Incentive Mechanisms for Device-to-Device Communications

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Abstract

D2D communication has recently been proposed as a promising technique to improve resource utilization of cellular networks by offloading the traffic through base stations to local direct links between devices. While various optimization frameworks have been intensively studied, little attention has been given to how to attract users to adopt D2D communication. In this article we fill the gap by designing incentive mechanisms to encourage users to work under D2D mode. We consider two basic market types, open markets and sealed markets, where users have information of all users or only their own, respectively. For open markets, we design a Stackelberg game based incentive mechanism that can achieve Nash equilibrium. For sealed markets, we design an auction based incentive mechanism that guarantees truthfulness.

Driven by the ever-increasing popularity of smartphones and tablets in recent years, wireless cellular networks have become one of the major access systems to the Internet for a huge number of customers due to their pervasive availability. Various mobile applications on such portable devices have generated a large amount of data traffic. For example, it is reported that the mobile data produced in North America was 222 PB per month in 2012 [1], and will continually grow in the foreseeable future. For example, Cisco forecasts that global mobile data traffic will increase 13-fold between 2012 and 2017 [1].

To accommodate such huge traffic demands, wireless cellular networks have been evolving to provide higher network capacity by integrating many new technologies. This evolution started from the second generation (2G) standard in the early 1990s, as the first digital cellular system supporting voice services and low-speed data transmission. We are now in the fourth generation (4G) era with two candidates being actively developed today: 3GPP LTE-Advanced and IEEE802.16m.

As an enhanced version of LTE (Long Term Evolution), LTE-Advanced [2] will meet or exceed the requirements of the 4G standard with 100MHz bandwidth and 1Gb/s peak data rate. To achieve these objectives, it integrates emerging technologies that can be classified into two categories: one aiming to provide higher channel capacity, i.e. the multi-antenna technique and carrier aggregation, and the other focusing on developing new communication models, i.e. device-to-device (D2D) communication [3].

Different from many existing works focused on the first category, in this article we study D2D communication [3], which has not received much attention. D2D communication can significantly improve resource utilization of wireless cellular networks by letting a pair of devices in proximity of each other communicate over a direct link instead of through a base station. Consider a scenario where a user would like to share a video or photo with his friend nearby using cellular networks. Traditionally, all data transmissions should go through the base station, i.e. the data should first be uploaded to the base station along cellular uplinks, and then forwarded to the receiver along cellular downlinks. When D2D communication is applied, a direct link between two devices can be established for data transmission, eliminating the need for assistance from a base station. Since the two devices evolved in D2D communication are usually close to each other with a limited interference range, the base station can provide services to other users simultaneously under the same channel.

Recent studies on D2D communication [4, 5] mainly focus on developing various optimization frameworks, e.g. to maximize throughput or to improve energy efficiency, all based on an assumption that the base station, as a central controller, can determine the transmission modes of cellular users. However, in practice, cellular users would have no incentive to enable D2D mode unless they receive satisfying rewards from the network operator. It is hence crucial to design incentive mechanisms to encourage users to adopt D2D communication.

In this article we design incentive mechanisms for D2D communication based on a market model, where the network operator and mobile users are selfish and rational players that are only interested in maximizing their own profit. Two types of markets are considered: open markets and sealed markets. The former allows players to share their strategy knowledge with each other, while the latter only to their own and the network operator. For the open market, we design a Stackelberg game-based incentive mechanism with a fixed total budget announced by the operator for rewarding D2D users, who will compete with each other by switching to D2D mode. For the sealed market, we design an auction-based incentive mechanism in which each potential D2D pair asks for a payment from the network operator for switching to D2D mode. The network operator evaluates the prices asked by users, and determines to trade network resources with a set of winning users.

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In the rest of this article, we first introduce the network infrastructure, and then present the game-based and auction-based incentive mechanisms. Finally, some simulation results are presented to show the performance of our proposals.

Network Infrastructure

We consider a single-cell multi-channel wireless network consisting of a base station (BS) and a set of mobile users (MUs) as shown in Fig. 1. Each channel can be shared among several MUs by time division multiplexing. The network resources in both frequency and time domains can be represented by a matrix as shown in Fig. 1, where each time frame under any channel is referred to as a network resource unit. Traditionally, users should make a payment to obtain network resources, that is, cellular uplinks or downlinks, indicated by solid arrows in the figure, over which a device communicates with the base station, while others on the same channel should stay silent to avoid interference. For example, MU_1 communicates with MU_2 by dividing its purchased network resource unit into two subframes. In the first subframe, MU_1 sends data to the base station along an uplink. In the second subframe, the base station forwards the data to the receiver MU_2 along a downlink.

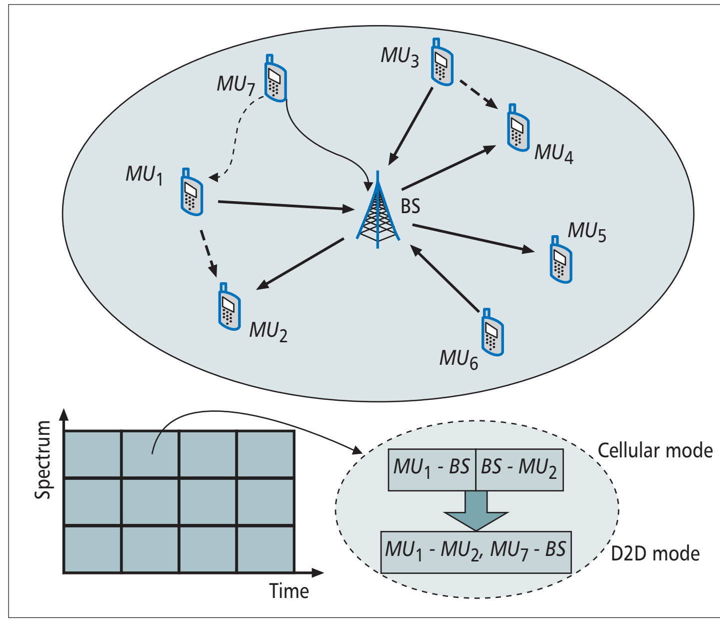

Figure 1. Infrastructure.

When D2D communication is enabled, two devices in a communication pair can establish a direct link, as the dashed arrow shows in Fig. 1. As the base station is not involved in D2D communication, it can provide services for other users, for example, user MU_7 in Fig. 1, simultaneously with the transmission of D2D pair, MU_1 and MU_2.

The devices that can potentially use D2D communication are represented by a set of source-destination (S-D) pairs denoted by $V = \{v_1, v_2, \ldots, v_n\}$. Different from the traditional interference-free cellular mode, an S-D pair under D2D mode would suffer from the interference incurred by other active cellular links due to spatial multiplexing, resulting in a degraded channel capacity. We model such negative influence as a cost c_i per time frame for each S-D pair $v_i \in V$ under D2D mode.

For the network operator, D2D communication is preferred because of its great potential to improve resource utilization of cellular networks. On the other hand, mobile users are usually selfish and not willing to switch to D2D mode because of possible interference. To encourage cellular users to transmit under D2D mode, we design incentive mechanisms whose basic idea is to let the network operator reward D2D users to compensate their cost.

Incentive Mechanism for Open Markets

In open markets, users' information and their actions are public. By observing others, each user individually makes its own decision on resource trading to maximize its profit, which motivates us to apply game theory in our incentive mechanism design. Game theory provides a formal analytical framework with a set of mathematical tools to study the complex interactions among rational players. It can predict what might happen when agents with conflicting interests interact.

Typically, a game consists of three basic components: a set of players, a set of actions, and a set of preferences. In the cellular network considered in this article, mobile users and base stations are players with different actions and preferences. The action set of each mobile user includes its decisions about the number of network resource units it is willing to transmit under D2D mode. The evaluation of each action is represented by users' preferences. For example, a mobile user prefers two resource units to three units for D2D transmission if the benefits rewarded by the base station overwhelm the overhead of incurred influence under two-unit D2D transmission, and otherwise under three units. In game theory, the preference relationship is expressed by a numerical representation called the utility function. In our case, the utility function u_i of S-D pair $v_i \in V$ is defined as its received reward minus the cost that would be incurred due to interference.

The base station, as another kind of player in our game, decides the amount of total payments to D2D users. On the other hand, it gains income by selling network resources obtained from D2D pairs to other users waiting to access the network. Obviously, the base station prefers larger incomes and less payment to maximize its profit. Such a preference can be described by a utility function u_{bs} that is defined by subtracting the payment from the total incomes.

Mechanism Design

Due to the existence of two kinds of players, i.e. mobile users and base stations, we apply the Stackelberg game theory in our mechanism design. In a Stackelberg game, one player acts as a leader that moves first, and the rest act as followers that move subsequently. The objective is to find an optimal strategy for the leader, assuming that the followers react in a rational way to optimize their objective function given the leader's action. Specifically, in our mechanism the base station that declares its strategy first is the leader, and the mobile users that react to the leader's strategy are followers.

In order to encourage D2D communication, the network operator (i.e. base station) first announces a total budget R that will be rewarded to D2D pairs and trading rules, as shown in Fig. 2. The trading rules indicate how to reward each user according to their contributed resource units. In this article we consider that the reward of each S-D pair is proportional to its contributed network resources. For example, if only one S-D pair switches to D2D mode, it receives all payments R from the base station. When another S-D pair contributes the same number of network resource units, both pairs will receive a half of R. Note that other trading rules can also be applied in our mechanism following a similar process.

After receiving the announcement, each S-D pair $v_i \in V$, as a follower in the game, decides the number of network resource units, denoted by t_i, it is willing to transmit under D2D mode by taking the total budget, trading rules, other users' actions, and its overhead under D2D communication into consideration. Note that t_i is up to the number of resource units that v_i has reserved for cellular communication. When t_i is specified as zero, it indicates that the S-D pair v_i will not switch to D2D mode, and thus no reward will be received.

Finally, they submit their decisions back to the base station that will pay some reward to D2D pairs to finish the resource trading. All of the above message exchanges between the base station and mobile users are conducted over some control channels or frames reserved for our mechanism.

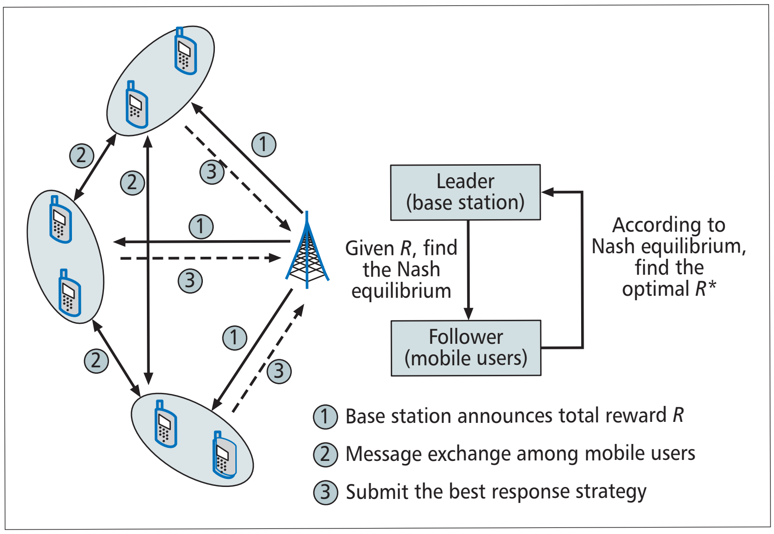

Figure 2. The Stackelberg game based incentive mechanism.

Game Analysis

In this section we analyze the proposed Stackelberg game based incentive mechanism from the perspectives of the leader and followers.

We first consider followers. Given the total payment R, and the strategies of others, each S-D pair will contribute a number of network resource units leading to its maximum profit, which is called the best response strategy. Since users' strategies are public in the open market, each S-D pair will adjust its value of t_i according to the actions of others. A natural question is whether there is a stable state in our design such that no pair has incentive to change its strategy. The answer to this question corresponds to an important concept in game theory: the Nash equilibrium. A set of strategies are in a Nash equilibrium if no player can improve its utility by changing its strategy unilaterally. Note that the Nash equilibrium does not necessarily mean the optimal resource utilization of the whole network.

If all mobile users start from strategies that lead to a Nash equilibrium by predicting game results, then none of them has an incentive to choose a different strategy. Otherwise, if mobile users start from nonequilibrium strategies, our mechanism can guarantee the convergence to the Nash equilibrium because each mobile user can adjust its strategy according to the observation of others' decisions.

In addition to the existence of a Nash equilibrium, we are also interested to know whether it is unique. When multiple Nash equilibriums exist, it is difficult to coordinate all users to converge to the same Nash equilibrium. Based on the results in [6], and the fact that utility function u_i is continuous and concave, there exists a unique Nash equilibrium in our design, which can be obtained by solving a set of equations that are formed by letting the partial derivative of u_i with respect to variable t_i equal to zero.

We then consider the leader that uses a backward induction to determine the value of total payment R, as shown in Fig. 2. Given a total payment R, the base station can obtain the unique Nash equilibrium according to the above analysis. In other words, it can predict how many resource units will be contributed by each S-D pair. By expressing the utility function as a function of R, the base station can choose the optimal R^* leading to the maximum profit.

Incentive Mechanism for Sealed Markets

In sealed markets, each S-D pair only communicates with the base station, and does not share its information with other pairs. The sealed markets are usually applied to scenarios with privacy-preserving requirements, where no pair has the knowledge of others' strategies, or even their existence. It imposes new challenges for the incentive mechanism design.

In this section we present an auction-based incentive mechanism for sealed markets. An auction is a popular market-based mechanism that allows fair and efficient resource allocation [7–9]. Typically, there are three kinds of players in an auction: buyers, sellers, and the auctioneer. Buyers and sellers submit prices to the auctioneer for buying and selling commodities, respectively. Following the terminology in auction theory, the price submitted by a buyer and a seller is referred to as bid and ask, respectively, which are specified according to their valuation on the commodities. After collecting all bids and asks, the auctioneer determines resource allocation and trading prices for buyers and sellers.

In this section we focus on how to establish a truthful auction for trading network resource units between the base station and S-D pairs based on D2D communication.

Mechanism Design

We design a reverse auction for network resource trading, in which the base station acts as both the buyer and auctioneer, and S-D pairs are sellers. The auction process is shown in Fig. 3. The base station first announces a set of resource demands, denoted by $E = \{e_1, e_2, \ldots, e_m\}$, each of which represents a network resource unit with several constraints, such as which channel the resource unit belongs to, what time it should be provided, and the maximum allowed interference from D2D pairs.

After receiving the announcement, each pair v_i submits a vector of asks $A_i = \{a_{i1}, a_{i2}, \ldots, a_{im}\}$, where $a_{ij} \in A_i$ denotes the lowest price at which it is willing to offer the resource unit e_j by switching to D2D mode. When v_i cannot provide a resource unit satisfying the constraints of e_j, it sets the corresponding ask $a_{ij} = 0$. Note that any ask vector A_i is privately known by pair v_i and the base station, and v_i has no ask knowledge of others. This can be implemented by encrypting the bid information or transmitting it over dedicated channels.

When the ask information from all S-D pairs has been collected, the base station executes an auction algorithm with two functions. First, it determines a set W of winners in the auction, i.e. the set of S-D pairs that successfully sell resource units to the base station by switching to D2D mode. Second, it calculates a price p_i paid to each winning pair $v_i \in W$. For the losing pairs, they will still work under cellular mode and get paid nothing. Finally, the base station announces the auction results to all participants, and closes the auction.

Auction Algorithm

The most critical component in our incentive mechanism design is the auction algorithm executed by the base station for winner and price determination. We integrate the well

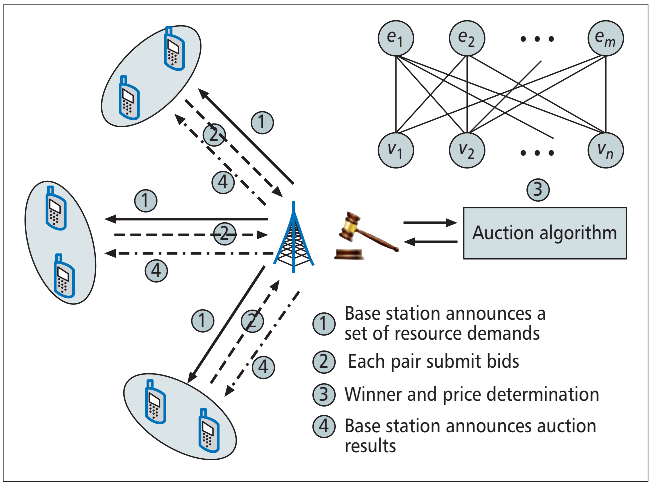

Figure 3. The auction-based incentive mechanism.

known VCG algorithm [10] into our reverse auction design with the objective of satisfying the following three economic properties.

Individual Rationality: Each seller determines its asks with the objective of maximizing its profit, which is represented by a utility function that is defined as its payment minus its valuation of the resource unit. Our auction algorithm should guarantee individual rationality, i.e. all sellers in the auction obtain a non-negative utility. In other words, no S-D pair will be paid less than its ask.

Truthfulness: All participants in the auction should ask/bid according to their true valuation for the network resources, i.e. no S-D pair can improve its utility by submitting an ask different from its true valuation, no matter how other pairs ask. Truthfulness is the most important property that should be achieved in our auction algorithm design because if any user can increase its utility by misreporting its true valuation, the auction will be vulnerable to market manipulation, harming the profit of sellers and buyers.

Social Welfare Maximization: The sum of asks submitted by winning S-D pairs is maximized. It reflects the efficiency of the auction algorithm.

The basic idea of the VCG algorithm is to first allocate resources to minimize the total asks, and then to pay each S-D pair the "opportunity cost" that describes the cost its presence introduces to all the others. Specifically, in our proposed mechanism the auction algorithm works as follows.

Step 1: Given the asks from all S-D pairs, we create a bipartite graph as shown in Fig. 3, where the upper side is the resource demands, and the lower side is the sellers. They are connected according to the ask information $\{A_1, A_2, \ldots, A_n\}$. The edge weight between e_j and v_i is set to the reciprocal of the ask, that is, a_{ij}.

Step 2: We find a feasible resource allocation with the minimum total asks by using a bipartite matching algorithm [11] with optimality guarantee. The computational time complexity can achieve $O(X^2 \log X + XY)$ with the Dijkstra algorithm and Fibonacci heap [12], where X and Y denote the number of nodes and edges, respectively, on the bipartite graph.

Step 3: The auctioneer determines a set of winners by including the S-D pairs that are successfully matched with resource units under the optimal resource allocation obtained in the last step. Let $D(V, E)$ denote the total asks under an optimal resource allocation given V and E. According to the VCG algorithm [10], the price that the base station should pay to the winning S-D pair v_i is $p_i = D(V\backslash\{v_i\}, E) - D(V\backslash\{v_i\}, E\backslash\{f(v_i)\})$, where $f(v_i)$ denotes the resource unit assigned to v_i. The payment for each losing S-D pair is zero.

Example

For a better understanding, we use an example to show the working process of the auction. We consider a single-cell network with $V = \{v_1, v_2, v_3\}$ and $E = \{e_1, e_2\}$. The asks submitted by S-D pairs are $A_1 = \{3, 8\}$, $A_2 = \{7, 2\}$, and $A_3 = \{6, 4\}$, respectively. We construct a bipartite graph, and find an optimal resource allocation leading to the minimum total asks. As a result, S-D pairs v_1 and v_2 become winners, and v_3 loses in the auction. The price paid to each winner is calculated as follows: $p_1 = D(\{v_2, v_3\}, E) - D(\{v_2, v_3\}, \{e_2\}) = 8 - 2 = 6$, and $p_2 = D(\{v_1, v_3\}, E) - D(\{v_1, v_3\}, \{e_1\}) = 7 - 3 = 4$.

Open Issues

Although D2D communication improves the resource utilization of cellular networks by exploiting spatial multiplexing, some open issues still need to be dealt with when we apply our D2D incentive mechanisms in practical cellular networks. These challenges are briefly discussed in this section.

To implement D2D communication, a D2D device discovery mechanism should first be provided to identify all potential D2D pairs. Several device discovery mechanisms have been studied in [13]. For example, in the simplest direct discovery, each MU searches for nearby MUs autonomously by periodically broadcasting discovery signals. Doppler *et al.* [3] have proposed a centralized scheme to discover D2D pairs by letting the base station first identify a pair of nodes within the same cell, and then request them to measure the link quality.

In addition to device discovery, D2D communication technology is another challenge that should be addressed. In principle, any wireless communication technology supported by mobile devices can be used for D2D communication, e.g. LTE Direct, Bluetooth, and WiFi. However, integrating these technologies into existing cellular systems would incur modifications in both the physical and MAC layers.

Until now we have considered simple markets where the interaction between mobile users and base stations is either sealed or open. In practice, we need to deal with more complicated markets with various constraints. To show the basic mechanisms we propose are still applicable to various market settings, we consider an open market with communication constraints [14], in which mobile users are allowed to send ask messages with limited size to the base station, that is, their asks information cannot arrive at the base station at the same time. The auction will be divided into several stages. In any stage, each mobile user sends several bits of its ask, which will be known by others. Only after all bits are transmitted will the mechanism determine the resource allocation and payments. Obviously, each user can determine the bits it will transmit at a stage by observing others' transmissions up to this stage. By applying the auction algorithm in [14], we can still achieve Nash equilibrium with large social welfare.

Performance Evaluation

In this section we present simulation results to show the performance of our proposed incentive mechanisms. We first consider the Stackelberg game based incentive mechanism in open markets, and study the influence of the number of S-D pairs on the maximum utility of the base station. The value of λ is set to 10. We specify the cost of S-D pairs under D2D mode as uniform distributions with different ranges. As shown in Fig. 4, the base station's utility increases as the number of S-D pairs grows under all cases, because the market becomes more competitive when a larger number of S-D pairs join the network. On the other hand, the utility improvement becomes smaller as the network size declines. For example, increasing

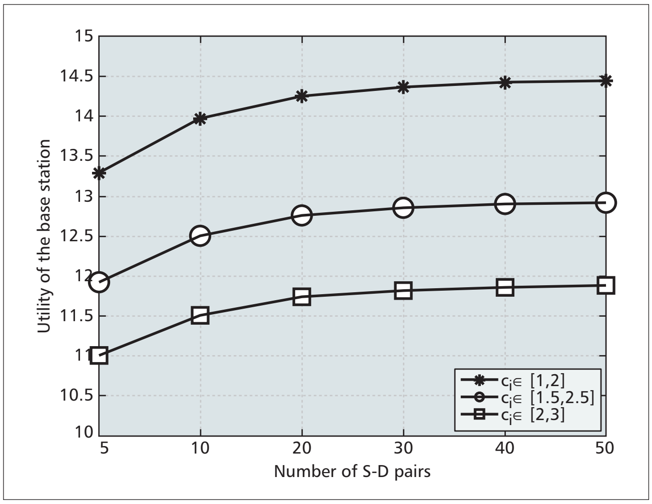

Figure 4. Utility of base station vs. number of S-D pairs.

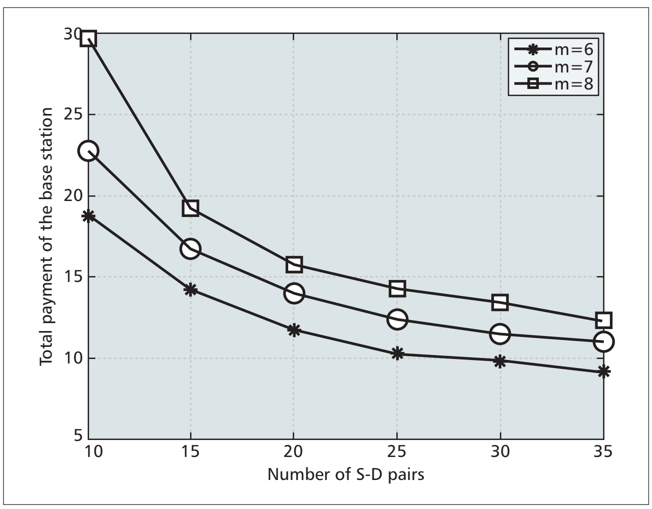

Figure 5. Total payments of base station vs. number of S-D pairs.

the number of S-D pairs from five to 10 can bring a five percent improvement of utility when $c_i \in [1, 2]$. However, the improvement is only 0.1 percent when the number of S-D pairs increases from 40 to 50. Moreover, we observe that a larger value of c_i will decrease the utility of the base station, because S-D pairs intend to share less network resources when the cost under D2D mode is higher.

We then study the performance of the auction based incentive mechanism in sealed markets. As shown in Fig. 5, the total payment of the base station decreases as the number of S-D pairs grows. We attribute this phenomenon to the fact that the base station has a higher probability to select the cheaper sellers when more S-D pairs join the network. The decreasing trend becomes smaller because the ask diversity has been extensively exploited by the base station in larger networks. In Fig. 5 we also show the curves with different resource demands. It is obvious that fewer demands will produce lower payment.

Conclusion

In this article we designed two incentive mechanisms for D2D communication, one for use in open markets and one for use in sealed markets. In open markets where each user shares its information with others, we propose a Stackelberg game based incentive mechanism, and show that our design can achieve a unique Nash equilibrium. Based on this Nash equilibrium, the base station can derive the optimal total payment leading to maximum profit. In a sealed market where users only share information with the base station instead of with other participants in the network, we designed an auction base incentive mechanism that can achieve truthfulness.

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