Mobility-Aware Incentive Mechanism for Relaying D2D Communications

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Abstract-- Device-to-Device (D2D) communications emerged as a promising technology to improve the efficiency of 5G cellular networks. However, users should be encouraged to participate in content sharing and relaying, which are necessary for D2D communications. Thus, an incentive mechanism is essential to encourage the content owners and relay nodes to participate in D2D communications. In this study, a contract-based incentive mechanism is proposed for relaying D2D communications. In contrast to previous work, this mechanism simultaneously motivates both content owners and relays to participate in D2D communications. Furthermore, user mobility is considered in the proposed approach. Assuming that the devices in the network are mobile, mobility awareness can be effective in the performance of the proposed incentive mechanism since we need more appropriate contracts that are less likely to be violated due to link failures which are the results of the mobility. Therefore, in the proposed mobility-aware incentive mechanism, the selection of the contract is performed according to the predicted location of devices in the next time step, as obtained from Markov method. The simulation results show that the proposed incentive mechanism increases the participation of devices in D2D content sharing compared to the baseline. Also, it is more likely that a content owner earns more utility due to the cooperation of a relay, which leads to an increase in the utility of the base station. Moreover, the increased data transmission rate which is obtained via encouraging relays to participate in D2D communications, reduces the latency and increases the residual energy of the devices. Also, using the proposed mobility-aware incentive mechanism, the utility of BS is improved compared to a similar scenario without mobility awareness.

Keywords-- Incentive mechanism, relaying D2D communication, mobility-awareness, contract theory.

I. Introduction

With the increasing popularity of mobile phones due to the spread of the Internet and various applications, the growth of demands for content access is inevitable. Not only does this increase costs for network operators, but also it is not possible to respond to all requests with acceptable quality. Therefore, Device-to-Device (D2D) communications have been introduced as a promising technology in cellular networks to improve network performance [1].

In cellular networks, two users usually communicate with each other through a base station (BS), while D2D communications allow nearby users to communicate directly without involving BS and the only task of the BS is network control. D2D communications increase network capacity, expand cellular network coverage, and reduce network power consumption [1-2]. Moreover, due to the short distance between D2D devices, the speed of data transfer increases and the latency decreases, which leads to a rise in the quality of services [3].

The use of D2D communications requires two main phases: The first phase is the discovery phase, where users that are close to each other and can communicate directly are discovered. The second phase is the communication phase, in which all processes such as mode selection, resource allocation, and interference management take place [3].

Both licensed and unlicensed bands may be used by D2D communications. According to this, the D2D communications are divided into two categories, inband D2D communications, and outband D2D communications. Inband D2D communications exploit the cellular spectrum for their communications and are divided into two categories, i.e. overlay and underlay. In underlay mode, the spectrum is shared between D2D and cellular communications, and in overlay mode, a portion of the cellular spectrum is separated for D2D communications. Outband D2D communications exploit an unlicensed spectrum and are divided into two categories, i.e. controlled and autonomous. In controlled communications, cellular and D2D communications are controlled by the cellular infrastructure, and in autonomous communications, the control of D2D communications is delegated to D2D devices [2]. In our research, inband underlay D2D communications are considered.

From the other point of view, D2D communications are divided into two main categories, i.e. direct communications where two devices can communicate directly with each other and relaying communications where two devices communicate with each other using one or more devices that act as relays. Relay selection and management are accomplished by the BS or devices

[4-6]. When the link quality between two devices is poor, choosing a suitable device as a relay would be helpful to strengthen the link quality [7]. In addition, using relays in D2D communications increases the data transmission rate, which reduces data transmission time and power consumption [8].

Many studies in the field of D2D communications assume that content owners and relays always participate in D2D communications. However, incentives are required to compensate the participation cost of users, including their energy and computation resources. In recent researches, incentive mechanisms have been attended for direct D2D communications [9-11] and also for cooperative communications [12-14] to motivate content owners and cooperative relays, respectively. However, simultaneously encouraging both the content owners and the relays has not been addressed in D2D communications. Moreover, the mobility of D2D devices may affect the incentive mechanisms while previous studies have not addressed it.

In this study, an incentive mechanism is proposed for relaying D2D communications that in contrast to previous work, 1) simultaneously encourages both content owners and relays to participate in D2D communications based on contract theory [16], and 2) considers user mobility to design and select the contracts based on the predicted location of devices.

The rest of this paper is organized as follows. Section II is a detailed literature survey. Section III presents the proposed incentive mechanism. The mobility-aware contract selection is discussed in Section IV. Finally, Sections V and VI are dedicated to simulation results and conclusions, respectively.

II. Related Work

In this section, the most important researches on incentive mechanisms for D2D and cooperative communications are reviewed.

In some of the researches such as [9][17-21], Stackelberg game and auction theory have been exploited. To participate in the D2D communications, authors in [9] consider two markets, i.e., the open market and the sealed market, and introduce two incentive mechanisms for such markets. In the open market, each D2D pair knows the information and performance of the other D2D pairs, and the Stackelberg game is used to encourage users. In a sealed market, each D2D pair communicates only with the BS and does not share its information with other D2D pairs. Therefore, each pair does not know the strategy of the other pairs and does not even know about the existence of pairs, which results in an asymmetry information scenario. In this market, the auction algorithm is utilized to encourage users. Moreover, in [17], an incentive mechanism is presented for D2D communications based on the Stackelberg game to reduce power consumption. In storing and sharing data, users need incentives to compensate the costs of participating, including storage space and consumed energy. Reference [18] uses the Stackelberg game to propose an incentive mechanism for users' participation in the process of data storage in cellular networks. Also, authors of [19-20] offer incentive frameworks based on the Stackelberg game in which the network operator encourages some users to act as transmitters of D2D communications and distribute the content to requesting nearby users. In [21], an auction-based incentive mechanism is designed to maximize cellular traffic offloading. Some mobile phones act as relays and help traffic offloading by storing data. Mobile network operators select some relays according to a greedy algorithm and encourage them to move to dense locations to improve the performance of the relays and increase the amount of traffic offloading.

In some of the researches such as [10-11][15][22-28], contract theory is used to design incentive mechanisms. In [10], an incentive mechanism is proposed to promote D2D communications to utilize idle users. In wireless communication systems, some of the resources are usually idle or underused. Using these resources increases traffic offloading and network throughput. In this mechanism, using contract theory, idle mobile phones are encouraged to transfer data to other users through D2D communications. Authors in [11] use contract theory to overcome asymmetric information in the design of incentive mechanisms for D2D communications to reduce BS traffic and increase the capacity of the cellular network. In [22], an incentive mechanism is proposed for promoting multicast D2D communications using contract theory under two scenarios of symmetric information and asymmetric information. To prevent repetitious transfers, the operator encourages local users (who have already stored content) to share the content through D2D communications. In [23] an incentive mechanism for the process of delayed traffic offloading in cellular networks under the asymmetric information scenario based on contract theory is introduced. The process is modelled on a monopoly market in which the operator acts as a monopolist and designs optimal contracts. In [24] an incentive mechanism for full-duplex relay systems is proposed. It is assumed that some users already store popular contents in their memory, and other users can receive those contents with the help of an intermediate device and through D2D communications. Some devices need incentives to store popular data and share it with other devices when needed. In [25] an incentive mechanism for cooperative storage in a distributed storage system is presented.

In cooperative communications, the quality of the channel between the transmitter and the receiver is assumed to be poor, so the transmitter needs the help of several nodes as relays. These cooperative communications can effectively improve the performance of spectrum and wireless network coverage. In [15], an incentive mechanism is designed based on contract theory for the cooperation of nodes as relays. Channel status information between the relay and the destination is private information that the source overcomes this private information by designing optimal contracts and encourages the nodes to operate as the relay. In [26] a contract theory-based mechanism for encouraging relays in cooperative communications under a dual asymmetric information scenario is proposed. This research focuses on the design of optimal contracts, first by employing a supervisory node to monitor information and operation, and then without a supervisor node. Authors in [27] have modelled cooperative communications as a labour market. The incentive mechanism for relay cooperation has been investigated using contract theory under three scenarios: symmetric information, single asymmetric information, and dual asymmetric information. Similar to [27], authors in [28] introduce an incentive mechanism to encourage relays, but the contracts are dynamically designed to fit in a dynamic network environment over a while.

In summary, while incentive mechanisms in direct D2D communications and cooperative communications have been widely studied, no literature has investigated the problem of simultaneously motivating both the content owners and the relays in relaying D2D communications. Moreover, mobility has not been attended to incentive mechanisms proposed in previous studies. In the following sections, we propose a mobility-aware method to encourage both the content owners and the relays to participate in D2D communication with the goal of increasing the utility of the BS. As the data transmission rate is usually higher in relaying D2D communications, the proposed method reduces the latency and increases the residual energy of the devices.

III. System Model

In relaying D2D communications, an incentive mechanism is essential to encourage the nodes to participate in D2D communications. In this study, the proposed incentive mechanism motivates both content owners and relay nodes to participate in relaying D2D communications. In this context, a cellular network is considered which consists of one base station (BS) in the center of the cell, and N_c cellular communications and N_d direct or relaying D2D communications, as shown in Fig 1. Each direct D2D communication includes a content provider (CP) and a content requester (CR), while each relaying D2D communication has a relay node in addition to the CP and the CR. The number of contents is equal to K, and it is assumed that there is one content provider for each content requester. Also, it is assumed that the size of all contents is L bits. The owner and the requester of content X are shown by CP_X and CR_X, respectively. Each content requester can receive its desired content from the BS or a relevant content provider using direct/relaying D2D communication.

The proposed incentive mechanism for relaying D2D communication increases the participation of devices in D2D content sharing since using relay devices usually results in higher quality D2D communications than direct D2D communications. For instance, consider a direct D2D link between CP2 and CR2 (as shown in Fig. 1) with a speed of 1Mbps. This D2D communication could be sped up if a device (near the sender and the receiver devices) participates as a relaying node. Using this relay, the indirect link has a higher speed (2Mbps), which is equal to the minimum of the rate between CP2 and the relay node (3Mbps) and the rate between the relay node and CR2 (2Mbps). Increasing the number of such D2D communications is attractive for the network operators, particularly in crowded places such as university campuses, workplaces, shopping centers, and amusement parks. This is due to the fact that encouraging nearby users to participate in content sharing and relaying decreases the traffic load of the cellular network's core. Also, the speed of data transfer increases and the latency decreases because of the short distance between the D2D devices, which leads to user satisfaction.

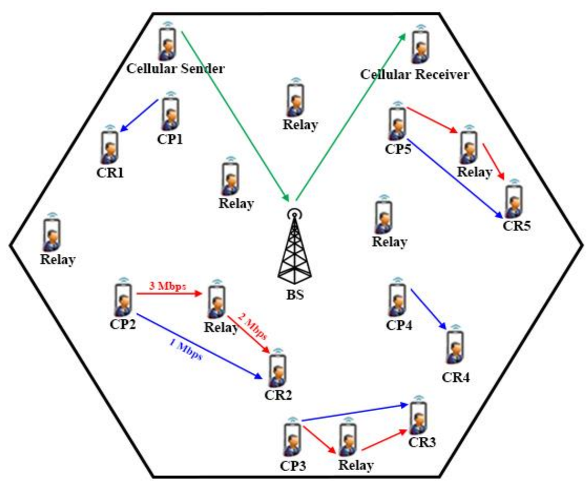


Fig. 1. System model

CPs have different preferences for establishing D2D communications. The CPs are aware of their preferences, while the BS is unaware of the preferences of the CPs. So, there is an information asymmetry between the BS and the CPs [29].

The proposed method is inspired by the method of [11]. In [11], the BS designs various contracts and offers to the CPs to motivate them to deliver content to the CRs using direct D2D communications. Each contract is a pair *(T(R), R)* where *T* is the reward and *R* is the performance that the BS expects from the CP to be satisfied. *T(R)* is a strictly increasing function of *R*. Instinctively, a CP with better performance should receive more rewards and vice versa. Each CP calculates its utility based on the received contracts and selects the contract that provides the maximum utility. Then, by choosing the most appropriate contract and responding to the BS, it reveals its performance according to the preferences for the BS. If a CP does not accept any of the contracts, it is assumed that it has signed the contract *(0,0)*. In this research, we extend the method of [11] to motivate both the CPs and the relays simultaneously in a relaying D2D communication.

In relaying D2D communications, relays also have different preferences for participation, and there is an information asymmetry between each CP and the relays. In other words, each relay is aware of its preferences while each CP is not aware of the relay's preferences. So, there is an information asymmetry between the CPs and the relays too. Therefore, when the BS offers some contracts to the CPs, each CP chooses a set of devices as relays and sends some new contracts to them. Then, based on the adopted contract with the selected relay, the CP selects the most appropriate contract from those offered by the BS and responds to the BS. Hence, each CP not only reveals its performance to the BS according to its preferences, but also reveals its mode of communication (direct or relaying) to it. Table 1 lists the notations used in the paper and their definitions. In the following, first, we explain the types of CPs/relays and then discuss the structure of contracts.

A. Types of CPs and relays

Type is used to present the preference of a CP or a relay for participating in a D2D communication [11]. Type is determined based on various parameters such as battery technology, remaining battery level, link quality, storage capacity, and privacy concerns of a device. A high type CP or relay not only performs better and will receive more reward but also it is more preferable than low type ones for the BS regarding performance objectives.

In this research, we assume that the type of each CP or relay in a D2D link is based on the link quality. Thus, the type of a CP may be different in the direct and relaying modes, and the better the link quality of a device in a D2D link, the higher its type. For example, as shown in Fig. 1, the data rate of the direct link between CP2 and CR2 is 1Mbps, while the data rate of the relaying link is higher (2Mbps). Thus, the type of CP2 in relaying link is higher than its direct link.

Table 1. The notations and their definitions in the paper

Parameter	**Definition**
$type_i$	The type of a CP or a relay in a CP-relay link or relay-CR link
$type_i^{D/R}$	The type of a CP in a direct D2D link (based on CP-CR link quality)/ The type of a CP in a relaying D2D link
$type_{i(t+1)}$	The type of a CP or a relay in a CP-relay link or relay-CR link at Time *t+1*
$type_{i(t+1)}^{D/R}$	The type of a CP in a direct D2D link/ in a relaying D2D link at Time *t+1*
$(t_{Rel_i}, t_{CP_i}, R_i)$	$type_i$ contract
θ_i	Type-dependent coefficient that depends on $type_i$ CP or relay
$\theta_{i(t+1)}$	Type-dependent coefficient that depends on $type_i$ CP or relay at Time *t+1*
$U_{BS}^{D/R}(i)$	The utility of the BS by choosing $type_i$ contract for direct (D)/ relaying (R) D2D communication
U_{CP_i/Rel_i}	utility of $type_i$ CP/ $type_i$ relay

It is assumed that the number of types belongs to a finite and discrete set, so the range between minimum and maximum possible qualities is quantized into N_d levels, and each level is assigned to one of the N_d types. Therefore, the set of types is $\{type_1, \ldots, type_{N_d}\}$ where $type_1 < \cdots < type_i < \cdots < type_{N_d}$. It should be noted that several D2D links can belong to the same type. As the type of a D2D device in a D2D link depends on its link quality, the type of a CP in a direct D2D link may be improved using an appropriate relay.

Similar to [11], we assume that the BS is not aware of the type of CPs and relays for D2D communication, and the only information available for the BS is the probability of the existence of each type which is represented by λ_i where $\sum_{i=1}^{N_d} \lambda_i = 1$.

B. Contracts

The BS designs separate contracts according to the probability of the existence of each type and sends contracts to all CPs. Since the BS does not know whether each type is for a direct or a relaying D2D communication, each contract is designed as a triplet. For example, the *type$_i$* contract for a CP is denoted by $(t_{Rel_i}, t_{CP_i}, R_i)$ where R_i is the expected performance, and t_{CP_i} and t_{Rel_i} are the offered rewards for the CP and the probable selected relay, respectively. It is assumed that the values of t_{CP_i} and t_{Rel_i} are equal. In other words, we assume T_i as the total reward where half of it is dedicated to CP and the other half is dedicated to the selected relay if relaying mode is decided. Hence, only half of the total reward is allocated to the CP if the direct mode is selected. Formally, the rewards of CPs/relays in direct and relaying mode are obtained from Equations (1) and (2), respectively

$$t^D_{CP(i)} = \frac{T_i}{2}, t^D_{Rel(i)} = 0 \quad (1)$$

$$t^R_{CP(i)} = t^R_{Rel(i)} = \frac{T_i}{2} \quad (2)$$

The performance R_i is assessed in terms of the CP's data transmission rate during D2D communication, which depends on the signal to interference plus noise ratio (SINR) of the receiver. In a cellular network with D2D underlay, not only the receiver suffers from cellular users' interferences, but also it suffers from other D2D users' interferences because of spectrum reuse. We assume that for direct D2D communication, the CP transmits data to the CR, reusing the uplink band of a cellular user. Hence, the performance (data rate) of a $type^D_i$ CP in direct D2D communication in an uplink reused band is given by

$$R^D_i = W\, log_2\left(1 + \frac{P_{CP_i}\left|h_{CP_i,CR_i}\right|^2}{I_{Cell}+I_{D2D}+N_0}\right), \quad (3)$$

where P_{CP_i} is the transmit power of CP_i, i.e. $type^D_i$ CP, $\left|h_{CP_i,CR_i}\right|^2$ is the channel gain between CP_i and CR_i, I_{Cell} is the interference from cellular users, I_{D2D} is interference caused by other D2D users on this D2D communication, N_0 is the additive white Gaussian noise (AWGN), and W is the channel bandwidth [11]. For example, in Fig. 1, CP2 has a speed of 1Mbps in direct D2D communication and it can select a contract with eventually 1Mbps performance.

Similarly, when D2D communication is in the relaying mode, we assume that the CP reuses the uplink band of a cellular user for forwarding data to the relay, and the relay reuses the downlink band of a cellular user for forwarding data to the CR. Therefore, the performance (data rate) of a $type^R_j$ CP in relaying D2D communication using relay *m* is given by

$$R^R_j = Min\left\{R_{CP_j,Rel_m}, R_{Rel_m,CR_j}\right\}, \quad (4)$$

where R_{CP_j,Rel_m} is the achievable rate between CP_j and relay *m* and R_{Rel_m,CR_j} is the achievable rate between relay *m* and CR_j which are obtained similar to Equation (3). For example, in Fig. 1, CP2 has a speed of 2Mbps in the indirect mode and it can select a contract with eventually 2 Mbps performance.

In the following section, we introduce the proposed incentive mechanism by explaining the algorithms performed by the BS, CPs, and relays and also the algorithm for optimally preparing the contracts.

IV. Proposed Incentive Mechanism

In this section, we present the proposed algorithms performed by the BS, the CPs, and the relays to encourage the content owners and also the relays to participate in the D2D communications. Afterward, we discuss the proposed method for the contract design in the BS.

A. The algorithm performed by the BS

Algorithm 1 shows the procedure performed by the BS. First, some CRs request their desired contents from the BS. Then, the BS uses a discovery algorithm to detect appropriate CPs for the contents (Line1). If discovered CPs are locally available to the CRs, the BS designs a set of contracts in the form of $\{(\frac{T_n}{2}, \frac{T_n}{2}, R_n), n = 1 \dots N_d\}$ to motivate CPs to participate in a direct or relaying D2D communication and sends contracts to the CPs (Line 3). Each CP, depending on the quality of direct D2D link to the CR (direct D2D communication), chooses *type$_i$* contract and also depending on the quality of available D2D link to the best possible relay (relaying D2D communication), chooses *type$_j$* contract and respectively sends the response in the forms of $(0, \frac{T_i}{2}, R_i)$ and $(1, \frac{T_j}{2}, R_j)$ to the BS. In these returned contracts which are different from initial contracts, 'zero' indicates that the selected contract is for direct D2D communication, and only the CP receives the reward ($\frac{T_i}{2}$). Also, 'one' means that the selected contract is for a relaying D2D communication and the BS has to reward both the CP and its relay (each with $\frac{T_j}{2}$ reward). If a CP does not find a suitable relay to cooperate, it will return one contract in the form of $(0, \frac{T_i}{2}, R_i)$ to the BS, where T_i and R_i have been selected only based on the quality of its direct D2D link to the CR.

After receiving the response from CPs, the BS signs one contract with each CP. Therefore, for CPs who have sent two contracts, the BS would choose only the contract that leads to more utility (Lines 5-11). For example, if the utility from *type$_i$* contract (which is related to a direct D2D communication) is greater than the utility of the *type$_j$* contract (which is related to a relaying D2D communication), the BS signs the *type$_i$* contract with the CP and vice versa. If no response is received from a CP, it is assumed that it has signed the contract *(0, 0, 0)*.

The utility of the BS in choosing the above mentioned $type_i$ contract which was for direct D2D communication is obtained from

$$U_{BS}^{D}(i) = R_i - c\frac{T_i}{2}. \quad (5)$$

Also, by choosing the $type_j$ contract which was for relaying D2D communication, the utility of the BS is calculated as

$$U_{BS}^{R}(j) = R_j - cT_j. \quad (6)$$

Algorithm 1. The algorithm performed by the BS

Input: CR_X is requesting content X where $1 \le X \le K$

1. CP_X = content_provider_discovery (X)
2. **if** distance (CP_X, CR_X) < D) *//CP_X is locally accessible*
3. **Broadcast** the list of designed contracts $\{(\frac{T_n}{2}, \frac{T_n}{2}, R_n), n = 1 \dots N_d\}$
4. **Wait** for the response from CP_X
5. **if** $(0, \frac{T_i}{2}, R_i)$ and $(1, \frac{T_j}{2}, R_j)$ are returned by CP_X where $R_i < R_j, T_i < T_j$
6. **Calculate** BS's utility using Equations (5) and (6)
7. **if** $U_{BS}^{D}(i) \ge U_{BS}^{R}(j)$
8. **Sign** contract $(t_{Rel_i}, t_{CP_i}, R_i)$ with CP_X where $t_{Rel_i} = 0$ and $t_{CP_i} = \frac{T_i}{2}$
9. **else**
10. **Sign** contract $(t_{Rel_j}, t_{CP_j}, R_j)$ with CP_X where $t_{Rel_j} = t_{CP_j} = \frac{T_j}{2}$
11. **end**
12. **else if** contract $(0, \frac{T_i}{2}, R_i)$ is returned by CP_X
13. **Sign** contract $(t_{Rel_i}, t_{CP_i}, R_i)$ with CP_X where $t_{Rel_i} = 0$ and $t_{CP_i} = \frac{T_i}{2}$
14. **else**
15. **Sign** contract *(0,0,0)* with CP_X
16. **Serve** the request directly
17. **end**
18. **end**

In the above equations, the utility of the BS is equal to the difference between the data rate provided by the D2D communication (R_i or R_j) and the reward paid to the CP and probably to the relay for delivering the content as inspired by [11]. $\frac{T_i}{2}$ is the reward paid to the $type_i^D$ CP in direct D2D communication, and T_j is the total reward paid to the CP and the cooperating relay in above mentioned $type_j$ contract. Also, c is equivalent to each BS's unit cost. For the BS, a D2D communication which is according to the $type_i$ contract, would be beneficial if $U_{BS}(i) \ge 0$. Otherwise, the BS does not choose this D2D communication. Assuming the existence of N_d types of D2D communications (direct or relaying) where the probability of each type is equal to λ_i, the expected utility of BS in the worst case is equal to [11]

$$U_{BS} = \sum_{i=1}^{N_d} \lambda_i (R_i - cT_i). \quad (7)$$

Since BS does not know how many communications would be direct and how many would be relaying, Equation (7) considers the worst case, i.e. when all of the D2D communications are relaying. In general, if we assume that each type is relaying with a probability of α and is direct with a probability of $(1-\alpha)$, then the expected utility of the BS can be calculated as

$$U_{BS} = \sum_{i=1}^{N_d} \lambda_i (R_i - \frac{1}{2}(\alpha + 1)cT_i). \quad (8)$$

Given N_d types, the complexity of contract design (Line 3 of Algorithm 1) is $O(N_d)$ [22] as will be discussed in Subsection IV-D. Also, it is obvious from the algorithm that if the number of D2D pairs is N_d and all CPs return two forms of contracts, the computational complexity is $2N_d$. Therefore, the computational complexity of Algorithm 1 is $O(N_d)$.

B. The algorithm performed by the CPs

Algorithm 2 shows the procedure performed by the CPs. After receiving the contracts from the BS, each CP obtains its type based on the quality of its direct link to the relevant CR, which is calculated as

$$type_i^D = \frac{|h_{CP_X, CR_X}|^2}{I_{Cell} + I_{D2D} + N_0}. \quad (9)$$

Then, each CP calculates its utility from the direct D2D communication based on each of the received contracts and selects a contract that provides the maximum utility (Lines 2-3). Contracts are designed in such a way that each CP will receive the maximum utility by choosing the contract that is exactly matched to its type. In other words, a $type_i^D$ or $type_i^R$ CP in a D2D link receives the maximum utility by choosing the $type_i$ contract i.e. $(\frac{T_i}{2}, \frac{T_i}{2}, R_i)$. As mentioned, in our simultaneous incentive mechanism, we assume that the CP will receive half of the total reward according to the contract whether the relay is used or not. The utility of a CP is its received reward minus its cost, which is represented in terms of power consumption. Therefore, depending on probability α (the probability that a link is relaying or direct), the utility of $type_i^D$ or $type_i^R$ CP from the contract $(\frac{T_i}{2}, \frac{T_i}{2}, R_i)$ is obtained from

$$U_{CP_i} = \theta_i(\alpha V(\frac{T_i}{2}) + (1-\alpha)V\left(\frac{T_i}{2}\right)) - c'R_i = \theta_i V\left(\frac{T_i}{2}\right) - c'R_i, \quad (10)$$

where θ_i is a type-dependent coefficient that depends on $type_i^D$ or $type_i^R$ CP, and $V(T)$ is a reward evaluation function that is a strictly increasing concave function of T, where $V(0) = 0, V'(T) > 0$, and $V''(T) < 0$ for all T. Whether the relay is used in a D2D communication or not, the evaluation function is the same and only its input argument varies according to the amount of reward. The reward evaluation function increases rapidly in low types but increases slowly in high types. Finally, c' is the CP's unit energy cost for providing the required data rate (R_i). For simplicity, hereafter, we consider $c' = 1$.

The quality of the relaying D2D communication may be higher than the direct D2D communication. Thus, in the following, each CP selects several candidate relays intending to increase its utility (Lines 4-11). First, each CP selects a set of relays based on the distance and then calculates the link quality between itself and each relay, which is equal to

$$type_j = \frac{\left|h_{CP_X,Rel_m}\right|^2}{I_{Cell}+I_{D2D}+N_0}, \quad m = 1 \dots M. \tag{11}$$

If the link quality between the CP and the relay is better than the link quality between the CP and the CR (i.e., the quality of the direct D2D communication), that relay remains in the set of candidate relays of that CP. Otherwise, that relay is removed from the set. Therefore, each CP contains a set of candidate relays $Rel = \{Rel_1, Rel_2, \dots, Rel_m\}$. Since each CP does not know the link quality between each relay and the CR, it selects the most appropriate contract only based on the link quality between itself and the relay. If the link quality between a CP and its selected relay is $type_j$, CP selects contract $(\frac{T_j}{2}, \frac{T_j}{2}, R_j)$ and sends a new form of contract to the relay as $\left(\frac{T_j}{2}, R_j\right)$ where R_j is the expected data transmission rate from the relay and $\frac{T_j}{2}$ is the reward offered to the relay.

When the relays responded to the bidding CP (Line 12), the CP selects only one relay for cooperation (Lines 13-19). This relay is the one that provides the best relaying D2D communication and a higher type of communication than direct D2D communication. Thus, assuming that the CP in direct D2D communication is of $type_i^D$ and with a selected relay in relaying D2D communication is of $type_j^R$, CP responds to the BS in the form of contract as $(0, \frac{T_i}{2}, R_i)$ and $(1, \frac{T_j}{2}, R_j)$. It should be noted that for each CP that sends these two contracts to the BS, the selected contract for relaying D2D communication is a higher type than the selected contract for direct D2D communication. Sending these two contracts by the CP (Line 23) indicates that CP can participate directly under $type_i$ contract or by using a relay under $type_j$ contract. If a CP does not find a suitable relay to cooperate, it sends only $type_i$ contract in the form of $(0, \frac{T_i}{2}, R_i)$ to the BS (Line 21). Sending one contract indicates that the CP can only cooperate directly.

Algorithm 2. The algorithm performed by each CP_X

Input: $\{(\frac{T_n}{2}, \frac{T_n}{2}, R_n), n = 1 \dots N_d\}$

Output: contract (a, b, c)

---

1. **Calculate** the quality of direct link to CR_X using Equation (9) and **find** its type, i.e. $type_i^D$
2. **Calculate** the utility per each input contract $\{(\frac{T_n}{2}, \frac{T_n}{2}, R_n)$, $n = 1 \dots N_d\}$ based on $type_i^D$ using $U_{CP(i)} = \theta_i V\left(\frac{T_n}{2}\right) - R_n$
3. **Select** the contract $(0, \frac{T_{argmax_i U_{CP(i)}}}{2}, R_{argmax_i U_{CP(i)}})$
4. $m=1$ *//m=1 …M (M is the number of relays that are in the neighborhood of CP_X)*
5. **for** each Rel_m where $distance(CP_X, Rel_m) < D$
6.   **Calculate** the quality of the link to Rel_m using Equation (11) and **find** the type of the link, i.e. $type_j$
7.   **if** $type_j > type_i^D$
8.   **Send** $(\frac{T_j}{2}, R_j)$ contract to Rel_m
9. $m=m+1$
10.   **end**
11. **end**
12. **Wait** for the result from Rel_m, for $m=1 \dots N$, $N \le M$ *//N is relays which CP_X has sent contract to them*
13. $A=0$, $B=0$, $BestRel= 0$
14. **for** each Rel_m where $m=1 \dots N$
15.   **if** $(\frac{T_j}{2} \ge A)$ and $(R_j \ge B)$
16. $A=\frac{T_j}{2}$, $B= R_j$
17. $BestRel= Rel_m$
18.   **end**
19. **end**
20. **if** $BestRel=0$
21.   **Return** $(0, \frac{T_i}{2}, R_i)$ to the BS
22. **else**
23.   **Return** $(0, \frac{T_i}{2}, R_i)$ and $(1, A, B)$ to the BS
24. **end**

This algorithm not only calculates the utility of each input contract but also sends the contracts to N relays (Lines 5-11) and evaluates the responses (Lines 14-19). Thus, if the number of contracts is N_d, the computational complexity of Algorithm 2 will be $O(N_d + N)$. This computational complexity is not significant and can be tolerated by current cellphones.

C. The algorithm performed by the relays

Algorithm 3 shows the procedure performed by the relays. After receiving a contract from a CP, each relay checks the accessibility of the relevant CR (Line 1). If the CR is not accessible with regards to the D2D distance threshold *D*, it refuses cooperation. Otherwise, the relay obtains the quality of the link to the relevant CR (Line 2), which is calculated as

$$type_k = \frac{\left|h_{Rel_m, CR_X}\right|^2}{I_{Cell}+I_{D2D}+N_0}, \quad m = 1 \dots N, k \in \{1, \dots, N_d\} \tag{12}$$

Then, the relay calculates its utility per the received contract (Line 3). The utility of a $type_k$ relay from the contract $\left(\frac{T_j}{2}, R_j\right)$ is calculated as

$$U_{Rel_k} = \theta_k V\left(\frac{T_j}{2}\right) - R_j, \tag{13}$$

Each relaying D2D communication consists of a CP-relay link and a relay-CR link where the data transmission rate of the relaying D2D communication is equal to the rate of the link with the lowest capacity. From the other perspective, a link with higher capacity consumes less power to support a required rate and vice versa. θ_k is a coefficient proportional to the type of the relay-CR link, which can be in three states relative to θ_j (which is proportional to the type of CP-relay link). In the first case, if the type of CP-relay link is equal to the type of relay-CR link, i.e. $\theta_k = \theta_j$, the relay gets the maximum utility from the cooperation because the contract is exactly matched its type. In the second case, if the type of relay-CR link is better than the type of CP-relay link, i.e. $\theta_k > \theta_j$, the relay can reduce the consumed power while provides the required data rate. In this case, although the relay does not earn the maximum utility since it does not use its maximum power, it yet will receive non-negative utility. In the third case, if the type of relay-CR link is worse than the type of CP-relay link, i.e. $\theta_k < \theta_j$, cooperation is not profitable due to the fact that using the relay leads to degradation of the rate supported by CP-relay even by using the maximum possible transmission power. In general, cooperation is accepted only in the first and second cases where the utility is greater than or equal to zero. Similar to CPs, relays can accept or reject any type of contract. If a relay refuses a contract, it is assumed that the relay has signed a contract *(0,0)*.

If the number of D2D communications is N_d and each node is the relay candidate of all D2D communications, the computational complexity of Algorithm 3 for establishing all N_d communications is $O(N_d)$. This computational complexity is not considerable and could be tolerated by current cellphones.

Algorithm 3. The algorithm performed by Rel_m

Input: contract $(\frac{T_j}{2}, R_j)$

Output: contract (b, c)

1. **if** distance (Rel_m , CR_X) < *D* *//locally accessible*
2.   **Calculate** the quality of the link to CR_X using Equation (12) and **find** the type of the link, i.e. $type_k$
3.   **Calculate** the utility from contract $(\frac{T_j}{2}, R_j)$ using Equation (13)
4.   **if** $U_{Rel_k} \geq 0$
5.   **Return** $(\frac{T_j}{2}, R_j)$ to CP_X
6.   **else**
7.   **Return** *(0,0)* to CP_X
8.   **end**
9. **else**
10.   **Return** *(0,0)* to CP_X
11. **end**

D. Optimizing the Contracts

In this section, we denote constraints that should be satisfied in designing contracts, and then we formulate an optimization problem to find the best contracts to achieve the maximum utility of the BS. To sufficiently motivate CPs and relays to offload traffic through D2D communications, the following constraints must be satisfied in designing the contract [11]:

Individual Rationality (IR): To motivate a CP or relay, the received reward must compensate the energy consumption for CP or relay during D2D communication. Otherwise, the CP or relay would not participate in D2D communication. Therefore, the utility of $type_i^D$ or $type_i^R$ CP in D2D communication with the selected contract $(\frac{T_i}{2}, \frac{T_i}{2}, R_i)$ must be non-negative

$$U_{CP_i} = \theta_i V\left(\frac{T_i}{2}\right) - R_i \geq 0, \quad i \in \{1, \dots, N_d\}. \tag{14}$$

Similarly, the utility of $type_k$ relay with the selected contract $(\frac{T_j}{2}, R_j)$ must be non-negative

$$U_{Rel_k} = \theta_k V\left(\frac{T_j}{2}\right) - R_j \geq 0, \quad j, k \in \{1, \dots, N_d\}. \tag{15}$$

Nevertheless, the CP and relay may ask more reward than just compensating their energy consumption to cooperate in D2D communication. We consider the fair case where all devices are assumed to have the same cooperative attitude. In this case, the utility of $type_i^D$ or $type_i^R$ CP (Equation (14)) and the utility of $type_k$ relay (Equation (15)) can be rewritten as

$$U_{CP_i} = \theta_i V\left(\frac{T_i}{2}\right) - R_i \geq \beta, \quad (16)$$
$$i \in \{1, \dots, N_d\}, \beta > 0.$$

$$U_{Rel_k} = \theta_k V\left(\frac{T_j}{2}\right) - R_j \geq \beta, \quad (17)$$
$$j, k \in \{1, \dots, N_d\}, \beta > 0.$$

Here, β is the minimum acceptable utility, and a CP/relay will cooperate if its utility is more than β.

Incentive Compatible (IC): Contracts should be designed in such a way that each type of CP prefers its contract to other contracts. In other words, each $type_i^D$ or $type_i^R$ CP in D2D communication must receive the maximum utility when it selects the contract $(\frac{T_i}{2}, \frac{T_i}{2}, R_i)$ as

$$\theta_i V(\tfrac{T_i}{2}) - R_i \geq \theta_i V(\tfrac{T_j}{2}) - R_j, \quad (18)$$
$$i, j \in \{1, \dots, N_d\}, \quad i \neq j.$$

Monotonicity: For any contract, $T_i > T_j$ if and only if $\theta_i > \theta_j$ and $T_i = T_j$ if and only if $\theta_i = \theta_j$.

Proof [11]. First, we proof if $\theta_i > \theta_j$ then $T_i > T_j$. According to IC constraint:

$$\theta_i V(\tfrac{T_i}{2}) - R_i \geq \theta_i V(\tfrac{T_j}{2}) - R_j \quad (19)$$
$$\theta_j V(\tfrac{T_j}{2}) - R_j \geq \theta_j V(\tfrac{T_i}{2}) - R_i. \quad (20)$$

If we add the above inequalities together, we will have:

$$\theta_i V(\tfrac{T_i}{2}) + \theta_j V(\tfrac{T_j}{2}) \geq \theta_i V(\tfrac{T_j}{2}) + \theta_j V(\tfrac{T_i}{2}), \quad (21)$$
$$\theta_i V(\tfrac{T_i}{2}) - \theta_j V(\tfrac{T_i}{2}) \geq \theta_i V(\tfrac{T_j}{2}) - \theta_j V(\tfrac{T_j}{2}),$$
$$V(\tfrac{T_i}{2})(\theta_i - \theta_j) \geq V(\tfrac{T_j}{2})(\theta_i - \theta_j).$$

Regarding $\theta_i > \theta_j$, we know $(\theta_i - \theta_j) > 0$. So, both inequalities can be divided by $(\theta_i - \theta_j)$ and $V(\frac{T_i}{2}) > V(\frac{T_j}{2})$ is obtained. We know $V(T)$ is a strictly increasingly function of T. Thus, as $V(\frac{T_i}{2}) > V(\frac{T_j}{2})$, we obtain $T_i > T_j$.

Then, we prove that if $T_i > T_j$, then $\theta_i > \theta_j$. According to IC constraint and similar to (19), (20), and (21), we can achieve:

$$\theta_i (V(\tfrac{T_i}{2}) - V(\tfrac{T_j}{2})) \geq \theta_j (V(\tfrac{T_i}{2}) - V(\tfrac{T_j}{2})). \quad (22)$$

Considering $T_i > T_j$ and $V(T)$ as a strictly increasingly function of T, $V(\frac{T_i}{2}) > V(\frac{T_j}{2})$ and $V(\frac{T_i}{2}) - V(\frac{T_j}{2}) > 0$. Therefore, both inequalities can be divided by $V(\frac{T_i}{2}) - V(\frac{T_j}{2})$ and $\theta_i > \theta_j$ is obtained. Hence, we have proved that $T_i > T_j$ if and only if $\theta_i > \theta_j$. Similarly, we can prove that $T_i = T_j$ if and only if $\theta_i = \theta_j$.

Therefore, a CP with a higher type should receive a higher reward than a CP with a lower type, and if two CPs receive the same reward, both belong to the same type and vice versa. Given these explanations, for each contract, the following constraint must be satisfied

$$0 \leq T_1 < T_2 < \cdots < T_i < \cdots < T_{N_d}. \quad (23)$$

Since T is a strictly increasing function on R, according to Constraint (23), for data transmission rate, the following condition must be satisfied

$$0 \leq R_1 < R_2 < \cdots < R_i < \cdots < R_{N_d}, \quad (24)$$

and for the utility of CPs, the following condition must be met

$$0 \leq U_{CP_1} < \cdots < U_{CP_{N_d}}. \quad (25)$$

As shown in Equation (25), the utility of $type_1$ CP can be 0, but the utilities of other CPs are more than 0. Also, Equations (24) and (25) mean that a better type link not only provides a higher data transmission rate but also receives more utility than the lower type. From the above constraints, it can be concluded that if a high-type CP (which contains a high-type link) chooses a low-type contract from the BS, it should provide a lower data transmission rate and receive a lower reward. As a result, it will not earn its maximum achievable utility. Also, if a low-type CP opts for a high-type contract, the reward that it receives will not compensate the high cost of energy consumption to provide a high data transmission rate, and in this case, the utility would usually be negative. Each CP can receive maximum utility by choosing a contract of its type among all the received contracts. However, each relay will not always get its maximum utility because it only receives one contract from the CP and will participate if its utility from that contract is non-negative.

By satisfying the above constraints, it is guaranteed that the contracts are self-revealing [11]. In other words, when a CP (relay) selects a contract and responds to the BS (relevant CP), its preferences are revealed to the BS (relevant CP).

The optimization problem: The contracts must be optimally designed concerning the aforementioned constraints to maximize the utility of BS. So, the problem of designing contracts is formulated as the following optimization problem

$$\max_{(T,R)} \sum_{i=1}^{N_d} \lambda_i \left(R_i - \tfrac{1}{2}(\alpha + 1)cT_i\right), \quad (26)$$
$$(a)\ \theta_i V(\tfrac{T_i}{2}) - R_i \geq \beta$$
$$(b)\ \theta_i V(\tfrac{T_i}{2}) - R_i \geq \theta_i V(\tfrac{T_j}{2}) - R_j$$
$$(c)\ 0 \leq T_1 < T_2 < \cdots < T_i < \cdots < T_{N_d}$$
$$i, j \in \{1, \dots, N_d\}, \beta > 0.$$

Equation (26) maximizes the expected utility of the BS regarding Equation (8). Constraints (a), (b), and (c) are individual rationality (IR), incentive compatible (IC), and monotonicity, respectively. According to Conditions (a) and (b), there are N_d individual rationality constraints and $N_d \times (N_d-1)$ incentive compatible constraints that must be satisfied.

To solve the above problem, the constraints can be reduced in several steps like the problems introduced in [11], [16]. After reducing constraints, the optimization problem of Equation (26) is simplified to

$$\max_{(T,R)} \sum_{i=1}^{N_d} \lambda_i (R_i - \tfrac{1}{2}(\alpha+1)cT_i), \quad (27)$$
$$(a)\ \theta_1 V(\tfrac{T_1}{2}) - R_1 = \beta$$
$$(b)\ \theta_i V(\tfrac{T_i}{2}) - R_i = \theta_i V(\tfrac{T_{i-1}}{2}) - R_{i-1}$$
$$(c)\ 0 \le T_1 < T_2 < \cdots < T_i < \cdots < T_{N_d},$$
$$i \in \{1, \dots, N_d\}, \qquad \beta > 0.$$

Solving this problem, we consider the fair case where $\alpha = \frac{1}{2}$, i.e., each type is direct or relaying with the probability of $\frac{1}{2}$. Moreover, we assume that $\beta = 0$. The setting with $\beta = 0$ is preferred because our main focus is to maximize the BS utility that is achieved by providing the minimum required utility for the participants. The problem can be solved for other values of α and β, similarly. Finally, this problem is solved according to Constraints (a) and (b), and then the third constraint is checked. The Lagrange multiplier method is used to solve this problem [16]. Given N_d types, the time complexity of solving this problem is $O(N_d)$ [22].

V. Mobility-aware incentive mechanism

In this section, the mobility-aware incentive mechanism is considered. Assuming that the devices in the network are mobile, mobility awareness can be effective in the performance of the proposed incentive mechanism. Due to the mobility of devices, the quality of D2D links changes over time and some devices may exit the communication range of CPs/relays. Therefore, we need more appropriate contracts that are less likely to be violated due to link failures/quality degradations. If the quality of the D2D communication improves with the movement of each of the transmitter, receiver, and relay devices in the near future, a higher type contract can be selected at the time of the decision. However, if the link needs higher power consumption to be supported in the near future or may be disconnected due to mobility, a lower type contract should be selected. Although the proposed idea does not result in optimal solutions, it improves performance under mobility condition. Therefore, in the proposed mobility-aware incentive mechanism, the selection of the contract is performed by the CPs and relays according to the predicted location of the CP, relay, and CR in the next time step. Hence, the algorithms executed by the content provider and the relay are modified accordingly, as shown in Algorithms 4 and 5.

In this study, the Markov method is used to predict the location [30]. The order-k Markov predictor takes a sequence of recent locations *(e.g.* a_1, a_2, ..., a_n*)* as the spatial history of each user and tries to find the next place according to the *k* recent locations in the history. The locations of CP_X, CR_X, and Rel_m in the future (*t+1*) are shown by $CP_{X(t+1)}$, $CR_{X(t+1)}$, and $Rel_{m(t+1)}$, respectively.

In Algorithm 4, after receiving the set of contracts, and the predicted locations of the CR and relays, each mobile CP predicts its location in the future time step based on the transmission time of the desired content (*t+1*) and checks the accessibility of the relevant CR in the future time step (Line 1 and 2). Then, it calculates its type based on the quality of the direct link to its relevant CR at Time *t+1* as

$$type^D_{i(t+1)} = \frac{\left|h_{CP_{X(t+1)},CR_{X(t+1)}}\right|^2}{I_{Cell}+I_{D2D}+N_0}. \quad (28)$$

Afterward, each CP calculates its utility at Time *t+1* from the direct D2D communication based on each of the received contracts and selects a contract that provides the maximum utility (Lines 4 and 5). Next, it selects a set of relays according to their current location regarding distance *D* and also requests their locations in the future. Then, based on its predicted location and the predicted locations of others (CR and relays), it calculates the quality of its link to relay *m* at Time *t+1* using the following equation

$$type_{j(t+1)} = \frac{\left|h_{CP_{X(t+1)},Rel_{m(t+1)}}\right|^2}{I_{Cell}+I_{D2D}+N_0}. \quad (29)$$

Finally, it sends contracts to the relays and receives their responses (Lines 7-14), and decides about the best contract like Algorithm 2. The order-k Markov predictor's complexity is *O(k)*, where *k* is a constant. Therefore, the computational complexity of this algorithm is similar to Algorithm 2.

In Algorithm 5, after receiving the contract from the relevant CP and the predicted location of the CR, each relay first checks the accessibility of the relevant CR (Line 1). If the CR is accessible, the relay also predicts its location in the future time step based on the transmission time of the desired content and also considers the predicted location of CR_X to check its accessibility in the future (Line 2). If CR_X is accessible in the future, the relay calculates the quality of the link to $CR_{X(t+1)}$ as

$$type_{k(t+1)} = \frac{\left|h_{Rel_{m(t+1)},CR_{X(t+1)}}\right|^2}{I_{Cell}+I_{D2D}+N_0}. \quad (30)$$

Then, the relay would perform the contract selection operation based on the predicted locations as already discussed in Algorithm 3. The computational complexity of this algorithm is also similar to Algorithm 3.

Algorithm 4. The algorithm performed by each moving content provider, CP_X

Input: contracts $\{(\frac{T_n}{2}, \frac{T_n}{2}, R_n), n = 1 \dots N_d\}$, $CR_{X(t+1)}$, $\{Rel_{m(t+1)}, m = 1 \dots M\}$

Output: contract *(a,b,c)*

1. **Predict** CP_x location at Time *t+1*, i.e. $CP_{X(t+1)}$
2. **if** distance($CP_{X(t+1)}$, $CR_{X(t+1)}$) < *D //locally accessible in future*
3. **Calculate** the quality of the direct link to $CR_{X(t+1)}$ using Equation (28) and **find** the type of the direct link, i.e. $type^D_{i(t+1)}$
4. **Calculate** the utility per each input contract $\{(\frac{T_n}{2}, \frac{T_n}{2}, R_n), n = 1 \dots N_d\}$ based on $type^D_{i(t+1)}$ using $U_{CP_{i(t+1)}} = \theta_{i(t+1)} V\left(\frac{T_n}{2}\right) - R_n$
5. **Select** the contract $\left(0, \frac{T_{argmax_i U_{CP_{i(t+1)}}}}{2}, R_{argmax_i U_{CP_{i(t+1)}}}\right)$
6. $m = 1$
7. **for** each Rel_m where distance$(CP_X, Rel_m) < D$ & distance$(CP_{X(t+1)}, Rel_{m(t+1)}) < D$
8. **Calculate** the quality of the link to Rel_m at Time *t+1* using Equation (29) and **find** the type of the link, i.e. $type_{j(t+1)}$
9. **if** $type_{j(t+1)} > type^D_{i(t+1)}$
10. **Send** $(\frac{T_j}{2}, R_j)$ to Rel_m
11. $m = m + 1$
12. **end**
13. **end**
14. **Wait** for result from Rel_m, where *m=1 … N, N ≤ M*
15. **end**

VI. Simulation Results

In this section, the performance of the proposed method is analyzed in several different simulation scenarios using custom simulations in MATLAB, and the results are compared with the incentive mechanism presented in [11].

First, a single-cell network which consists of a BS, one cellular communication, 20 D2D communications, and 200 relays is considered. The devices are randomly placed in the environment with a uniform distribution. The number of types is also equal to 20. In other words, for each type, there is a D2D communication (direct or relaying), i.e., $\lambda_i = \frac{1}{N_d}$, where N_d is the number of communications and λ_i is the probability of the existence of each type. The type of each communication is defined based on its link quality which is quantized to one of the 20 defined levels corresponding to 20 types. Therefore, the value of $\theta_z, z = 1 \dots i \dots j \dots k \dots N_d$ is calculated as $\frac{N_d + (z-1)}{N_d} * 1000$. The BS's unit cost is $c = 0.01$ and the evaluation function is $V(T) = ln(1 + T)$. Other parameters are shown in Table 2. Some of the simulation parameters such as cell radius, noise power density, transmission power, and the number of D2D communications are the same as the ones in [11].

Algorithm 5. The algorithm performed by each moving relay, Rel_m

Input: contract $(\frac{T_j}{2}, R_j)$, and $CR_{X(t+1)}$

Output: contract (b, c)

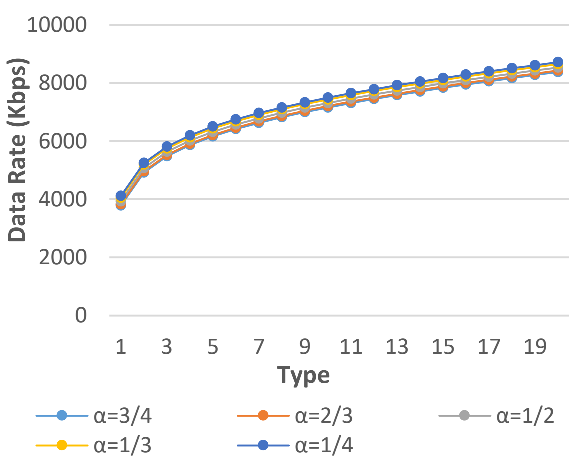
1. **if** distance (Rel_m , CR_X) < *D //locally accessible*
2. **Predict** the locations of Rel_m at Time *t+1*, i.e. $Rel_{m(t+1)}$
3. **if** distance ($Rel_{m(t+1)}$, $CR_{X(t+1)}$) < *D*
4. **Calculate** the quality of the link to $CR_{X(t+1)}$ using Equation (30) and **find** the type of the link, i.e. $type_{k(t+1)}$
5. **Calculate** the utility from contract $(\frac{T_j}{2}, R_j)$ using $U_{Rel_k} = \theta_{k(t+1)} V\left(\frac{T_j}{2}\right) - R_j$
6. **if** $U_{Rel_k} \geq 0$
7. **Return** $(\frac{T_j}{2}, R_j)$ to CP_X
8. **else**
9. **Return** *(0,0)* to CP_X
10. **end**
11. **else**
12. **Return** *(0,0)* to CP_X
13. **end**
14. **else**
15. **Return** *(0,0)* to CP_X
16. **end**

To illustrate the monotonicity of contracts, Figs. 2a and 2b show the data transmission rates and rewards of different types of D2D communications for various probabilities of D2D relaying communications (α). As can be seen in Figs. 2a and 2b, data transmission rates and rewards increase with the type of D2D communication. In addition, it is obvious from Figs. 2a and 2b that as the probability of relaying D2D communications decreases, the data rates achieved by CRs and the rewards achieved by CPs and relays slightly increase. Given that the reward of relaying communication is twice the reward of direct communication, the BS decreases the data rate and the reward to keep its utility maximum. As seen in these evaluations (Figs. 2a and 2b), the impact of α is not so considerable. Therefore, we choose α=0.5 for the next simulation studies of the paper. To illustrate the individual rationality and the incentive compatibility of contracts, Fig. 2c shows the utility of $type_5$, $type_{10}$, and $type_{15}$ communications based on all received contracts. As can be seen in Fig. 2c, each communication type receives a non-negative utility by choosing its relevant contract, which indicates the individual rationality of contracts. Also, the utility of each CP is a concave function, and it receives its maximum utility when it chooses its own contract, which indicates the incentive compatibility of contracts. In addition, when these three communication types choose the same contract, their utilities are $U_5 < U_{10} < U_{15}$, which indicate the higher types receive more utility than the lower types and vice versa.

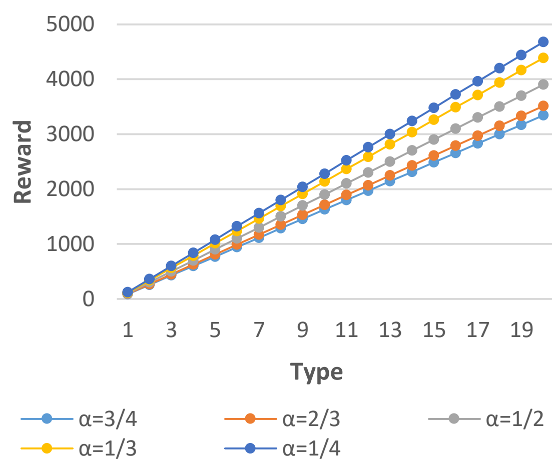
As mentioned before, we can consider various acceptable utility thresholds (β) for the devices, as indicated in Constraint (a) of the optimization problem of Equation (26). In this case, designed contracts are slightly different and affect the utility of CPs and BS. Figs. 3a and 3b show the utility of the CPs and BS versus different values of β. As seen in Figs. 3a and 3b, when CPs or relays cooperate with a threshold higher than 0, the utility of the CPs increases, and the utility of the BS decreases accordingly. The reason is that the BS should give more rewards to the CPs/relays to encourage them to participate in D2D communication.

Table 2. Simulation parameters

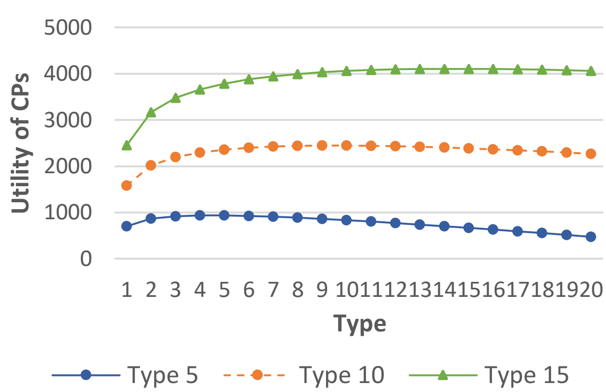
Parameter	**Value**
Cell radius	500 m
Maximum D2D distance	100 m
Antenna height	2 m
The bandwidth of each channel	1 MHz
Noise power density	-174 dBm/Hz
Transmission power	Device:23dBm, BS:46dBm
File size	64 KB
The initial energy of the devices	5 Joule
Propagation model	Two Ray Ground



(a)

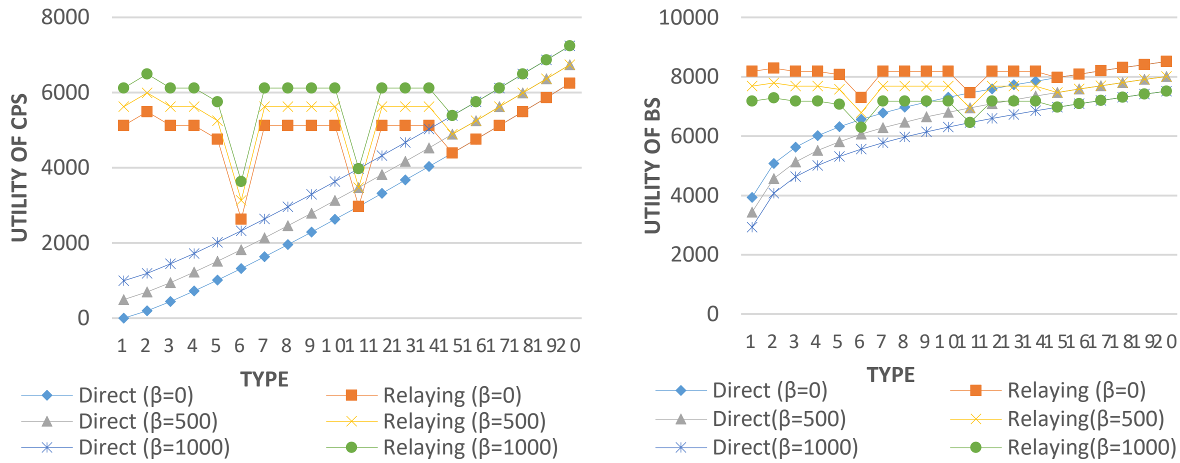


(b)



(c)

Fig. 2: The monotonicity, individual rationality, and the incentive compatibility of contracts



(a) (b)

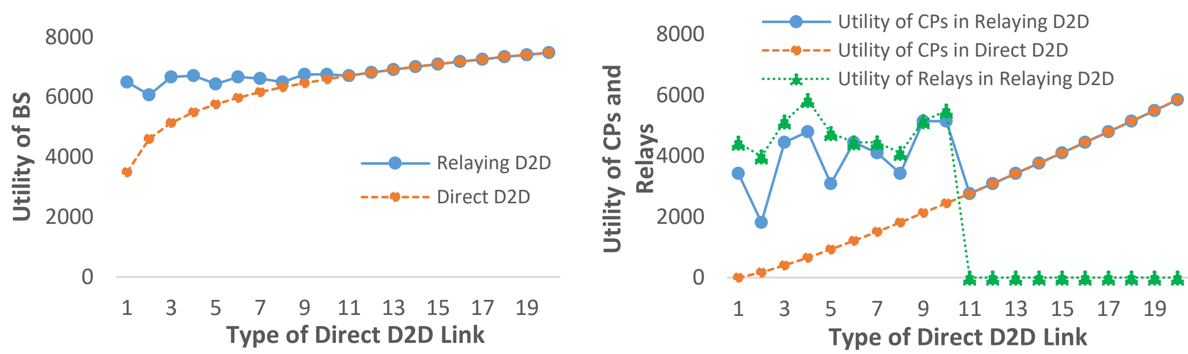
Fig. 3: The utility of CPs and BS under different values of acceptable utility threshold (β) for the devices

A. Evaluation of the proposed incentive mechanism for relaying D2D communications

In the following, the performance of the proposed incentive mechanism is evaluated and compared with the incentive mechanism of [11]. Choosing a suitable relay is effective in improving the link quality and increasing the utility of the BS and CPs. When the quality or the type of relaying D2D communication is better than a direct one, better contracts can be chosen, and thus, the utilities of the BS and CPs increase. Fig. 4a shows the utility of BS in direct [11] and relaying D2D communications. As can be seen in Fig. 4a, in direct D2D communications, the low-type direct D2D links (due to the poor link quality) provide lower data rates and lower utility for the BS in contrast to high-type ones. Therefore, the BS prefers high-type relaying D2D communications to low-type direct ones, which leads to a higher utility for the BS (up to 90% when the quality of direct D2D link is low). For high-type direct D2D communications, the quality does not significantly change by the use of relays. So, the utility of the BS is not considerably different. In other words, when direct D2D links are high-type, relaying links are not preferred. The utility of the CPs and relays from direct and relaying D2D communications are shown in Fig. 4b. As can be seen in Fig. 4b, in low-type direct D2D links, a CP attains lower utility from the direct link than a relaying D2D link with an appropriate relay. As a result, having relaying D2D communications option, CP receives more reward and utility. However, relaying option does not increase the utility considerably when there are high-type direct D2D links. In relaying D2D communications, relays are also rewarded. The points in Fig. 4b where the CP and the selected relay have the same utility, indicate that the channel quality of CP-relay and relay-CR links are of the same type, and the points where the utility of the relay is more than the utility of the CP indicates that the type of the relay-CR link is higher than the CP-relay link. The results show that the idea of incorporating relays in D2D communications increases the utility of BS and CPs compared to the incentive mechanisms that only consider direct D2D communication.

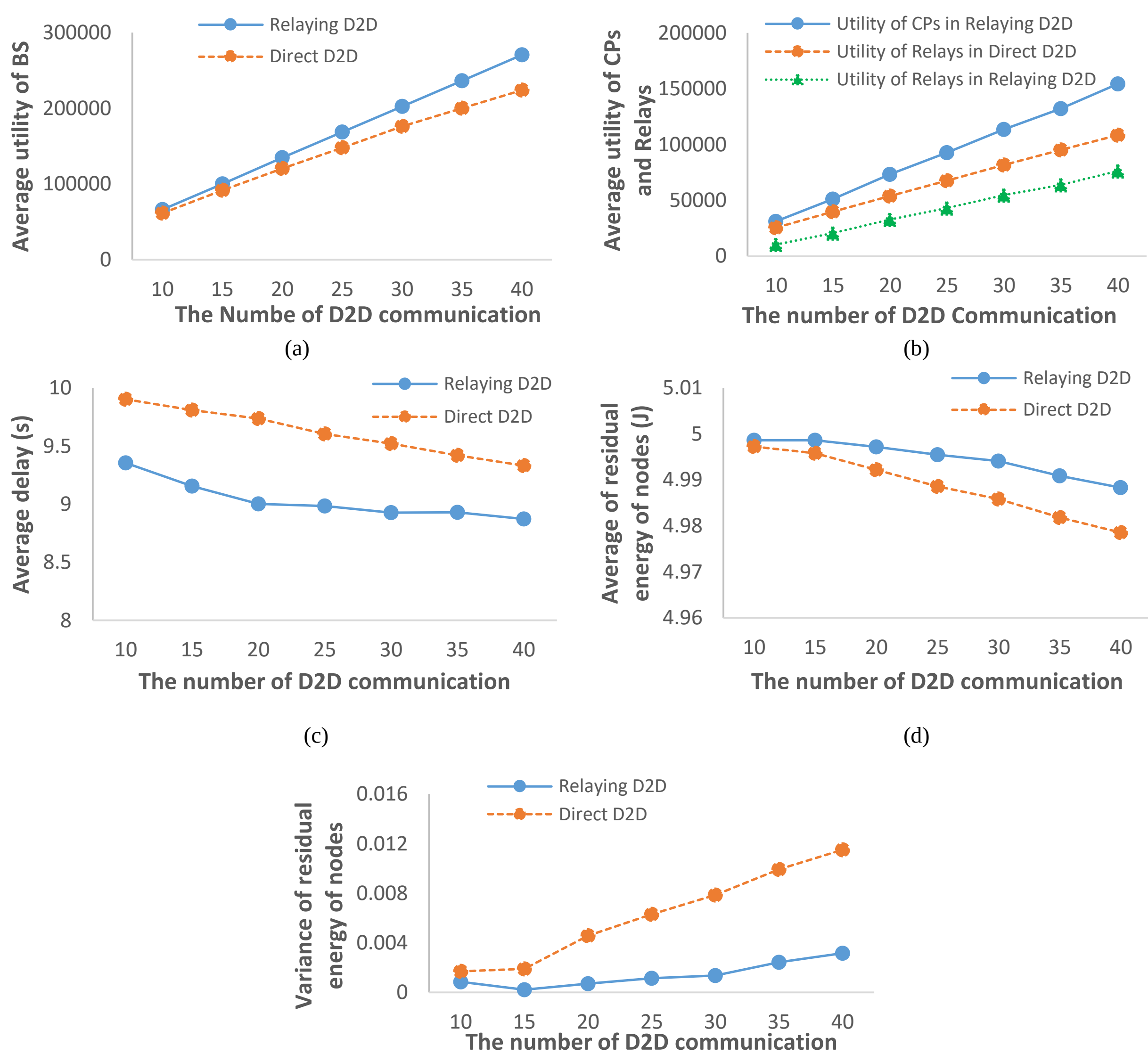
After that, the performance of the proposed method is investigated concerning the number of D2D communications in the system. Fig. 5a shows the average utility of the BS versus the number of communications. In Fig. 5a, it is evident that in relaying D2D communications, the average utility of the BS increases more as the number of communications increases compared to direct D2D communications. Relaying D2D communication provides more data transmission rate than the low-type direct one and it increases the utility of the BS. This improvement is up to 20% as the number of D2D communications increases. Fig. 5b compares the average utility of CPs and relays of the proposed method to the method introduced in [11]. As the number of communications increases, the average utility of the CPs and relays increases since some relaying D2D communications provide higher data transmission rates than low-type direct counterparts and will receive more reward and utility. As the number of communications increases, this improvement is more considerable.

Fig. 5c compares the proposed incentive mechanism to the method of [11] in terms of average delay. As the number of communications increases, the average delay of both methods decreases; however, the average delay is up to 7% less than the baseline method for relaying D2D communications because some of the direct D2D links are low-type and provide a lower data transmission rate and higher delay while high-type relaying D2D links could be used instead.



(a) (b)

Fig. 4: Performance comparison versus the type of direct D2D link (Relaying D2D is the proposed method and Direct D2D is the method of [11])



(a) (b)

(c) (d)

(e)

Fig. 5: Performance comparison versus the number of D2D communications (Relaying D2D is the proposed method and Direct D2D is the method of [11])

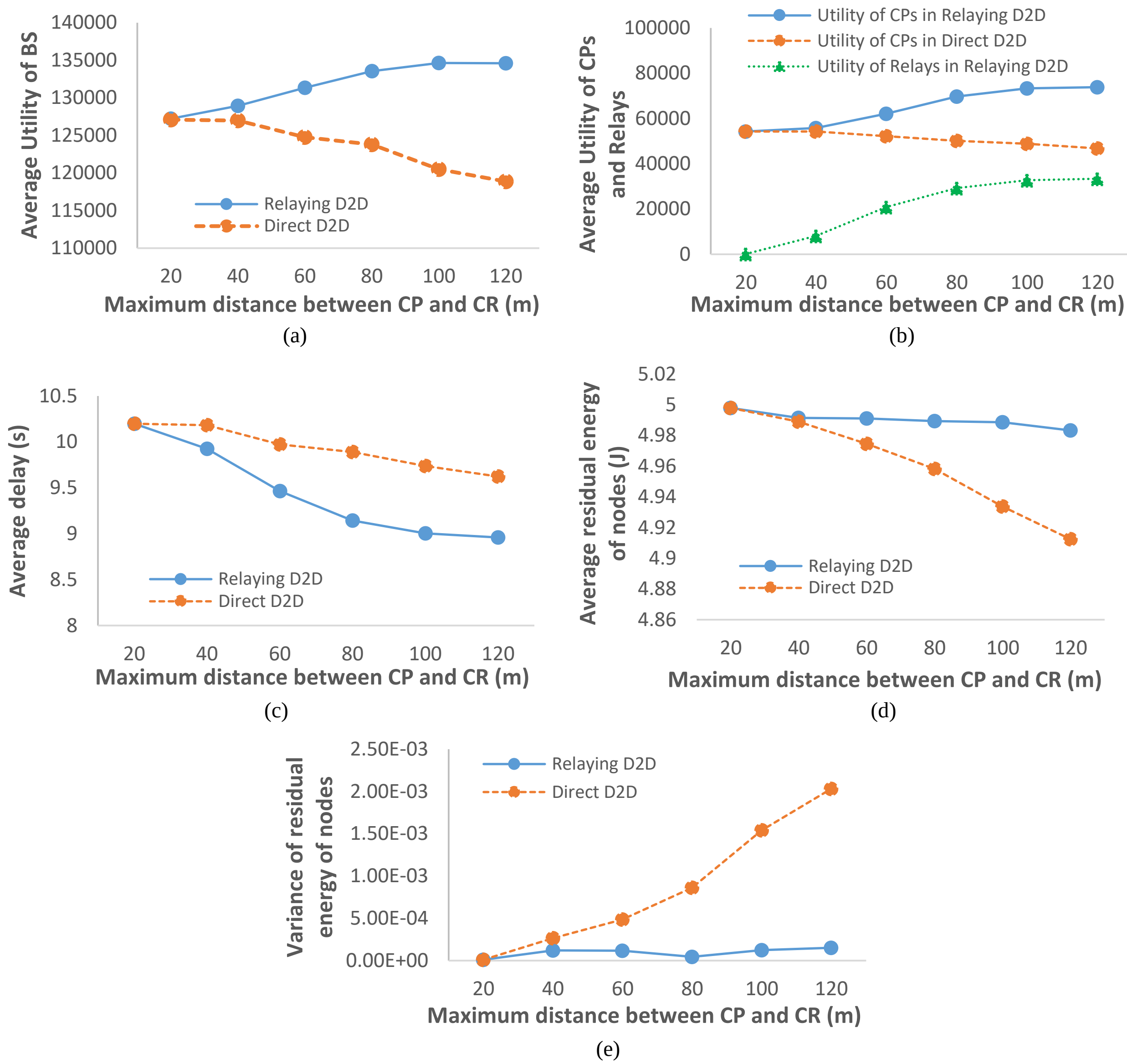


Fig. 6: Performance comparison versus the maximum distance between CP and CR (Relaying D2D is the proposed method and Direct D2D is the method of [11])

Figs. 5d and 5e demonstrate the average and variance of the residual energy of devices. As the number of communications increases, the average residual energy of the devices decreases. In the method [11], this energy loss is more rapid. Also, the variance of the remaining energy of devices is higher and increases more rapidly, indicating more energy consumption and imbalanced energy consumption in the baseline method. The average residual energy of devices in the proposed method is higher than the baseline due to the fact that relaying D2D links may provide a higher data transmission rate than some low-type direct ones, which reduces data transmission time and energy consumption accordingly. Therefore, the network lifetime increases using the proposed method.

In the following, the performance of the proposed method is investigated regarding the maximum distance between devices of each D2D pair. Fig. 6a compares the average utility of BS in the proposed method and the method of [11]. In Fig. 6a, as the distance between the devices of a pair increases, the average utility of the BS in the baseline method decreases while in the proposed method increases (up to 13%) since as the distance between devices increases, more low-type direct D2D links exploit high-type relaying D2D links. Fig. 6b shows the average utility of CPs and relays. In Fig. 6b, as the distance between the devices of each pair increases, the average utility of CPs in the baseline method decreases. However, in the proposed method, a higher utility is attained. When the distance between devices is short, the quality of direct D2D links would be good, and as a result, the proposed incentive mechanism does not need to employ many relays. So, for low distances, the utility of the CPs in both methods is almost equal.

Fig. 6c compares the proposed method to the baseline in terms of average delay. As can be seen in Fig. 6c, the average delay of the proposed method is less than the baseline. By increasing the distance between devices, some direct D2D communications would not be established or fail. However, in the proposed method, by increasing the distance between the pairs, more communications use a relay which results in a higher data transfer rate and lower latency.

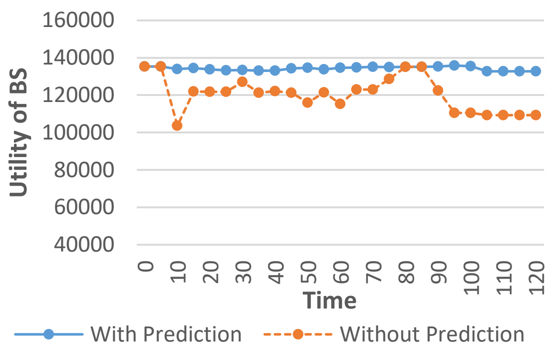
Figs. 6d and 6e show the average and variance of the residual energy of the devices. With increasing distance between devices, the average residual energy of the devices in the proposed method does not decrease significantly, while it drops sharply in the baseline. Because the exchange of data over long distances increases the energy consumption of the devices, encouraging relays to participate in relaying D2D communications increases the energy efficiency and lifetime of devices significantly using the proposed method.

B. Evaluating the performance of the proposed mobility-aware incentive mechanism

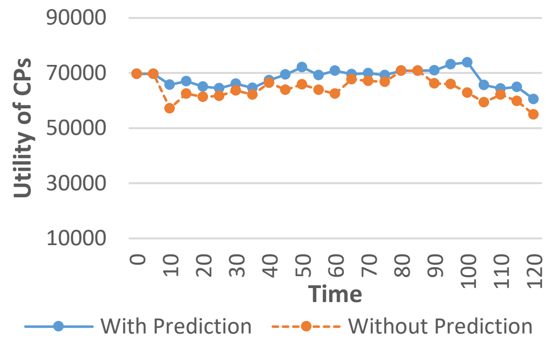
In this section, the performance of the proposed mobility-aware incentive mechanism is evaluated. The utilities attained by the BS and the CPs using the proposed incentive mechanism for relaying D2D communications with and without the aid of location prediction are compared in Fig. 7. The simulation parameters are set as Table 2. To simulate the mobility of devices, we assume a simple scenario that is consisted of several horizontal and vertical roads. The mobile nodes will move along these roads. Half of the devices (randomly selected) move along the horizontal and the other half along the vertical roads at a constant speed. Fig. 7a shows the utility of the BS in the proposed method in the course of simulation time. When using location prediction, CPs and relays predict their locations in a future time step according to the duration of sending the desired content (file) and based on their future location, they perform the contract selection operation. As seen in Fig. 7a, the utility of the BS is improved almost 30% using the mobility prediction compared to the scenario of not exploiting prediction. This is due to the fact that the movement of the devices may reduce the quality of the links in a direct/relaying D2D communication or the links may be broken, which leads to utility degradation if we do not consider future locations. Fig. 7b compares the utility of the CP for the case of using location prediction or not. As illustrated, the cumulative utility of CPs has also been increased using the predicted locations for similar reasons.

The performance of the proposed mobility-aware incentive mechanism is evaluated versus the number of D2D communications. Figs. 8a and 8b show the average utilities of the BS and the CPs. The average utilities of the BS and the CPs are higher in the proposed method when using prediction compared to not exploiting the prediction. It is due to the fact that the movement of the devices may decrease the quality of the links, and these cases are considered when mobility prediction is used. Fig. 8c compares the proposed method with mobility prediction to the one without mobility prediction in terms of average delay. As the number of D2D communications increases, a reduction in the average delay of both methods is observed. Furthermore, the use of mobility prediction is also resulted in lower average delay. Figs. 8d and 8e exhibit the average and variance of the residual energy of the devices. As the number of D2D communications increases, the average residual energy of the devices decreases. When mobility prediction is not used, the energy loss is higher due to the weak link quality caused by mobility. Degradation of the link quality leads to higher energy consumption for the data transfer on the weak D2D links that are contracted. Also, when the mobility prediction is not used, the variance of the remaining energy of the devices is higher and also increases more rapidly, indicating further imbalance in the energy consumption. This higher variance is because although some links become weak, some others get strength due to mobility.

Figs. 9a and 9b compare the average utilities of the BS and the CPs versus the maximum distance between the devices involved in the D2D communication. As can be seen in Figs. 9a and 9b, higher average utility is achieved for the BS and the CPs with the use of mobility prediction. Fig. 9c shows the average delay results. Also, Figs. 9d and 9e show the average and variance of the residual energy of the devices. As can be seen in Figs. 9d and 9e, the average delay is lower and the residual energy of the devices is higher in the method using mobility prediction. Moreover, the longer the distance between the CPs and CRs, the better the delay reduction and the energy consumption of the proposed mobility-aware method compared to the one without mobility prediction. Therefore, mobility prediction is essential to be considered for long-distance D2D communications as they are more liable to link quality degradation or breaks.

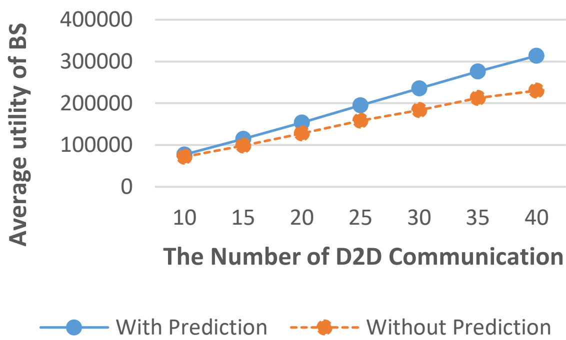


(a)

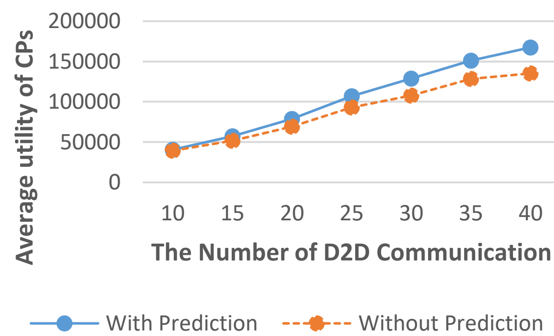


(b)

Fig. 7: The performance of the proposed incentive mechanism (with and without prediction) versus the simulation time



(a)



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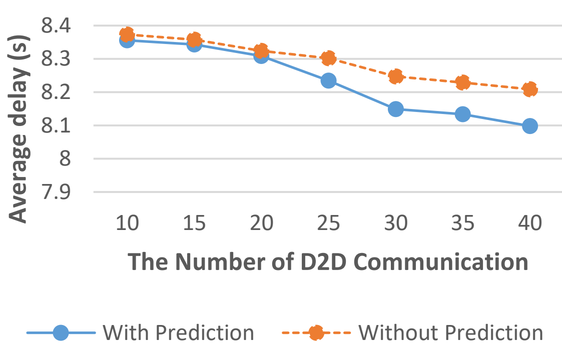
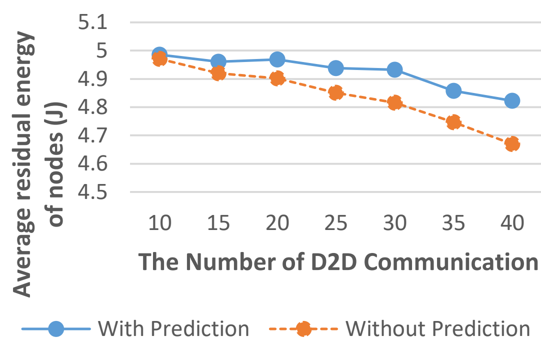
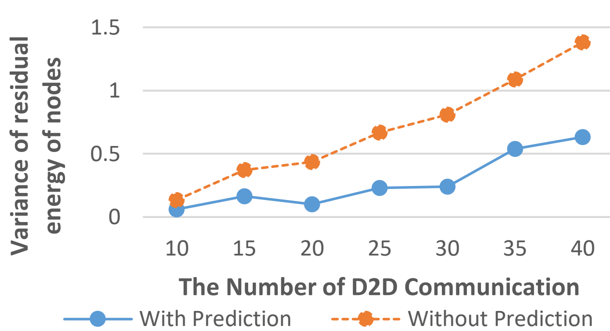


(c)

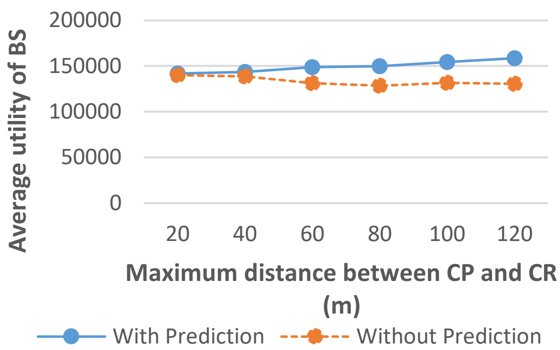


(d)

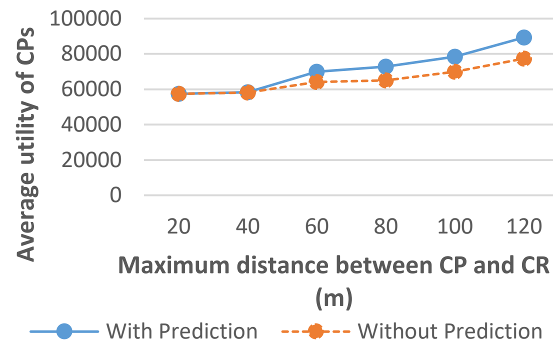


(e)

Fig. 8: The performance of the proposed incentive mechanism (with and without prediction) versus the number of D2D communications



(a)



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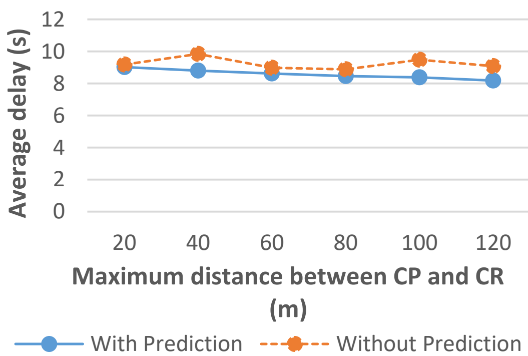

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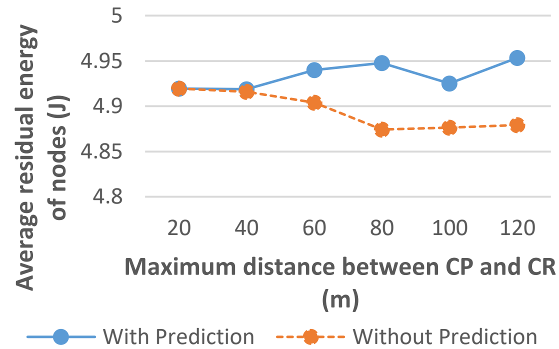

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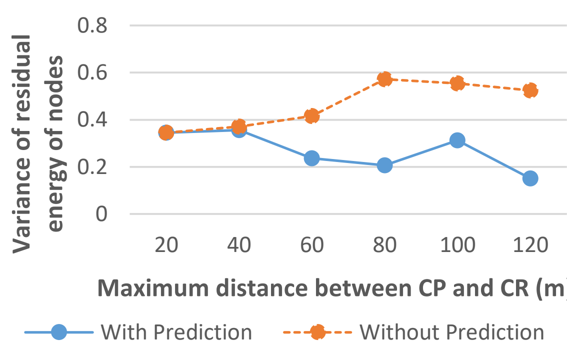

(e)

Fig. 9: The performance of the proposed incentive mechanism (with and without prediction) versus the maximum distance between CPs and CRs

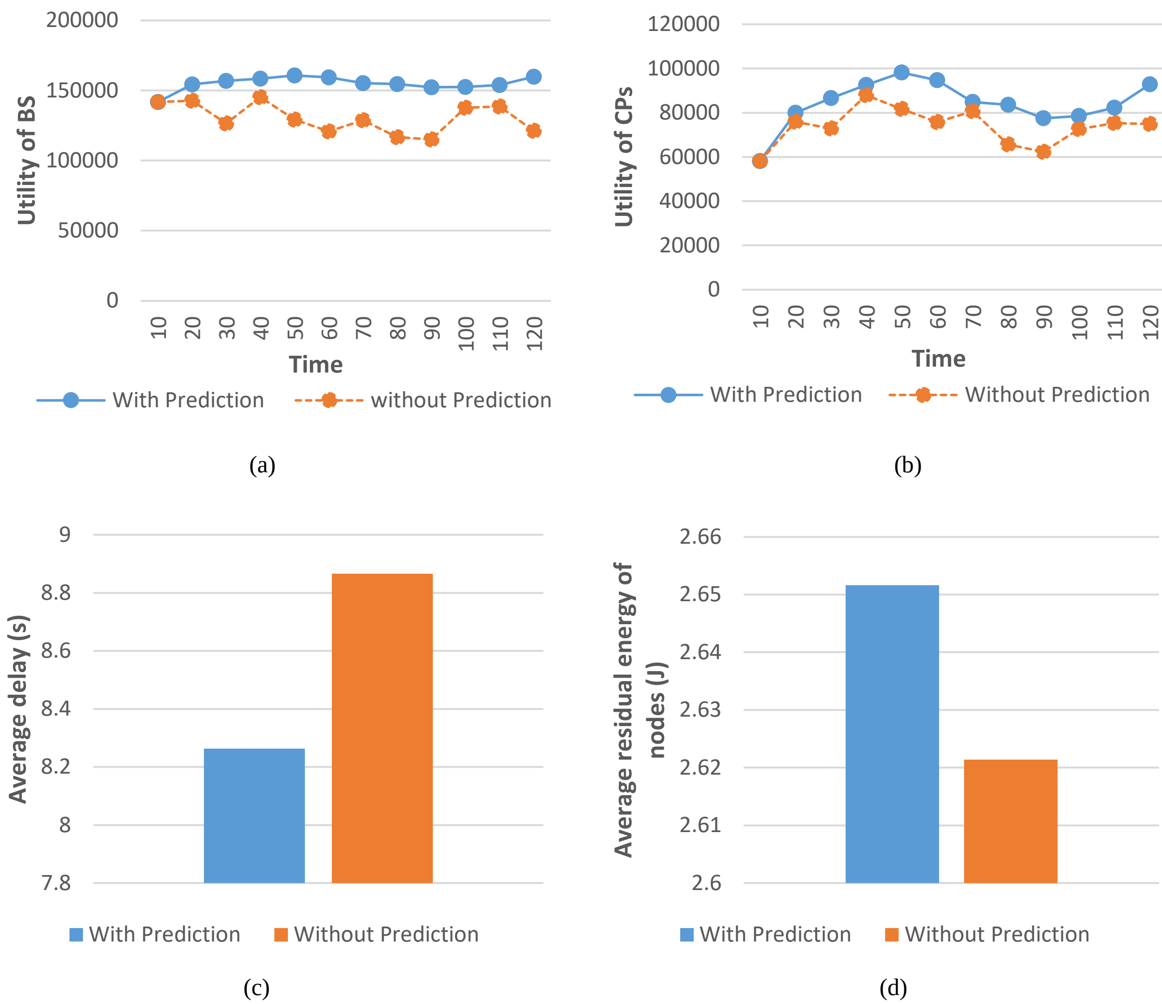

Fig. 10: The performance of the proposed mobility-aware incentive mechanism on the UCY dataset

Moreover, we evaluate our proposed mobility-aware incentive mechanism in a real movement scenario. For this purpose, we exploit the mobility trace represented in the UCY dataset [31] that contains three subsets, namely, Univ, Zara1, and Zara2. We use the first subset of the dataset and rescale it to a scene with a cell radius of 500 meters. We use this dataset because it is captured from the mobility of a real pedestrian crowd which is an admissible mobility scenario for real D2D applications. Figs. 10a and 10b evaluate the proposed method in terms of the utilities of the BS and the CPs in the course of simulation time. As illustrated in Figs. 10a and 10b, the utilities of the BS and the CPs are improved using mobility prediction compared to the scenario of not exploiting prediction. Figs. 10c and 10d evaluate the proposed method in terms of the average delay and the average residual energy of the devices. As can be seen in Figs. 10c and 10d, using prediction results in lower average delay and higher average residual energy.

C. Discussion

As mentioned in the previous section, we should consider monotonicity, individual rationality, and incentive compatibility in the design of the contracts. The evaluation results are illustrated in Figs. 2a, 2b, and 2c support these constraints. As can be seen in Figs. 2a and 2b, data transmission rates and rewards increase with the type of D2D communication, which indicates the monotonicity of the contracts. In Fig. 2c, each communication type receives a non-negative utility by choosing its relevant contract, which indicates the individual rationality of the contracts. Also, the utility of each CP is a concave function, and it receives its maximum utility when it chooses its own contract, which indicates the incentive compatibility of contracts.

As was our main objective, the proposed incentive mechanism increases the participation of the devices in D2D content sharing. It is due to the fact that encouraging both CPs and relays usually improves the utility of CPs and even the BS. Various simulation results such as Figs. 4a and 4b confirm this claim. Moreover, as the number of D2D communications (Figs 5a, 5b), and the distance between the involved D2D devices (Figs 6a, 6b) increase, the utility improvement of the BS and the CPs is more considerable. Also, the proposed incentive mechanism increases the quality of D2D communications. When the number of D2D communications or the distance between D2D devices increases, more D2D communications exploit the relaying D2D links. Consequently, the delay decrease, and the network lifetime increase as shown in Figs. 5c, 5d, 6c, and 6d. Some of the direct D2D links are low-type and lead to a lower data transmission rate and higher delay and energy consumption. However, high-type relaying D2D links could be used and reduce the data transmission latency and energy consumption.

In the evaluations, we also considered various acceptable utility thresholds (β) for the participation of the devices. The results (Figs. 3a and 3b) showed that the utilities of CPs and BS are affected by β. When devices cooperate with a threshold higher than 0, the utility of the CPs increases, and the utility of the BS decreases since the BS tries to give more rewards to the devices to incentivize them.

Finally, the evaluation of the proposed mobility-aware incentive mechanism showed improvement in the BS and CPs utility (Figs. 7a, 7b, 10a, and 10b) using the mobility prediction. Also, the average delay and energy consumption are improved as shown in Figs. 8c, 8d, 9c, 9d, 10c, and 10d. As the movement of the devices may reduce the quality of the links in D2D communication, considering the predicted future locations of the devices in the selection of the contracts improves the performance of the proposed incentive mechanism. Hence, higher prediction accuracy results in more incentivizing D2D links that are stable in future and results in higher performance. Therefore, prediction methods with higher accuracy are preferred. Also, the proposed mobility-aware method should work better in environments with more regular movements.

VII. Conclusion

In this study, an incentive mechanism was introduced for relaying D2D communications under asymmetric information. In the proposed incentive mechanism, both the CP and the relay are encouraged to participate in relaying D2D communication. Contract theory is used to develop the proposed incentive mechanism, and optimal contracts are designed to maximize the utility of the BS. The results of the proposed incentive mechanism were compared to an incentive mechanism for direct D2D communications. The results showed that the participation of the devices in D2D content sharing increases with the use of the proposed method. As the number of D2D communications and the distance between the involved D2D devices increase, the utility improvement of the BS and the CPs is more substantial. Also, the results demonstrate that the proposed incentive mechanism improves the quality of D2D communications. Furthermore, the residual energy of the nodes is higher using the proposed method than the baseline.

Moreover, user mobility is considered in the proposed approach. Assuming that the devices in the network are mobile, mobility awareness can be effective in the performance of the proposed incentive mechanism. Because we need more appropriate contracts that are less likely to be violated due to link failures or quality degradations which are the results of mobility. Therefore, in the proposed mobility-aware incentive mechanism, the selection of the contract is performed according to the predicted location of devices in the next time step. The utilities of the BS and the CPs are improved using the mobility prediction compared to the scenario of not exploiting prediction. In this paper, we suppose that all devices have the same acceptable utility threshold for cooperation. Solving the problem for the case of devices with different cooperative attitudes is suggested as future work. Using game theory to simultaneously encourage the CPs and relays to participate in D2D communications is another suggestion for future work.

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