $I_{l_j} \leq I_{l_j'}$, all the NEs are Pareto optimal.

Proposition 1 explains that when $I_{l_j} \leq I_{l_j'}$, there is no channel which has lower interference than the others. In an NE if a pair wants to increase utility by changing its strategy by employing the same interface on another channel $l_j'$, neighbor pairs on that channel change their strategy or remove their interface. As there is no empty channel, when a pair moves the interface to another channel, some other pairs lose part of their utility due to a new strategy.

## V. PROPOSED ALGORITHM

In previous section IV we have demonstrated a selfish D2D pair can achieve NE. With this formulated non-cooperative game, we need to develop an algorithm that can illustrate the process of interactions between D2D pairs. Therefore, we consider different set of available information and introduce three distinct algorithms. The purpose of these algorithms is to support D2D pairs to achieve Nash equilibrium from an initial configuration. The algorithms are as follows

1) cooperative with global information (*Social*),
2) distributed with global information (*Greedy*), and
3) distributed with local information (*Local*).

### A. SOCIAL

A coordinator iterates over a set of D2D pairs having information about each pair. The coordinator selects an interface for each pair which maximizes the aggregated utility (lines 6 − 14 in Algorithm 1). In this central algorithm, the D2D pairs select an interface based on the precedent event. Initially, all D2D pairs can be connected to the coordinator with any of the available interface. The process will repeat until all the pairs converge to the best decision. This algorithm is called *social* because it decides with cooperation with other D2D pairs and considers the overall welfare.

**Algorithm 1** *Social*

**Input:** $\mathbb{N}$: set of D2D pairs are formed.
$I_{l_j}, I_{l_j'}$: interference of other pairs on link $l_j$and $l_j'$ respectively.
**Output:** $s_i, \forall i \in \mathbb{N}$
**Initialize:** $s_i = s_{old} = \emptyset, \forall i \in \mathbb{N}$; $U_{max} = U_{sum}$
**while** $s_i \neq s_{old}$ **do**
  **for** $i \in \mathbb{N}$ **do**
    **for** $r \in \{1, 2, \ldots, n\}$ **do**
      Calculate $U_{sum}|i$ is in interface $r$
      **if** $U_{sum} > U_{max}$ **then**
        $U_{max} = U_{sum}$
        $s_i = r$
      **end if**
    **end for**
  **end for**
**end while**

**Algorithm 2** *Greedy*

**Input:** $\mathbb{N}$: set of D2D pairs are formed.
$I_{l_j}, I_{l_j'}$: interference of other pairs on link $l_j$and $l_j'$ respectively.
**Output:** $s_i, \forall i \in \mathbb{N}$
**Initialize:** $s_i = s_{old} = \emptyset, \forall i \in \mathbb{N}$;
**while** $s_i \neq s_{old}$ **do**
  $U_{max} = U_{l_j}$
  **for** $i \in \mathbb{N}$ **do**
    **for** $r \in \{1, 2, \ldots, n\}$ **do**
      Calculate $U_{l_j}|i$ is in interface $r$
      **if** $U_{l_j} > U_{max}$ **then**
        $U_{max} = U_{l_j}$
        $s_i = r$
      **end if**
    **end for**
  **end for**
**end while**

**Algorithm 3** *Local*

**Input:** $I_{l_j}$: interference of other pairs on link $l_j$.
**Output:** $s_i, \forall i \in \mathbb{N}$
**Initialize:** $s_i = s_{old} = \emptyset$;
**while** $s_i \neq s_{old}$ **do**
  **for** $r \in \{1, 2, \ldots, n\}$ **do**
    $U_{max} = U_{l_j}$
    Calculate $U_{l_j}|i$ is in interface $r$
    **if** $U_{l_j} > U_{max}$ **then**
      $U_{max} = U_{l_j}$
      $s_i = r$;
    **end if**
  **end for**
**end while**

### *B.* GREEDY

We now propose the *greedy* algorithm. Unlike *social*, *greedy* targets to improve the individual utility. Therefore, all the D2D pairs might not converge to the best decision. The *greedy* algorithm occurs in a coordinator and a decision is made in a proactive manner. The coordinator will make a decision for each pair iteratively and balances decisions to assure utility, i.e., the utility of a D2D pair due to a decision has no impact because of the next decision for another pair. Once a decision is made for all the pairs, the algorithm stops the iteration.

### *C.* LOCAL

We also propose a local heuristic algorithm that operates on individual D2D pairs. Both *social* and *greedy* operates with a coordinator and have information about D2D pairs in the network. In contrast, in this approach, each D2D pair has information about other pairs who exist on the same channel $m$. If a D2D pair changes its strategy, that will be always a different interface on the same channel but not other available channels. The strategy matrix for each D2D pair is much smaller compared to *social*. Therefore the computational overhead to end users is reduced greatly. Each pair will calculate its strategy and terminate upon completion of decisions.

#### 1) COMPLEXITY ANALYSIS

Our proposed heuristic *social* and *greedy* both sequentially compute $|\mathbb{L}||\mathbb{R}|(|\mathbb{N}|-1)$ utilities for each strategy and for every D2D pair, i.e., total $|\mathbb{N}||\mathbb{L}||\mathbb{R}|\times(|\mathbb{N}|-1)$ number of utilities per round of evolution. In our work, we have considered the evolution cycle to be 1, and the decision converges within one cycle if and only if the D2D pairs and channel number do not change during evolution. Therefore both *social* and *greedy* have a complexity of $\mathcal{O}(|\mathbb{N}||\mathbb{L}||\mathbb{R}|\times(|\mathbb{N}|-1))$. In case of *local* approach it targets the utility of individual pairs and the algorithms function on the edge users. As a result, the complexity of this approach varies among different pairs. Hence, the complexity for *local* is $\mathcal{O}(|\mathbb{R}|\times(K_{l_j}-1))$.

*Definition 3:* Efficiency: The efficiency $\phi$ of a strategy is defined as a proportion between the utility of selected strategy and best case strategy. It can be presented as $\phi(s_i) = \frac{U_{l_j}}{U_{max}}$.

*Definition 4:* Convergence Time: The convergence time of an algorithm depends on the duration for efficiency of strategy selection to reach on (i.e., $\phi(s) = 1$ ).

The convergence of algorithms depends on the number of users, available interfaces and channels in the network, which is tested through our simulation.

## VI. PERFORMANCE EVALUATION

To verify the performance of the proposed algorithms, we conduct extensive simulation using MATLAB. We considered devices with Bluetooth and Wi-Fi interfaces where both the interfaces can access the same spectrum band of 2.4GHz; thus some of the channels of the two radio systems are overlapped. We assume that in this noncooperative

**TABLE 2. Parameters.**

| Parameter | Value |
|---|---|
| Number of channels (Bluetooth) | 40 |
| Number of channels (WiFi) | 11 |
| Bandwidth (Bluetooth) | 2MHz |
| Bandwidth (Wi-Fi) | 20 MHz |
| Fading, shadowing | Reyleigh, 6dB |
| Path loss model | $148.1 + 40log10(d[m])$ |
| Noise spectral density | $-17$dBm/Hz |
| Antenna gain (Omni-directional) | Device: 0 dBi |
| Wi-Fi TX power | 20 dBm |
| Bluetooth TX power | 10 dBm |

game the user can select one interface between Bluetooth and Wi-Fi to achieve the best utility. In addition, to compare our algorithms, we evaluated three benchmark schemes, namely, exclusive Wi-Fi, exclusive Bluetooth, and liner program (LP) based solution. In exclusive Wi-Fi, all D2D pairs in the network are forced to communicate using Wi-Fi Direct and in exclusive Bluetooth, they are forced to communicate using Bluetooth. The LP provides an *upper bound* by solving the expression in equation (8). We can achieve this by selecting the proper value for $C_{l_j}$. Wi-Fi with a higher transmission power provides better data rate whereas it increases interference for the surrounding D2D pairs. On the contrary, Bluetooth has a lower data rate, but due to its small transmission power neighbor D2D pairs can achieve comparatively better data rate. Now the question is: *What is the best choice for a D2D pair?* Our simulation is to reflect a justification for such an argument.

## A. SIMULATION SETUP

We consider an area of 200m $\times$ 200m and users are uniformly distributed in that area. The SNR of a pair is measured based on the distance and the number of other pairs on the same channel. The default values for the overall simulation are listed in Table 2. Note that the maximum utility $U_{max}$ is calculated considering load balancing among all the available channels in the network. We compute the average value after 1000 independent runs for each set of parameters. The condition of a channel will be closely related if the two users are in the same vicinity. We distribute the noise level among the channels and users can determine the noise by path loss and some standard deviation. Therefore distant users cannot transmit on the same channel.

We compared our proposed algorithms with the benchmarks by varying the number of channels, data rates, and D2D pairs. The performance was obtained from the perspective of utility, energy consumption and efficiency, where the efficiency is defined as the amount of transmitted data per Joule.

## B. SIMULATION RESULTS

Fig. 4 illustrates the impact of the utility when the number of channels varies in the network but the number of D2D pairs is retained at 100. We can observe that the utility of Bluetooth is better than Wi-Fi when the number of channels

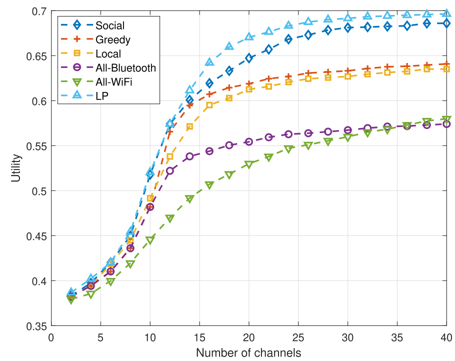


**FIGURE 4. Average utility per user in the networks.**

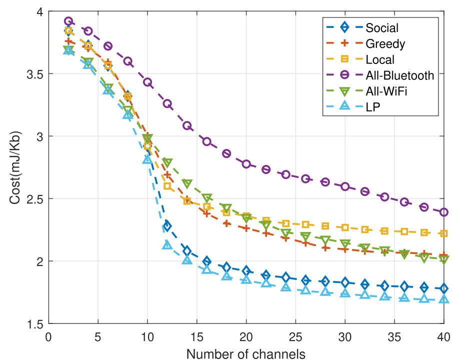


**FIGURE 5. Average cost per user.**

is small. This is due to interference by high-powered Wi-Fi transmission. The utility of Wi-Fi increases uniformly but still with 40 channels it is only 0.57. The performance of LP is similar to *social* and improves slightly with the number of channels. Though the number of channel increases, D2D pairs rendezvous on a random channel and the neighbor pairs can have the same channel for communication. Therefore, the utility is only improved by selecting a different or same radio interface on that channel. On the other hand, with the same number of channels, *social* improves the utility to 0.68, which is almost 19% improvement compared to exclusive Bluetooth and Wi-Fi. With a much smaller number of channels we can observe little improvement only in case of *social* but both *greedy* and *local* present identical utility compared to others. *Greedy* and *local* are outperformed by *social* due to their non-cooperative behavior though *greedy* has the same computational complexity.

Another finding is that increasing the number of channels can reduce the cost for each pair, as depicted in Fig. 5. The cost is considered for each pair to transmit per kilobits (Kb) of data. For instance, when the number of channels increases the average cost per user reduces for all the schemes. Bluetooth has a much higher cost compared to any other scheme as shown in Fig. 5, because of its lower bit rate. On the other hand, Wi-Fi shows significant improvement in the cost though totally outperformed by *social*. *Social* has an advantage in overall utility comparison which elevates the possibility of better output. LP depicts the minimum average

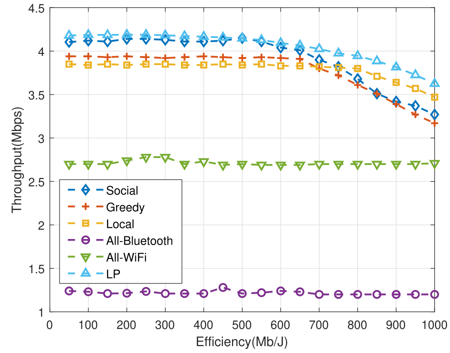


**FIGURE 6.** Average throughput per D2D pair.

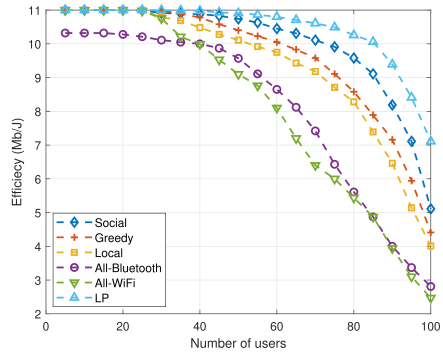


**FIGURE 8.** Average efficiency per D2D pair.

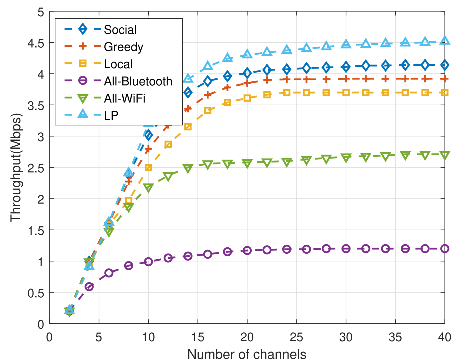


**FIGURE 7.** Average throughput as a function of the number of channels.

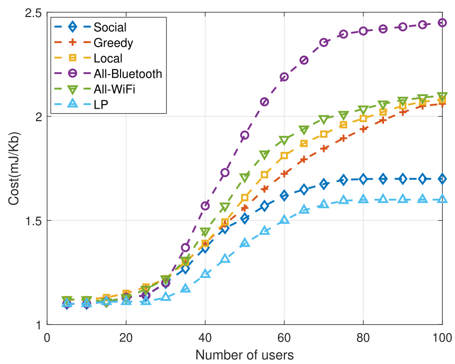


**FIGURE 9.** Average cost as a function of the number of users.

cost to achieve the utility in Fig. 4. With a lower number of channels *social* has a slightly higher cost, but it reduces significantly when the number of channels is more than 10 and it is less than 2mJ/Kb with 40 channels. Other two algorithms, *greedy* and *local* drain cost in the same manner for different numbers of channels. Nevertheless, we can claim that both schemes achieve better utility.

In Fig. 6 we can observe that the average throughput per user shows better performance than exclusive Wi-Fi and Bluetooth. This is obvious after the comparison of utility. Wi-Fi and Bluetooth show no impact on the increase in cost because these systems are biased to throughput. Hence, our proposed algorithms show a reduction in throughput as the cost increases. We aim to maximize the utility; therefore, in LP throughput is compromised and could not achieve more than 4.2Mbps. When the cost is $10^3$b/J, we can observe the throughput reduces by almost 22%. The average throughput per user with various numbers of channels is depicted in Fig. 7. All the proposed algorithms and Wi-Fi show an identical improvement until the number of channels is 10. After that Wi-Fi is completely outperformed by the proposed algorithms. Social performs close to the performance of LP. The performance gap is narrower when the number of channel is smaller. The reason is that when the channel number is less, both LP and *social* select proper radio interface to enhance better throughput. Bluetooth has a very low throughput compared to the others. One reason is that it hops for another channel when there is interference on the current channel. On the contrary, Wi-Fi takes a backoff window when the channel is busy.

To investigate the efficiency by considering throughput and energy together, we considered 40 channels for various numbers of users as shown in Fig. 8. With the increase in the number of users, the efficiency declines. The efficiency of all proposed schemes reduces due to the increasing number of D2D pairs. Different pairs on the same channel in close vicinity cannot avoid interference through the different selected interface for communication. When the number of users is high, the backoff time of Wi-Fi increases and Bluetooth faces higher interference, which causes their lower efficiency compared to the proposed algorithms. In respect of LP, *social* has the most significant performance. It has almost 70% improvement of efficiency compared to others when the number of users is 100.

Further, we compared the cost with various numbers of D2D pairs considering $N = 100$ as shown in Fig. 9. The cost is calculated to achieve the maximum utility for all the D2D pairs. We observe that the cost escalates with the number of pairs. Bluetooth consumes the most due to its hopping characteristics due to interference as explained before. For Wi-Fi, it is obvious that more pairs will increase the backoff time which is reflected in the result. Only *social* shows significant improvement of cost as in the strategy all the pairs are not in Wi-Fi mode, which reduces the load. Compared to LP, *social* cost only 0.1 mJ/Kb extra cost when the number of users is 100. And finally, we derived the average time

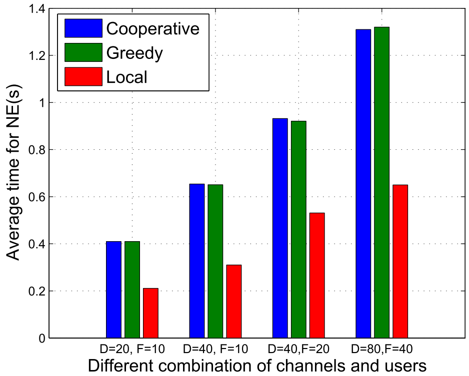


**FIGURE 10.** Average time to achieve a NE.

to achieve an NE for our proposed schemes in Fig. 10. We considered an *tic-toc* operation to measure the elapsed time. Fig. 10 shows *social* takes much more time compared to other schemes, which is evident owing to the complexity explained earlier. *Greedy* has a similar complexity and the result justifies that property. Though *local* has the lowest utility and throughput, it consumes the least time to achieve an NE because it does not deal with all the users and channels to make a decision for D2D communication.

## VII. CONCLUSION

In this paper, we propose a *radio interface selection* process motivated by the multiple D2D opportunity in wireless networks. In light of non-cooperative game theory, we have modeled a competition among different available radio interfaces and channels. We have also studied Pareto optimality of the NE. Finally, we have provided three heuristic algorithms, namely *social*, *greedy* and *local* to achieve an efficient strategy to achieve an NE. The proposed algorithms work in different network models and parameter sets. A practical network can improve overall throughput with the proposed game model.

The major observation of our analysis are:

1) proper radio *interface selection* can be modeled as a game that tends to convert in the form of NE solution, which is also Pareto optimal;
2) the equilibria are obtained based on an inverse relation of the multi-parameter cost function and utility function;
3) the proposed approach and their comparison show the trade-off between utility, efficiency, and cost with various sets of network parameters.

For future work, we will extend the *interface selection* process to account the type of traffic or the application running on the users. In fact, battery sojourn time can be considered as an influential factor for the decision. Last but not least, we will also study to reduce the complexity of the current approach.

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