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Coping with Spatial Unfairness and Overloading Problem in Mobile Networks via D2D Relaying

Pavel Mach, Zdenek Becvar, and Thrasyvoulos Spyropoulos

Abstract

Device-to-device (D2D) relaying is able to increase the network capacity, enhance the network coverage, or mitigate the interference to legacy cellular transmissions. These benefits are even emphasized if a proper incentives are offered to the users to motivate them to act as relays. We first survey the state-of-the-art incentives to show that despite a proper incentivization, the benefits from relaying are enjoyed typically only by the users directly involved in relaying, that is, either those in favorable locations to act as relays or those exploiting such relays to improve their performance. Nevertheless, many users, who are not satisfied with their quality of service (QoS), may not profit from D2D relaying due to their unfavorable locations. Besides, the current incentive mechanisms are not able to alleviate the overloading of the base station (BS) without violating QoS of already admitted users. Thus, to cope with the spatial unfairness and the overloading of BSs, we propose resource allocation framework extending D2D relaying benefits also to the users not directly involved in the relaying process. The proposed framework enables efficient reuse of radio resources and takes inspiration from economy concept of taxes. Moreover, it gives an opportunity to the users distributing spared radio resources to increase their virtual monetary gain, reputation, or even helping other users depending on mutual social relationships. The simulations demonstrate that the proposed concept improves the ratio of satisfied users and/or maximizes the number of newly admitted users for which the BS would not have radio resources otherwise.

Introduction

Device-to-device (D2D) communication is seen as a convenient way to increase the capacity and the energy efficiency of contemporary mobile networks [1]. At its inception more than a decade ago, the sole intended purpose of D2D communication was to send data directly between any two devices in proximity, thus bypassing a base station (BS) and saving radio resources in the process.

As D2D communication progressively matured, it has found additional intriguing use-cases and applications, such as content sharing and caching [2, 3]. Moreover, D2D communication can be exploited for relaying purposes (also known as D2D relaying) in order to increase the performance of users experiencing a low channel quality to/from the BS. Besides, D2D relaying can augment multi-casting/broadcasting services [4], facilitate a load balancing among adjacent BSs [5], or improve the computation offloading to edge servers [6]. Consequently, D2D relaying is a very useful tool for the existing 5G and the emerging 6G networks.

One of the crucial challenges for D2D relaying, however, is to ensure a *willingness* of the users *to offer relaying services* to other users, who are often complete strangers. This willingness can hardly be taken granted, given that devices used for relaying, such as smartphones or IoT devices, can suffer from an additional energy consumption. Similarly, even the users exploiting relaying services should be convinced to entrust their data to the intermediate relaying users. In this regard, several incentive strategies have been proposed throughout the years taking an inspiration from economy [7, 8], social aspects [9, 10], or reputation [11, 12]. Besides, an attractive option to motivate the relaying users is to give him/her some additional radio resources [13].

The existing incentive mechanisms typically provide benefits, in terms of capacity increase and/or energy consumption decrease, solely to the users *directly* involved in relaying, that is, to the users assisted by the relaying users and to the relaying users themselves. Still, there are users with a low channel quality to the BS that, unfortunately, cannot enjoy the benefits of relaying simply because no suitable relay is in their vicinity. Consequently, Quality of Service (QoS) requirements of these "unlucky" users with low-quality channels to the BS cannot be met due to this spatial unfairness. Besides, the existing incentive solutions are not able to alleviate an overloading problem, when the BS is not able to admit any new users without violating QoS of the already admitted users.

In this article, we first overview recent incentive approaches for D2D relaying maximizing the benefits of the users directly involved in D2D relaying. Then, to increase the number of users benefiting from D2D relaying, primarily those users who are not satisfied with their QoS or cannot

Pavel Mach and Zdenek Becvar are with Czech Technical University in Prague, Faculty of Electrical Engineering, Czech Republic; Thrasyvoulos Spyropoulos is with EURECOM, France.

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be admitted by the BS due to its overloading, we propose a novel resource allocation framework. The proposed framework builds upon the existing incentive mechanisms but it enables to extend the benefits of D2D relaying also to the users not directly involved in relaying itself. In particular, we propose to:

- *Reuse* resources allocated to D2D links (i.e., links between the users) by the cellular links
- *Tax* resources earned or saved by the users benefiting directly from relaying
- *Sell* the earned (or saved) resource to other users to convert the relaying gain into monetary gain, increased reputation, or to help others with strong mutual social relationship

Subsequently, the resources obtained from these mechanisms are distributed to the users not directly involved in relaying. We also discuss various optimization, implementation, and feasibility aspects of each proposed mechanism allowing their smooth and efficient implementation into mobile networks. Finally, we show that the proposed framework increases significantly the number of users satisfied with QoS and/or allows to admit many new users to be served even if the network is highly overloaded.

Overview of Incentive Strategies for D2D Relaying

This section discusses the most prominent incentive strategies giving benefits to the users directly participating in relaying (Fig. 1). Moreover, we outline key properties each incentive mechanism should support and describe the common approaches to reach mutual agreement among cooperating users.

Virtual Currency-Based Incentives

One family of incentives motivating the users to relay data is based on a virtual currency. The virtual currency can be represented by tokens paid to the users providing the relaying services [7]. The tokens are initially distributed by the network to the users. Afterwards, the token is given to the user whenever he/she agrees on the relaying service provisioning. The received tokens can be exploited by the relaying users in the future, when these users require some relaying service themselves. The potential problem with tokens is that the relaying users receive one token for relaying service disregarding the amount of relayed data or the relaying time/consumed energy. To remedy this problem, the relaying users can be paid in "credits" that can easily factor the amount of relayed data, capacity improvement, or simply duration of the relaying service [8].

Social Relationship-Based Incentives

The social relationship-based incentives build on the assumption that the users tend to interact preferentially with the people to whom they have some social tie, such as close friends, relatives, or co-workers [9]. The relationships can be modeled as a weighted graph, where the vertices correspond to individual users while the edges represent a "social closeness" between them. To define strength of the social tie, a specific weight to each connection (edge) is assigned [10] (Fig. 1). Based on such graph, the one subset of users prefer to act as relays for other subset of users with whom they have close social ties. It is reasonable to assume that social peers are willing to relay each other's traffic without any (monetary) cost or, at least, with some discount depending on the level of social trust [9].

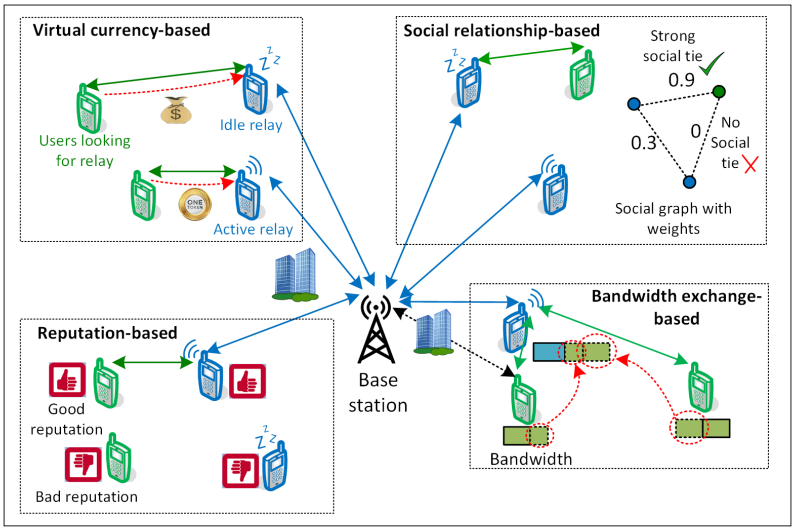

FIGURE 1. State-of-the-art incentive strategies for D2D relaying.

Reputation-Based Incentives

The relaying users can also be motivated via a reputation-based approach [11]. The users have either "bad" or "good" reputation, determined by the BS on a regular basis. Intuitively, the users with "good" reputation get help easily from others when they are in a need of relaying. Contrary, the users known to refuse helping others have hard times to find anyone volunteering to relay data due to "bad" reputation. Moreover, the BS is able to detect whether the relaying users send data at the appointed intervals and it assigns the reputation accordingly [11]. The binary reputation score, however, may not be sufficient to reflect the current users' behavior. Consequently, more flexible reputation is based on YouTube or Facebook "like" button, where the reputation is increased (or decreased) by 1 (or 0.5) if the users are satisfied (or not satisfied) with relaying [12].

Bandwidth Exchange-Based Incentives

All previous incentive mechanisms are based on an indirect reciprocity, where the relaying users benefit in the *future*. The bandwidth exchange-based incentives, on the contrary, gives an *immediate* benefit to the relaying users. The immediate benefit is represented by some part of the channel/resource blocks or more transmission opportunities [13] (Fig. 1). Hence, there is no risk in terms of the uncertainty whether the current relaying cost is outweighed by a reward in the future. The additional radio resources are, then, exploited by the relaying user to both relay data of other user(s) and to boost its own capacity and/or reduce the relay's energy consumption [13].

Properties of Incentive Mechanisms

All incentive concepts described in previous subsections should ensure *individual rationality* and *incentive compatibility*. The former one guarantees that all involved participants can benefit from

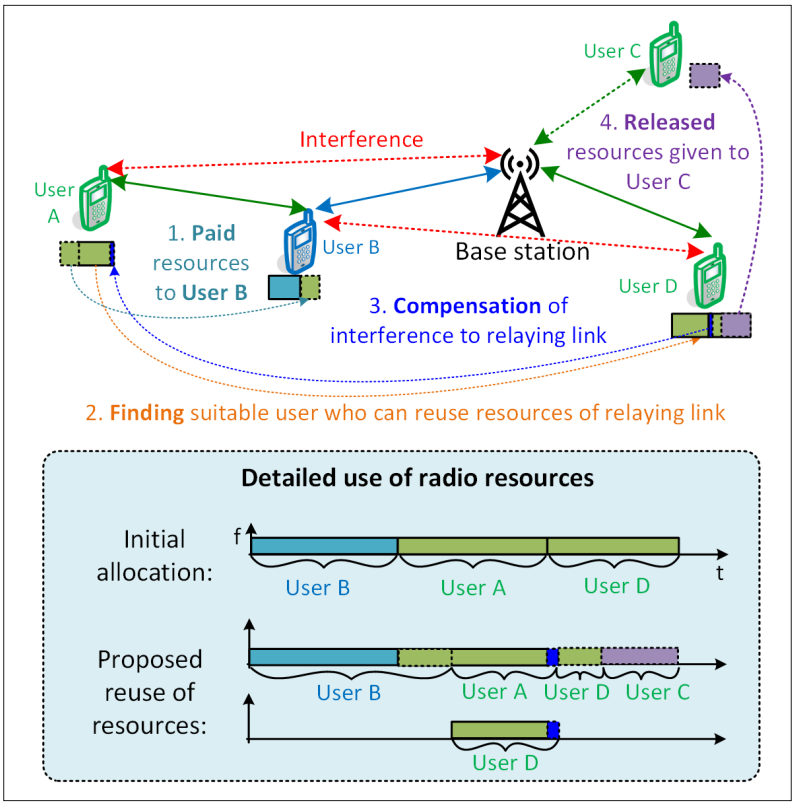

FIGURE 2. Illustrative principle of resources reuse by cellular link. After Users A and B become involved in D2D relaying, User D reuses resources of User A who is, at the same time, compensated by a part of resources initially allocated to User D. Then, the remaining resources initially allocated to User D are split to two parts: first part remain to user D to ensure his/her satisfaction while the second part is assigned to User C.

relaying, that is, the relaying cost in terms of the payment for relaying service or additional energy consumption of the relaying users does not outweigh the relaying gain [14]. The latter one, then, ensures that every participant in relaying maximizes his/her own gain if acting according to their real and true preferences [10, 14].

Moreover, each incentive mechanism should ensure that all users participating in relaying are satisfied by finding a proper trade-off between the relaying gain and the relaying cost. The common approach to solve this challenge is to apply *auction mechanism*, where the buyers in the auction submit bids and corresponding prices they are willing to pay. Subsequently, the auctioneer selects winning buyers to maximize social welfare [10]. Besides, *contract theory* is often applied so that the users select contracts to maximize their own utility [14]. Lastly, also *game theory*, such as indirect reciprocity game adopted in [11], is commonly exploited to stimulate the users' cooperation.

Proposed Framework

The incentive mechanisms described in the previous section are able to motivate the relaying users and, thus, all users directly participating in D2D relaying can fully enjoy its benefits. Unfortunately, there are still many users unable to meet their QoS requirements due to their poor channel quality to the BS while incapable to capitalize on D2D relaying concept due to their disadvantageous locations with respect to other users in proximity. Besides, the existing incentive approaches cannot help users that would like to access the BS that is currently overloaded. To extend the benefits of D2D relaying to these users, we propose a framework encompassing three mechanisms:

- Reusing of resources allocated to D2D links
- Taxing
- Selling of resources.

While the first two are managed by the BS, the last mechanism gives a more free hand to the users themselves to decide to whom the resources are assigned.

Reuse of D2D relaying links resources by cellular links

The main idea of the first mechanism is to reuse the resources allocated to the relaying links by the cellular users communicating directly with the BS. The proposed process of reuse is summarized in following four consecutive steps (Fig. 2).

In the first step, the user searching for relay (User A in Fig. 2) makes a deal with the relaying user (User B). In line with the bandwidth exchange-based incentives, User B gets a part of the resources from User A. Consequently, User B is able to both forward data of User A to/from the BS and to increase own capacity or save energy due to decreased transmission power. The exact determination of the amount of resources to be delegated to User B is out of scope of this article, but let's assume that both users benefit (e.g., resources can be allocated in a way that the relaying gain of both is the same [13]).

In the second step, the BS finds a suitable cellular user who can reuse resources allocated to the relaying link (i.e., the link between User A and User B in Fig. 2). By intuition, the reuse of relaying link's resources by the cellular user inevitably results in the interference to/from the cellular communication from/to D2D communication (Fig. 2). Nevertheless, interference from (or to) User A to (or from) the BS is usually not significant as the channel quality between these two is low. In fact, the low channel quality between User A and the BS is the main reason why relaying is initiated in the first place. Further, one can observe that interference from (to) User B to (from) User D depends strongly on the channel quality between these two. Thus, the ideal candidate cellular user to reuse the resources of the relaying link is the one that is far from the relaying user to mitigate interference imposed by the relay to the cellular user in downlink or vice versa in uplink.

Even though the interference to the relaying link is insignificant, there may be still a slight degradation in D2D relaying link quality. Consequently, during the third step, a part of the resources initially allocated to User D (i.e., the cellular user reuses resources of the relaying link) are assigned by the BS to D2D relaying link to compensate the interference generated to this user by the reuse.

In the last step, the resources initially allocated to User D are split into two parts. The first part of the resources is exploited by User D to satisfy his/her requirements. This is beneficial especially if User D cannot find any suitable relaying users and, at the same time, he/she has a weak channel to the BS. Then, the rest of the resources of User D are released and given to other user(s) (User C in Fig. 2).

Optimization, Implementation, and Feasibility Aspects: To maximize the benefit from the reuse, a selection of the users reusing the resourc-

es of individual relaying links should be optimized to minimize the interference between the cellular and D2D communications. The optimization problem can be understood as a selection of pairs, each composed from one user reusing resources of one relaying link. This corresponds to one-to-one matching problem solvable *optimally* in polynomial time by Hungarian algorithm [13].

Besides, to enable reuse of the resources, interference links should be known by the BS. While the interference between the BS and any user (e.g., User A in Fig. 2) is available via conventional channel estimation, the derivation of interference among users (e.g., User B and User D) can be demanding in terms of signaling, especially if there are many cellular users potentially reusing resources of many relaying links. Fortunately, the channel between any two users may be predicted with a high accuracy using deep neural networks [15], resulting in no or only very low signaling overhead.

Taxing Resources Earned Through Relaying

The application of only reuse mechanism may not always be sufficient to increase the number of users benefiting indirectly from relaying. To this end, we come up with the second mechanism, where the resources saved/earned by the users directly involved in relaying are taxed in a similar way as the taxes imposed by the government to its citizen. The principle of the taxation mechanism is summarized into three steps (Fig. 3).

The first step is analogous to the one utilized in the reuse mechanism, that is, in the establishing of D2D relaying link(s). Then, during the second step, the BS imposes a tax on both the resources earned by the relaying user (i.e., the resources obtained by User B) and the resources saved by the user exploiting relay (User A) due to superior channel quality between those two. This way, pool with taxed resources is created at the BS. Finally, the BS distributes the taxed resources from this pool to the users in a need, that is, to the users with either unfavorable channel quality to the BS that are not able to find any relay (User D) or even to the new users that cannot be served otherwise due to a high load of the BS (User C).

Optimization, Implementation, and Feasibility Aspects: The taxing mechanism should be properly optimized to maximize the revenue coming from taxed resources. A low tax rate results in small benefits coming to the users not involved in relaying. In contrast, a high tax rate may discourage the users to act as the relays resulting in small revenues going to the BS and in a subsequent decrease in the relaying gain. In theory, there is an optimum tax rate maximizing total tax revenue, as indicated by well-known Laffer curve. In practice, the optimum tax rate is very hard, if not impossible, to be determined due to its very complex nature and unpredictable people/users' behavior. Thus, we suggest to follow common taxing mechanisms based on either flat or progressive tax rate self-optimized via machine learning (e.g., by reinforcement learning).

To determine the taxes, the BS should be aware of the amount of resources obtained from relaying in the first place. Since the BS handles the resource allocation, it knows exactly the amount of both the earned resources by the relaying users and the saved resources by the users exploiting relays. Hence, the BS can determine the amount to be taxed by itself without any additional required signaling cost.

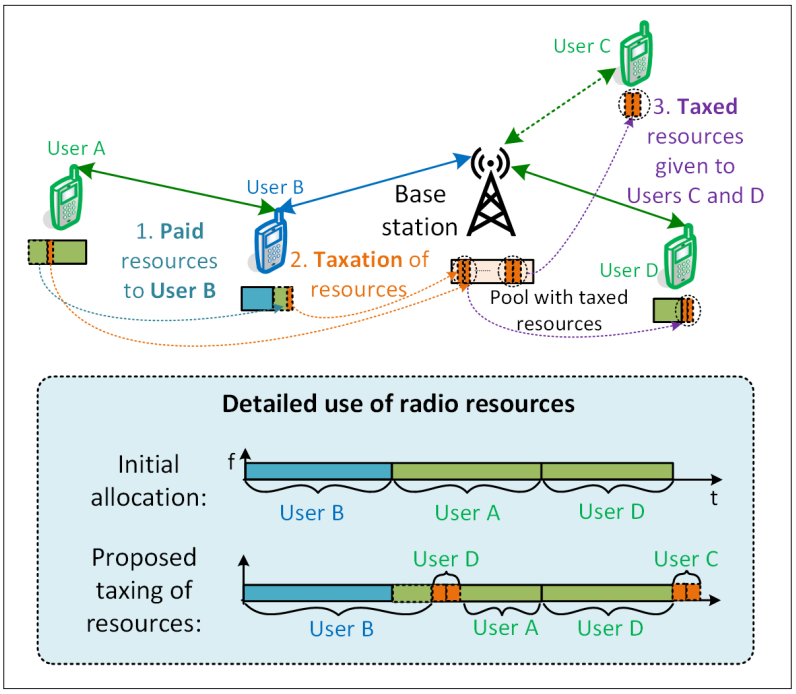

FIGURE 3. Illustrative principle of the concept of taxing resources obtained from relaying. The resources earned (saved) by User B (User A) via relaying are taxed by the BS and distributed to User D to improve his/her capacity. Moreover, taxed resources from other relaying users are given to User C who could not be served by the BS otherwise.

Selling of Resources Saved/Earned Through Relaying

The last piece of the puzzle forming the proposed framework is to sell and/or give resources obtained via relaying to other users that are still either not satisfied with provided services while no feasible relaying user is in their vicinity or have no resources at all due to high load of the BS. The whole mechanism can be summarized into the following subsequent steps (Fig. 4).

The first step consists again in the establishment of D2D relaying link between User A and User B. During the second step, some of the resources earned by User B for the provisioning of relaying services can be sold to other user(s) exploiting the auction mechanism and to obtain credits/tokens. These earned credits/tokens can be exploited in the future to pay the relaying services, similarly as in the case of virtual currency-based incentives. Further, the users may also give a helping hand to other users with whom they have close social ties. In fact, this approach can be seen as another way to motivate the users to relay data for others. For example, User B in Fig. 4 is willing to help to User D who is his/her friend. Since User B cannot relay data for User D due to an unfavorable mutual location, he/she decides to relay data for User A instead. Subsequently, User B gives (or sells with some discount) resources obtained from User A to User D. This way, User B is motivated to act as the relaying user to User A in order to help User C. Finally, in line with the reputation-based incentives, the resources can be also given freely to other users to increase their own reputation.

To further maximize the number of users benefiting from relaying, even User A can sell/give

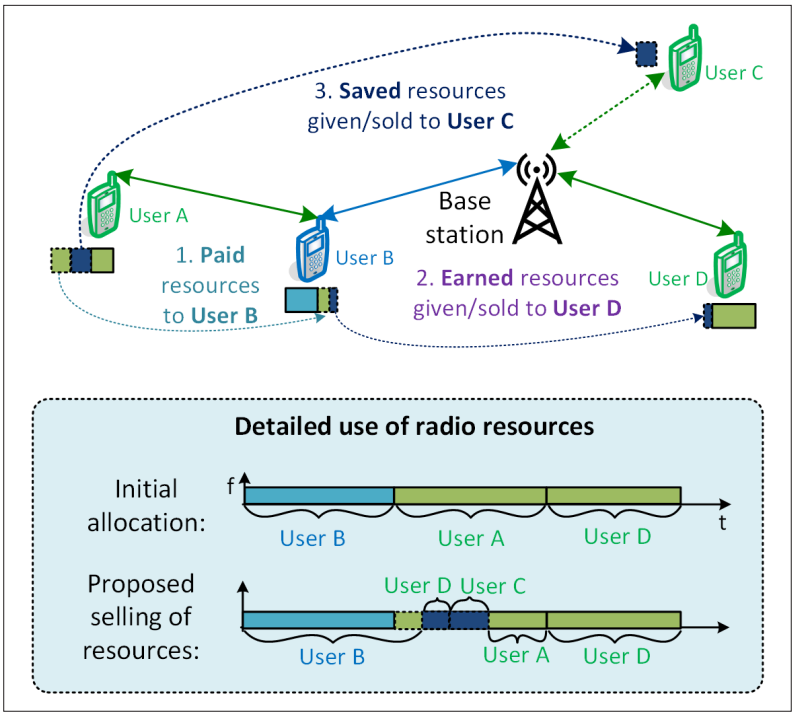

FIGURE 4. Illustrative principle of the proposed selling of resources saved/earned by the users benefiting directly from relaying. User A saves part of his/her resources due to relaying and these saved resources are sold or given to User C for whom the BS has no resources at all. Similarly, User B gives/sells certain portion of earned resources to User D who is able to enhance performance.

some saved resources in the same way as the relaying user himself/herself during the third step (e.g., to User C in Fig. 4). Of course, this option is feasible only if: User A would experience a higher gain than required, for example, if the channel quality between cooperating users is very high, and the resources of User A are not reused by other cellular user to avoid unpredictable rise in the interference.

Optimization, Implementation, and Feasibility Aspects: To maximize the amount of resources sold to the users in need, the auction mechanism should be optimized. The optimal auction maximizing the social welfare can exploit Vickrey-Clarke-Groves (VCG) mechanism, which is, however, of a high complexity. As an alternative to VCG, various game theory-based auction mechanisms can be adopted with the goal to find an equilibrium. In such games, there are: a set of players (i.e., buyers and the sellers of resources), a set of actions available to each player, and a payoff vector for the particular action being taken. Then, the goal is to maximize the payoff for each player during the game.

To make the auction feasible for practical networks, the BS should play the role of an auctioneer mediating the whole process during which the users offer the resources and sell them to the highest bidder. The auction mechanism generates signaling overhead coming from submitting of bids and offers to the auctioneer (i.e., the BS) and, then, announcing the results of the auction to individual users. Fortunately, this overhead is negligible if a simple bidding language is adopted. Moreover, the signaling overhead can be further reduced by, for example, concurrent bidding pattern, where each buyer has only one chance to make a bid.

Cooperation of Individual Proposed Mechanisms

Although the individual mechanisms can work as stand-alone solutions, the maximum gain is observed if all three are integrated together and are performed in the following steps:

Step 1: The BS employs the mechanism enabling reuse of resources of newly formed D2D links by the cellular users. This, subsequently, allows to release some additional resources from the cellular users.

Step 2: To acquire even more resources, the taxing is enforced by the BS on the resources obtained through D2D relaying provided that enough resources are gained via such relaying.

Step 3: The obtained resources remaining to the users after the taxation can be further distributed to the users still not satisfied with their QoS by *selling* mechanism. Note that, as explained earlier, the users whose resources are reused by other cellular users are forbidden to sell their resources to avoid unpredictable interference (e.g., User A in Fig. 2 cannot dispense part of his/her resources, as these are reused by User B).

Moreover, our proposal is complementary to D2D load balancing approaches [5] so that our framework is envisioned to be a "first phase" in coping with the overloading at a single-cell level. If some of the cells would still be overloaded, the load balancing operating at a multi-cell level is initiated in the "second phase."

Evaluation of Proposed Framework

Now, we outline the simulation scenario and we evaluate the gain of the proposed concept.

Simulation Scenario

The evaluation of proposed framework is done in Matlab. We assume 50 active users randomly located in an area with size of 500x500 m. Without loss of generality, the BS initially splits the available bandwidth (20 MHz) equally among all active users. We assume time division relaying to support low-complexity half-duplex relays (note that the proposed framework can be also extended to full-duplex relaying). The relaying users first receive data in a specific time slot and at certain frequency resources, for example, represented by resource blocks. Then, the received data is re-transmitted to the BS in the next resource blocks. The reception/transmission time is derived in line with [13]. The relay selection is done in a greedy manner, commonly used for this purpose (e.g., [13]) to maximize the relaying gain.

The simulation emulates an urban scenario with obstacles potentially obstructing the communication path between any transmitter and any receiver. In case of none line-of-sight communication, additional 20 dB attenuation of the signal is considered. We consider a multicell-like environment with the inter-cell interference at any receiver generated randomly according to Gamma distribution (see more detail in [13]).

To evaluate our proposal, we assume that the selection of cellular users reusing the resources of individual D2D links is done by Hungarian algorithm to achieve maximum gain} in terms of saved resources. In addition, the users are taxed only if the relaying gain is above certain threshold in order not to discourage them from relaying. Hence, the

users whose capacity is not improved enough (i.e., if their QoS requirements are not met) are not taxed at all. Otherwise, the users are obliged to pay 20% of their earned/saved resources to the BS. Finally, the users that are satisfied with the capacity improvement and still have some resources left after the taxing either sell them to other unsatisfied users and/or give these unused resources to a close friend(s).

To see the added value of our proposed framework, we confront its performance with the baseline scheme proposed in [13] representing current state-of-the-art, where only the users directly involved in D2D relaying benefit. We also discuss and analyze the performance of individual mechanisms when working both as stand-alone solutions or together.

The proposed framework either improves the performance of currently active users not involved in D2D relaying or allows to admit new users if the BS is overloaded. Thus, the proposed concept is evaluated for the following two objectives.

Objective 1 — Maximize the ratio of the users satisfied with their QoS: The users are assumed to be satisfied with their QoS if their capacity is improved by a specific value varying between 5% to 50%.

Objective 2 — Maximize the number of newly admitted users: All resources obtained through the proposed framework are only exploited to admit new users to the network. The capacity requirements of each newly admitted user is generated randomly.

Simulation Results and Discussion

Now let's investigate performance of the proposed framework for *Objective 1*. From Fig. 5, we observe that the ratio of satisfied users decreases if the required capacity improvement increases. This is understandable behavior due to the following facts: there are less resources coming from the proposed framework, as the users directly involved in relaying should be satisfied first; and the users ask for more additional resources to satisfy their QoS requirements. If each mechanism works as a stand-alone solution, the highest gain with respect to the baseline scheme is accomplished by the selling mechanism (up to 18.5%). Still, even the reuse or taxing mechanisms working separately outperform the baseline scheme by more than 13% and 15%, respectively, if the required capacity increase to ensure QoS is below 10%. If the required capacity increase to satisfy the QoS rises to 50%, however, the gain of reuse, taxing, and selling mechanism with respect to baseline decreases to 3.8%, 3.3%, and 9%, respectively. To make the gain of the proposal even more interesting, all three proposed mechanisms should work together resulting in a gain up to 20.7% with respect to the baseline scheme. The benefit of the full proposal is promising especially if the QoS requirements increase as it outperforms baseline nearly by 19% even if users require capacity boost equal to 50% to meet their QoS.

Figure 6 illustrates the percentage of newly admitted users facilitated by the proposed framework (Objective 2). It is worth to mention that no new users are served by the BS in case of the baseline scheme, as there are no released resources for the newly arrived users. Again, we observe similar trends as in Fig. 5 and the percentage of

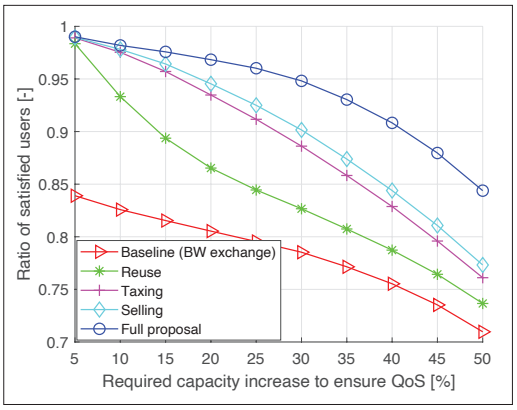

FIGURE 5. Ratio of satisfied users in relation to the required capacity improvement to ensure QoS (Objective 1).

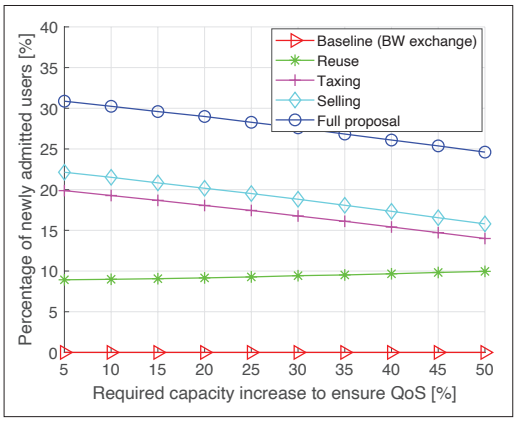

FIGURE 6. Percentage of newly admitted users over the required capacity improvement to ensure QoS (Objective 2).

newly served users decreases with an increase in the required capacity improvement, since there are less resources available for these new users. Only in case of the reuse mechanism, the ratio of newly served users is actually slightly increasing and outperforming taxing mechanism if required capacity increase becomes high. This phenomenon occurs due to the fact that more resources are, in general, allocated to the users assisted by the relays to serve their needs. Thus, more resources may be reused by the cellular users and, subsequently, also more resources are released by them. Figure 6 demonstrates that, compared to the baseline, reuse, taxing, and selling mechanisms can increase the number of newly admitted users by up to 10%, 13.8%, and 22.1%, respectively. If all proposed mechanisms work together, the number of newly served users increases even up to 30.9% with respect to the baseline.

Conclusion

In this article, we have first surveyed key state-of-the-art incentive approaches motivating the users to render the relaying services for others. Existing incentive approaches are able to improve performance of only those users that are directly involved in relaying while there are still remaining users that are not able to reap the benefits from relaying. To this end, we have proposed resource allocation framework, build upon existing incentives, so that the users not being directly involved in D2D relaying also benefit}. We have demonstrated the pro-

posed framework notably increases the number of users satisfied with their QoS and/or increases the number of users that could not be admitted otherwise due to the overloaded network.

In the future, the proposed framework can be jointly optimized with load balancing to further improve users' QoS and/or to make the network even more robust against the overloading problem.

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References

[1] F. Jameel *et al.*, "A Survey of Device-to-Device Communications: Research Issues and Challenges," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, 2018, pp. 2133–68.

[2] C. Yi, S. Huang, and J. Cai, "An Incentive Mechanism Integrating Joint Power, Channel and Link Management for Social-Aware D2D Content Sharing and Proactive Caching," *IEEE Trans. Mobile Comput.*, vol. 17, no. 4, Apr. 2018, pp. 789–802.

[3] X. Xu, J. Wang, and X. Tao, "Analytical Modeling for Caching Enabled UE-to-Network Relay in Cellular Networks," *IEEE Access*, vol. 6, 2018, pp. 51,061–68.

[4] K. Wu and M. Jiang, "Joint Resource Efficiency Optimisation for Overlay Device-to-Device Retransmissions," *Proc. IEEE 85th Vehicular Technology Conf.*, Sydney, NSW, Australia, June 2017, pp. 1–5.

[5] J. Liu *et al.*, "Device-to-Device Communications Achieve Efficient Load Balancing in LTE-Advanced Networks," *IEEE Wireless Commun.*, vol. 21, no. 2, Apr. 2014, pp. 57–65.

[6] J. Peng *et al.*, "D2D-Assisted Multi-User Cooperative Partial Offloading, Transmission Scheduling and Computation Allocating for MEC," *IEEE Trans. Wireless Commun.*, vol. 20, no. 8, Aug. 2021, pp. 4858–73.

[7] N. Mastronarde *et al.*, "To Relay or Not to Relay: Learning Device-to-Device Relaying Strategies in Cellular Networks," *IEEE Trans. Mobile Comput.*, vol. 15, no. 6, June 2016, pp. 1569–85.

[8] Z. Zhu *et al.*, "Time Reusing in D2D Enabled Cooperative Networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 5, 2018, pp. 3185–3200.

[9] M. Wu *et al.*, "Dynamic Socially-Motivated D2D Relay Selection With Uniform QoE Criterion for Multi-Demands," *IEEE Trans. Commun.*, vol. 68, no. 6, 2020, pp. 3355–68.

[10] W. Sun *et al.*, "Social-Aware Incentive Mechanisms for D2D Resource Sharing in IIoT," *IEEE Trans. Ind. Electron.*, vol. 16, no. 8, 2020, pp. 5517–26.

[11] Y. Gao, Y. Chen, and K. J. Ray Liu, "Cooperation Stimulation for Multiuser Cooperative Communications Using Indirect Reciprocity Game," *IEEE Trans. Commun.*, vol. 60, no. 12, 2012, pp. 3650–61.

[12] P. K. Mishra, A. K. Mishra, and S. Tripathi, "Relay Selection Scheme for Dynamic Network Scenario in Multi-hop D2D Communication," *Proc. ICCCS*, Singapore, 2019.

[13] P. Mach *et al.*, "Incentive-Based D2D Relaying in Cellular Networks," *IEEE Trans. Commun.*, vol. 69, no. 3, 2021, pp. 1775–88.

[14] F. Seifhashemi, B. S. Ghahfarokhi, and N. Moghim, "Mobility-Aware Incentive Mechanism for Relaying D2D Communications," *Computer Commun.*, vol. 2022, Aug. 2022, pp. 361–77.

[15] M. Najla *et al.*, "Predicting Device-to-Device Channels from Cellular Channel Measurements: A Learning Approach," *IEEE Trans. Wireless Commun.*, vol. 19, no. 11, Nov. 2020, pp. 7124–38.

Biographies

Pavel Mach received M.Sc. and Ph.D. in Telecommunication Engineering from the Czech Technical University in Prague, Czech Republic in 2006 and 2010, respectively. He is a senior researcher in 6G mobile research lab at CTU in Prague. He has been involved in several European projects (e.g., FREEDOM, TROPIC). He has published more than 70 conference or journal papers and is the co-inventor of several U.S. patents.

Zdenek Becvar received M.Sc. and Ph.D. in Telecommunication Engineering from the Czech Technical University (CTU) in Prague, Czech Republic in 2005 and 2010, respectively. He is a Full Professor at the Department of Telecommunication Engineering at CTU. He was on visiting researcher and/or professor at Budapest Politechnic, Hungary (2007), CEA-Leti, France (2013), and EURECOM, France (2016, 2019, 2023). From 2013 to 2017, he was a representative of the CTU in 3GPP/ETSI. His research is oriented on a development of future mobile networks (5G, beyond 5G, 6G) with special focus on optimization of radio resource and mobility management, edge computing, C-RAN, and architecture of mobile networks.

Thrasyvoulos Spyropoulos received the Diploma degree in electrical and computer engineering from the National Technical University of Athens, Greece, and the Ph.D. degree in electrical engineering from the University of Southern California. He was a Post-Doctoral Researcher with INRIA, and then a Senior Researcher with the Swiss Federal Institute of Technology (ETH) Zurich. He is currently a Professor with EURECOM, Sophia-Antipolis. He was a recipient of the Best Paper Award from IEEE SECON 2008 and IEEE WoWMoM 2012, and runner-up for ACM Mobihoc 2011, IEEE WoWMoM 2015 and 2021.