Device-to-Device Communication in 5G Cellular Networks: Challenges, Solutions, and Future Directions

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ABSTRACT

In a conventional cellular system, devices are not allowed to directly communicate with each other in the licensed cellular bandwidth and all communications take place through the base stations. In this article, we envision a two-tier cellular network that involves a macrocell tier (i.e., BS-to-device communications) and a device tier (i.e., device-to-device communications). Device terminal relaying makes it possible for devices in a network to function as transmission relays for each other and realize a massive ad hoc mesh network. This is obviously a dramatic departure from the conventional cellular architecture and brings unique technical challenges. In such a two-tier cellular system, since the user data is routed through other users' devices, security must be maintained for privacy. To ensure minimal impact on the performance of existing macrocell BSs, the two-tier network needs to be designed with smart interference management strategies and appropriate resource allocation schemes. Furthermore, novel pricing models should be designed to tempt devices to participate in this type of communication. Our article provides an overview of these major challenges in two-tier networks and proposes some pricing schemes for different types of device relaying.

INTRODUCTION

With the introduction of a myriad of smart handheld devices, user demands for mobile broadband are undergoing an unprecedented rise. The drastic growth of bandwidth-hungry applications such as video streaming and multimedia file sharing are already pushing the limits of current cellular systems. In the next decade, envisioned media-rich mobile applications such as tele-presence and 3D holography will require data rates simply not possible with fourth generation (4G) networks.

The ever growing demand for higher data rates and capacity require unconventional thinking for the next generation (5G) cellular systems. Cooperative communications has such promise! Cooperative communications represent a new class of wireless communication techniques in which network nodes help each other in relaying information to realize spatial diversity advantages. This new transmission paradigm promises significant performance gains in terms of link reliability, spectral efficiency, system capacity, and transmission range. Cooperative communication has been extensively studied in the literature, and *fixed terminal relaying* (which involves the deployment of low-power base stations to assist the communication between the source and the destination) has already been included in the 4G Long Term Evolution (LTE)-Advanced standard [1].

Fixed terminal relaying brings improvements in cellular systems, but the full potential of cooperation can be realized only through the implementation of *device relaying*. The term *device* here refers to a cell phone or any other portable wireless device with cellular connectivity (tablet, laptop, etc) a user owns. Device relaying makes it possible for devices in a network to function as transmission relays for each other and realize a massive ad hoc mesh network. This, of course, is possible with device-to-device (D2D) communication functionality, which allows two nearby devices to communicate with each other in the licensed cellular bandwidth without a base station (BS) involved or with limited BS involvement. This is obviously a dramatic departure from the conventional cellular architecture.

In the first four generations of cellular networks, D2D communication functionality has not been considered. This is largely because it has mainly been envisioned as a tool to reduce the cost of local service provision, which used to be fractional in the past based on the cellular operators' market statistics. The operators' attitude toward D2D functionality has been changing recently because of several trends in the wireless market [2]. For example, the number of context-aware services and applications is growing rapidly. These applications require location discovery and communication with neighboring devices, and the availability of such a functionality would reduce the cost of communication

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among devices. D2D functionality can also play a vital role in mobile cloud computing and facilitate effective sharing of resources (spectrum, computational power, applications, social contents, etc.) for users who are spatially close to each other. Service providers can further take advantage of D2D functionality to take some load off of the network in a local area such as a stadium or a big mall by allowing direct transmission among cell phones and other devices. Furthermore, D2D communication can be of critical use in natural disasters. In an earthquake or hurricane, an urgent communication network can be set up using D2D functionality in a short time, replacing the damaged communication network and Internet infrastructure.

In the current market, technologies such as WiFi or Bluetooth provide some D2D communication functionality. However, these work in unlicensed band, and the interference is uncontrollable. In addition, they cannot provide security and quality of service (QoS) guarantee as do cellular networks. Unwilling to lose the emerging D2D market, the cellular operators and vendors are exploring the possibilities of introducing the D2D communication capability into cellular networks, which has sparked interest in this topic. Some recent works on D2D in cellular systems have reported results on interference management issues and radio resource allocation [4–6] as well as on communication session setup and management procedures [3].

In this article, we first provide a categorization of D2D communication based on the degree of involvement of the cellular operator. Then we summarize some major challenges that need to be addressed before the introduction of D2D functionality. Specifically, we briefly discuss *security*, *interference management*, and *resource allocation* issues, and point out some directions for future research. In the rest of the article, we focus on pricing, another major challenge in the implementation of D2D in practice, and propose some pricing schemes tempting for both users and operators.

Overview of D2D Communication Types and Main Technical Challenges

In this article, we envision a *two-tier 5G cellular network* with so-called macrocell and device tiers. The *macrocell tier* involves base station (BS)-to-device communications as in a conventional cellular system. The *device tier* involves D2D communications. If a device connects the cellular network through a BS, this device is said to be operating in the macrocell tier. If a device connects directly to another device or realizes its transmission through the assistance of other devices, these devices are said to be in the device tier. In such a system, the BSs will continue to serve the devices as usual. However, at cell edges or congested areas, devices will be allowed to communicate with each other, creating an ad hoc mesh network.

In the realization of device-tier communications, the operator might have different levels of control. Based on the business model, it either exercises full/partial control over the resource allocation among source, destination, and relaying devices, or prefers not to have any control. Therefore, we can define the following four main types of device-tier communications (Figs. 1–4):

Device relaying with operator controlled link establishment (DR-OC): A device at the edge of a cell or in a poor coverage area can communicate with the BS through relaying its information via other devices. This allows for the device to achieve a higher QoS or more battery life. The operator communicates with the relaying devices for partial or full control link establishment.

Direct D2D communication with operator controlled link establishment (DC-OC): The source and destination devices talk and exchange data with each other without the need for a BS, but they are assisted by the operator for link establishment.

Device relaying with device controlled link establishment (DR-DC): The operator is not involved in the process of link establishment. Therefore, source and destination devices are responsible for coordinating communication using relays between each other.

Direct D2D communication with device controlled link establishment (DC-DC): The source and destination devices have direct communication with each other without any operator control. Therefore, source and destination devices should use the resource in such a way as to ensure limited interference with other devices in the same tier and the macrocell tier.

A two-tier cellular system, if carefully designed, can bring significant improvements over the classical cellular system architecture. Before the introduction of D2D functionality, several technical challenges, particularly in secu-

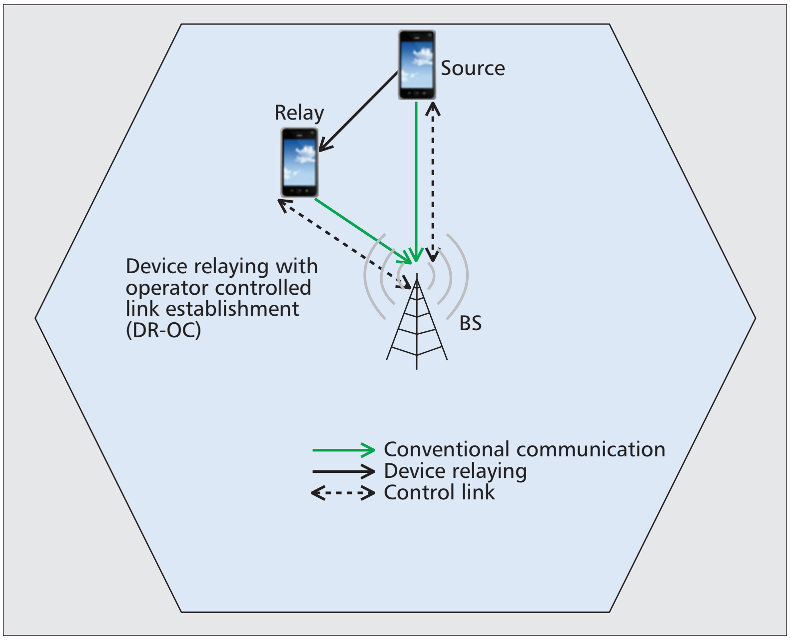

Figure 1. Illustration of device relaying communication with operator controlled link establishment (DR-OC). A device communicates with the BS through relaying its information via other devices.

rity and interference management issues, should be overcome.

Since the user data is routed through other users' devices, security must be maintained for privacy. One possible solution to ensure security is *closed access* for the devices that want to operate in the device tier. In closed access, a device has a list of "trusted" devices, and devices not on this list must use the macrocell tier to communicate with it. For example, the users in a neighborhood or workplace that know each other, or the users that have been authenticated via a trusted party such as an organization, can directly communicate with each other, satisfying a level of privacy. The devices in a group can set a proper encryption between each other to avoid divulging their information to other devices. In *open access*, on the other hand, each device can act as a relay for other devices without any restrictions. Since there is no type of supervision, security in such a case is a challenging open research problem. Security issues in D2D communication involve the identification of potential attacks, threats, and vulnerability of the system. Earlier works on the security issues of machine-to-machine communication [7–11] can be exploited to address security issues in open access D2D. For example, the work in [7] proposes a trusted environment to establish trust relationships among M2M equipment, while secrecy-based access control is discussed in [8]. Secure routing, software-based symmetric key cryptography, and detection of potential attacks are further investigated in [9–11].

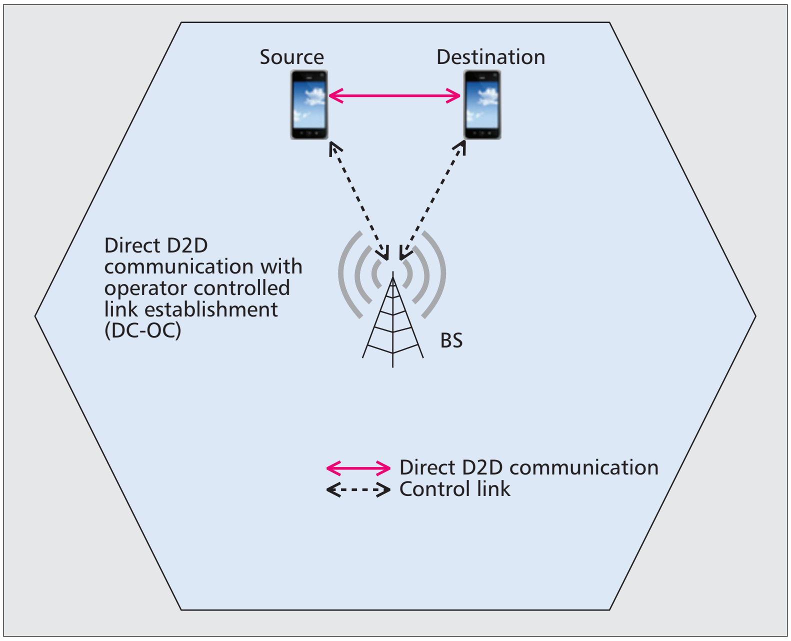

Figure 2. Illustration of direct D2D communication with operator controlled link establishment (DC-OC). The source and destination devices can talk and exchange data with each other without the need for a BS, but they are assisted by the BS through a control link.

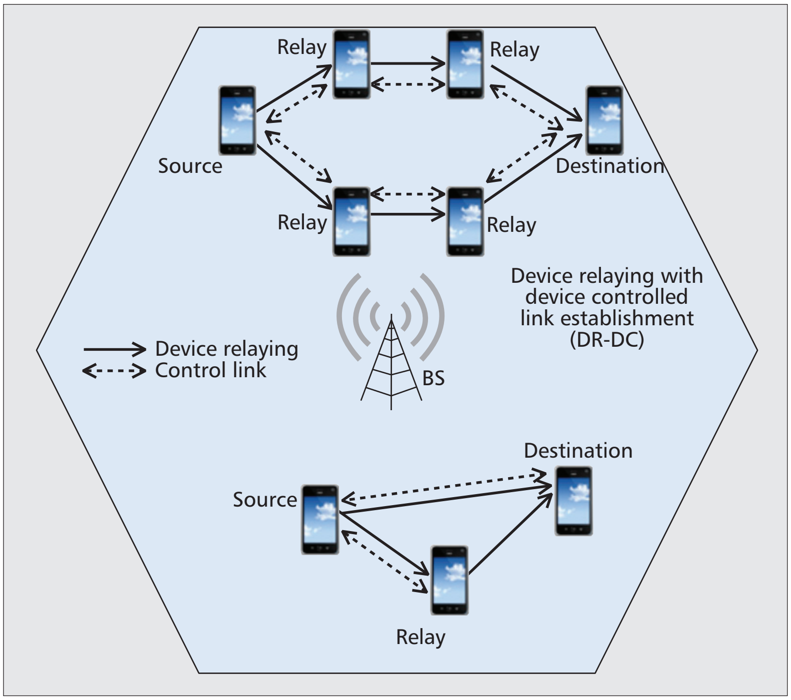

Figure 3. Illustration of device relaying communication with device controlled link establishment. (DR-DC). Source and destination devices directly talk each other and do not use any control link from the operator.

Another significant concern in a two-tier system is interference management. In DR-OC and DC-OC, resource allocation and call setup are performed by the BS. Therefore, the BS can alleviate the problem of interference management to some extent using centralized methods, a well-established research area in wireless communications. On the other hand, in DR-DC and DC-DC, there is no centralized entity to supervise the resource allocation between devices. Operating in the same licensed band, devices will inevitably impact macrocell users. To ensure minimal impact on the performance of existing macrocell BSs, a two-tier network needs to be designed with smart interference management strategies and appropriate resource allocation schemes. Besides the interference between the macrocell and device tiers, there is also interference among users in the device tier. To address resource allocation for this type of communication, different approaches such as resource pooling [4], non-cooperative game or bargaining game [12], admission control and power allocation [6], cluster partitioning, and relay selection [13] can be employed.

In DR-OC, as illustrated in Fig.1, since the BS is one of the communicating parties, some of the aforementioned challenges can be addressed by the control of the BS using existing methods [5]. The BS can authenticate the relaying devices and use the appropriate encryption to maintain sufficient privacy for the information of the devices. The BS can also manage spectrum allocation between the relaying devices to prevent them from interfering with other devices.

In DC-OC, shown in Fig.2, the devices communicate directly with each other with operator controlled link establishment. Specifically, the operator deals with access authentication, connection control, resource allocation, and monetary interaction between devices. It has full control over the D2D connections, including control plane functions (e.g., connection setup and maintenance), and data plane functions (e.g., resource allocation). The D2D connections in the device tier share the cellular licensed band with the regular cellular connections in the macrocell tier. The network can either dynamically assign resources to each D2D connection in the same way as a regular cellular connection or semi-statically assign a dedicated resource pool to all D2D connections.

In DR-DC and DC-DC, there is no BS or server to control the communication between devices. As shown in Figs. 3 and 4, multiple devices communicate with each other using cooperative or non-cooperative communication, and one or multiple devices can play the role of relays for the other devices. This type of communication is more challenging than the previous ones, since there is no centralized supervision of the relaying. Connection setup, interference management, and resource allocation should therefore be addressed using distributed methods. Before the data transmission phase, two devices need to find each other and the adjacent relays (i.e., peer discovery and D2D connection setup). The devices can periodically broadcast identity information so that other devices may be aware of their existence and decide whether or not they can start a D2D direct or device relaying communication [4].

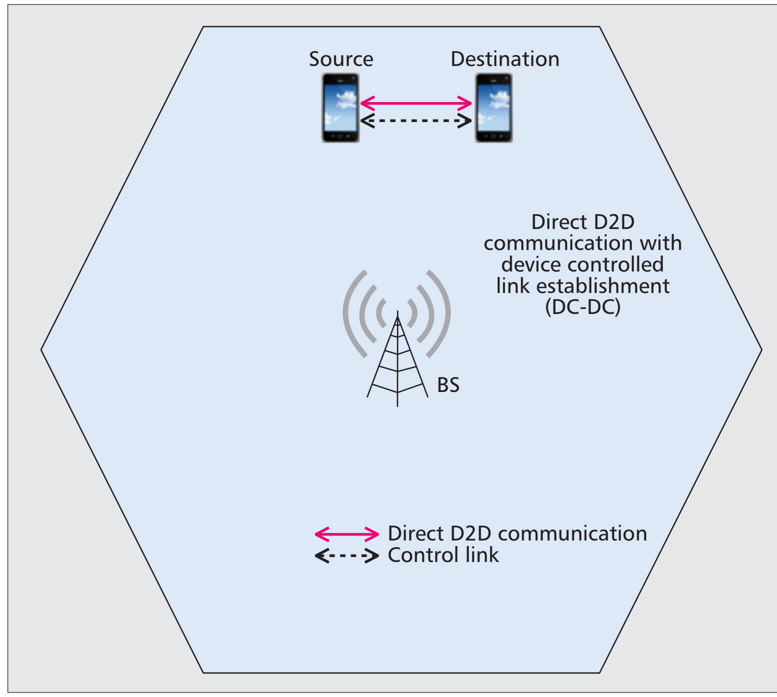

Figure 4. Illustration of direct D2D communication with device controlled link establishment. (DC-DC).

Pricing

Besides the technical challenges summarized in the previous section, a dilemma operators need to address is how they control and charge for D2D services. It is possible that some users, if charged for D2D services, may turn to traditional D2D technologies, which are free but have lower speed and less security. Therefore, the operators must answer the "pay for what" question before they can push forward the operator-controlled D2D technology, which requires extensive analysis of usage cases and business models.

Devices that act as relays for other users use their own resources such as battery, data storage, and bandwidth. Therefore, pricing models should also be designed to tempt devices to participate in this type of communication. Furthermore, in direct D2D communication, the devices need to have a secure environment for the process of selling and buying resources among themselves. The operator can control and create this secure environment for this kind of process. Therefore, it can expect some payment from the devices for the security and QoS in D2D communication.

In the following, we discuss pricing issues for each of the D2D communication types and propose some solutions using tools from game theory and auction theory.

Pricing for DR-OC

The main challenge in DR-OC is to provide sufficient incentives for relaying devices. Since they use their resources (e.g., battery, bandwidth) to relay the information of other devices, they need tempting monetary or other kinds of incentives to involve them in this type of communication. One possible option is that the operator can offer some discounts on monthly bills based on the amount of data they relay through their devices. Giving such discounts is reasonable from the operator's point of view, because the operator benefits from providing service to devices with lack of coverage or demanding data rates higher than available in the macrocell tier.

Another possible incentive for the relaying device is that instead of a discount on the monthly bill, the operator can offer some free services in exchange for the amount of data they have relayed.[1] For example, assume that the following utility function is defined [12]:

$$U_i = b_i \log_2 (1 + k_i\gamma_i) - M b_i p_i + \tilde{b}_i \log_2 (1 + k_i\tilde{\gamma}_i), \quad (1)$$

where b_i is the channel bandwidth used by the ith device, and its "revenue" from this usage is $b_i \log_1 (1 + k_i\gamma_i)$. Here, $k_i = 1.5/\ln(0.2/\mathrm{BER}_{tar})$ denotes the spectrum efficiency [7], γ_i is the average signal-to-noise ratio (SNR) for the link between the ith device and the BS, BER_{tar} is the target bit error rate, and M is the number of hops between the BS and the ith device in data transmission. As the middle term indicates, the ith device should pay $b_i p_i$ to the operator for its usage, where p_i is the unit price of spectrum. The last term in Eq. 1 is the revenue of the ith device from the awarded bandwidth ($\tilde{b}_i$) that is the incentive given by the operator to the device for acting as a relay. $\tilde{\gamma}_i$ denotes the average SNR for the link between the ith device and the BS during the transmission on awarded data. Assuming that there are N devices, the revenue for the operator can be calculated as

$$R = \sum_{i=1}^{N} M b_i p_i - M\tilde{b}_i p_i. \quad (2)$$

In Fig. 5, we illustrate the revenues of the operator and the devices in DR-OC and com-

[1] *To implement this in real time, the BS can send some control signals to users and give them the option to use the award data instead of conventional data transmission.*

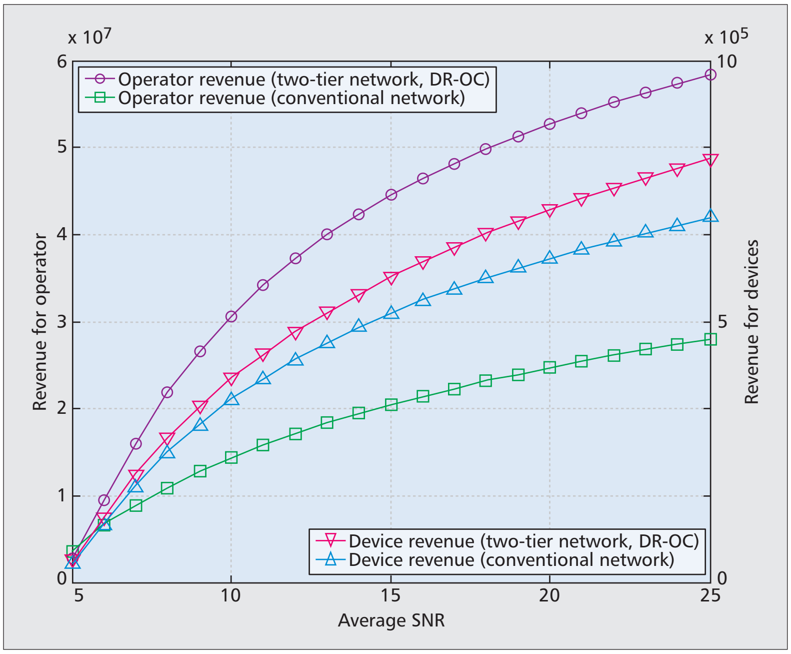

Figure 5. Comparison of device and operator revenues in conventional single-tier cellular system and proposed two-tier system with DR-OC.

pare with conventional (non-cooperative) communication. In DR-OC, the operator uses fixed pricing for the spectrum and offers free spectrum to the devices in exchange for data relayed by them. We assume b_i = 5 MHz, k_i = 0.2 and 5 ≤ γ_i ≤ 25 dB, and M = 1 (i.e., single-hop communication). The number of devices served by the operator is assumed to be 100 (N = 100). For awarded bandwidth of the devices, we assume $\tilde{b}_i$ = 2.5 MHz and 2.5 ≤ γ_i ≤ 12.5 dB. This indicates less throughput for the "reward." Since in cooperative communication the devices experience better QoS, it can be expected that they will be charged more by the operator in comparison to the conventional single-tier cellular system. We assume that the unit price of spectrum is 1 (i.e., p_i = 1) for the conventional (non-cooperative) case and p_i = 1.2 for the DR-OC case. Under these assumptions, it is observed from Fig. 5 that the revenues of the operator and devices in a two-tier network with DR-OC increase in comparison with those in a conventional single-tier cellular system. Specifically, for the given numerical values, the operator revenue doubled for high SNRs, while the revenue of the devices increases about 28 percent in the best case. Therefore, we can conclude that DR-OC is more beneficial for the operator.

Pricing for DC-OC

An important challenge in DC-OC is to have tempting pricing schemes to satisfy users with using this service rather than free WiFi or Bluetooth. Design of a pricing model can be considered as a spectrum trading problem. In spectrum trading, the objective of a seller is to maximize the revenue/profit, while that of a buyer is to maximize the utility of spectrum usage. However, these objectives generally conflict with each other. Therefore, an optimal and stable solution for spectrum trading in terms of price and allocated spectrum would be required so that the revenue and utility are maximized, while both the seller and buyer are satisfied and do not want to deviate from the solution. *Auction theory* provides a useful framework of mathematical tools for the design of pricing models. Since the device does not know the values bidders (other devices) attach to the resources, auctions provide an efficient mechanism for the device to get higher revenue than is obtainable via static pricing. Auctions are also beneficial for the bidders, since generally they assign commodities to the bidders who value them most. Another promising approach for designing effective resource allocation schemes in such an interference-limited environment is *game theory*. Game theory provides a set of powerful mathematical tools for the analysis of conflict and cooperation between intelligent, rational decision makers.

Among different kinds of auction mechanisms, a sealed-bid-first-price auction can be used as a tempting pricing scheme for DC-OC in a monopoly market[2] [12]. In this type of auction, the pair of devices who want to talk each other submit their bids to the BS. The BS selects the highest bids and allocates the channels. The BS can set a reserved price for a certain channel for which devices should submit a bid higher than the threshold price to win it. The BS can also sell the same channel to more than two users, assuming sufficient distance[3] to avoid interference, and gain more revenue from a channel in comparison to the non-cooperative case.

For an oligopoly market, when there are multiple sellers, one can use the Bertrand Game [12] for the design of pricing models. In this non-cooperative game, there are two different utility functions, one for the sellers and another for the buyers. Sellers and buyers try to maximize their revenue through the maximization of their utility functions. In this game, the devices that want to sell their resources determine a price and announce it to the devices who want to buy the resources. This game can be modeled as a Nash equilibrium problem where the aim is to find an equilibrium point such that no seller can improve its objective given the strategies chosen by the other sellers and the reaction of the buyers.

As an example to demonstrate the revenues of operators and devices in a two-tier cellular system with DC-OC, we consider the following scenario. Assume there is only one operator in the market that has 50 available channels, each with a bandwidth of 5 MHz, and the number of devices varies between 100 and 800. In a conventional single-tier cellular system, at any one time only 100 devices can talk to each other under the assumption of 50 available channels. Now assume a two-tier cellular system with DC-OC and set a reserved price r for the submitted bids. Therefore, devices can submit any bid higher than the reserved price based on their valuation of spectrum. Let p_C = 1 denote the unit price of spectrum in a single-tier cellular system. We further assume that the submitted bid for spectrum by the devices in a two-tier system can take values in the range of [r, $p_{\max}$], where $p_{\max}$ is the maximum value of bids. The operator collects all the bids and allocates the available channels to the highest bidders. The revenue of the operator

[2] If there is a single seller, it is called a monopoly market. On the other hand, if there is more than one seller, it is called an oligopoly market.

[3] Nowadays, most cell phones are smart and have GPS. Each pair who wants to submit their bid to the BS can include their positions using GPS. Also, there are other methods for positioning of devices, such as handset-based, SIM-based, WiFi, and hybrid, by which the BS can locate the position of the devices.

is the summation of all payments from the winning devices, while the revenue of the devices is the difference between their valuation and their payment to the operator [12].

In Fig. 6, we use the notation of currency unit (CU) instead of any particular currency, assume $r = 0.1$, $p_{max} = 2$, and illustrate the revenues for both operator and devices. It is observed that the revenue of the operator in DC-OC increases with the increasing number of devices since the value of their bids increases. On the other hand, in the single-tier cellular system, the revenue of the operator remains constant since the operator is already using the full network capacity. The revenue of the operator in the two-tier network with DC-OC is 10 percent more than that of the single-tier cellular system. The revenue of the devices in both cases decreases with the increasing number of devices. However, the amount of revenue that can be gained for the devices in a two-tier network is more than the single-tier counterpart by 48 percent when the number of devices is 100. This gain reduces to 6 percent when the number of devices increases to 800. Since the value of bids increases with the increasing number of devices, the revenue of devices decreases. It should be further noted that in DC-OC, since there are more channels available, the devices can enjoy more throughput than those in the single-tier cellular system.

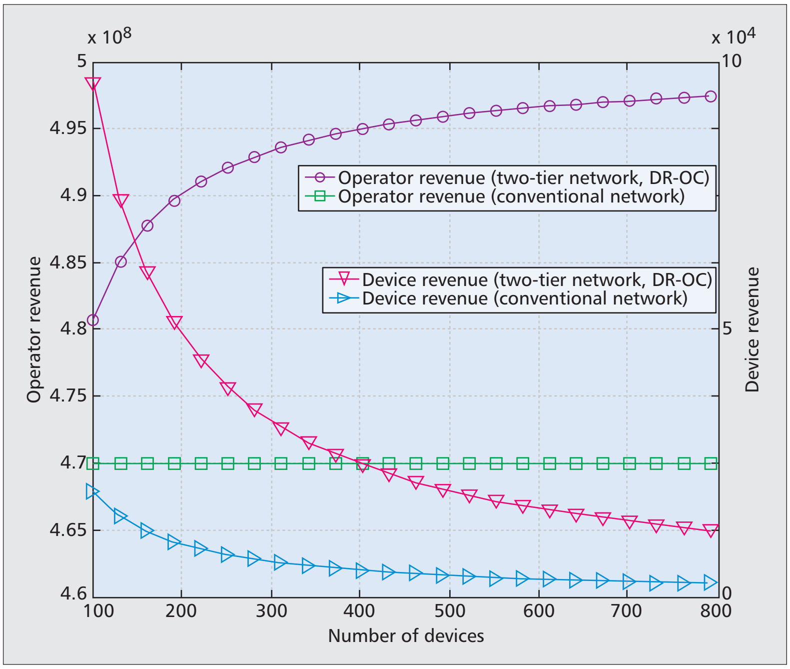

Figure 6. Comparison of device and operator revenues in conventional single-tier cellular system and the proposed two-tier system with DC-OC. A monopoly market is assumed and sealed-bid-first-price auction is used.

Pricing for DR-DC and DC-DC

Since the operator does not have any control over this type of relaying, it should not expect to make any profit from it. In closed access DR-DC, since devices know each other via different ways such as a relationship or being a member of a group or association, they can agree on a pricing scheme or simply relay the information without expecting any payment from other devices, similar to when a user sends a file using Bluetooth or WiFi for his/her friend. In open access DR-DC, users can adopt different pricing approaches such as market equilibrium, cooperative game, bargaining game, or double auction [12].

For the pricing among devices in DC-DC, we can assume that the users are selfish and have a set of social relationships, and hence will not display the same behavior toward all other devices. Since the selfish device will also need to send messages using other devices at times, it is in the selfish device's interest not to ask for monetary payment from the devices in its work group/community. For example, a pricing method is proposed in [14], where each device records encounters with other devices. Whenever a selfish device receives a message from another device, it refers to these records and calculates the percentage of meeting days, and the standard deviation of the daily meetings. Based on this, the selfish devices display altruistic behavior toward devices they meet often, and it is shown that these devices are better off than the devices that are always selfish.

Conclusions

In this article, we have envisioned a *two-tier 5G cellular network* with so-called macrocell and device tiers. In the realization of device-tier communications, the operator might have different levels of control based on the adopted business model. We have first provided a categorization of D2D communication considering the degree of involvement of the cellular operator. Then we have discussed some major technical challenges to be addressed for each type, such as security, interference management, and resource allocation issues. In the rest of the article, we have focused on pricing issues and proposed some pricing schemes for two-tier networks using tools from game theory and auction theory. Our numerical results have demonstrated that judiciously designed pricing schemes for a two-tier cellular network bring significant gains for both the operator and users in comparison to a conventional single-tier counterpart.

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