Efficient Token Circulation Strategies against Misers in Device-to-Device Relay Using Token-based Incentive Mechanisms

You-Chiun Wang and Fu-Chun Chang

Abstract—*Device-to-device (D2D) relay* not only broadens the service coverage of a *base station (BS)* but also raises the network capacity. When the channel quality of a *user equipment (UE)* is not good, it requests another UE to help relay its data from the BS. Since many UEs are owned by self-interested users, *token-based incentive (TBI)* mechanisms are developed to allow UEs selling and buying relay services by exchanging tokens, thereby pricking UEs on to act as relay nodes. However, such mechanisms are vulnerable to the *miser problem*, where malicious UEs keep collecting tokens from other UEs but never spend tokens. Eventually, negotiable tokens will gradually decrease, so more and more UEs have very few tokens to buy relay services, which restrains D2D relay. To conquer the miser problem, this paper proposes three token circulation strategies, which tax UEs and redistribute the taxed tokens to those UEs in need. Thus, we can prevent misers from hoarding tokens and breaking a TBI mechanism. The proposed strategies need not add extra tokens to the network, so they will not cause inflation of tokens. Simulation results show that our strategies can still keep high D2D throughput with the existence of misers, which protects TBI mechanisms and promotes the performance of D2D relay.

Index Terms—circulation, D2D relay, miser, relay, token.

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1 INTRODUCTION

THE technology of *device-to-device (D2D)* communication expands the applicability of cellular networks, which allows two neighboring *user equipments (UEs)* directly conversing with each other, without asking the *base station (BS)* to be an intermediary. Because cellular links and D2D links can share the spectrum resources, the spectral efficiency thus improves. In effect, this technology is viewed as an integral part of 5G networks [1].

When a UE moves close to the cell's edge, its channel quality from the BS may degrade accordingly. This edge effect could be mitigated by some techniques, such as single-user massive *multi-input multi-output (MIMO)* [2], [3]. However, in an urban environment, the densely located buildings impact penetration losses and make blockage effects (e.g., shadowing, reflections, scattering, and diffraction) become more severe [4]. Furthermore, the additional antenna gain would lead more multipath effects, especially in an indoor environment [5]. Thus, some UEs may still encounter bad channel quality even if they are not far away from the BS.

D2D relay is a common means to conquer the above predicament [6]–[8]. Fig. 1 shows an example. Suppose that a UE u_i wants to get data from the BS, but it is obstructed by a building. Due to serious blockage effects, u_i's channel quality from the BS may not be good, even if the single-user massive MIMO technique is used. In this case, u_i can ask another UE u_j whose signal quality is better to receive data from the BS on behalf of u_i and then forward the data to u_i (by D2D communication). Here, u_j is called a *relay node* of u_i. As compared with the case that u_i receives data right from the BS, using D2D relay via u_j can significantly raise throughput. The work [9] discusses some practical issues for D2D relay, such as spectrum sharing, caching, and interference management.

In practice, UEs may be mobile phones, tablets, or laptops whose owners are usually self-interested users. Therefore, it is unrealistic to presume that each UE will be compliant to provide the relay service for others. An incentive mechanism is essential to encourage most UEs to serve as relay nodes [6]. There have been various incentive mechanisms proposed (the detail will be discussed in Section 2.2). *Token-based incentive (TBI)* mechanisms are the most flexible and suitable for cellular networks. Specifically, virtual currencies (called *tokens*) are circulated among UEs to carry out the trade of relay services. When u_i wants u_j to be its relay node, u_i has to pay a token to u_j, as shown in Fig. 1. Thus, u_j sells its relay service and u_i buys that service. In this way, UEs can be encouraged to provide relay services to earn tokens, so as to use them later.

However, TBI mechanisms are vulnerable to the *miser problem*, where some malicious UEs (called "misers") hoard tokens on purpose. These misers are enthusiastic to sell relay services in order to gather tokens from surrounding UEs but never spend tokens on buying relay services from others. In this case, parts of the neighbors of a miser will have fewer and fewer tokens. Thus, a *poor region* is formed around the miser in which most UEs (except the miser) do not have sufficient tokens for trade, as shown in Fig. 1. Even if there exist just few misers, they may still cause great damage to a TBI mechanism, as these misers can roam to create many poor regions in the network. One naive solution is to periodically add extra tokens to the network. Unfortunately, this solution would lead to *inflation*, making tokens become worthless, which also destroys the TBI mechanism.

To solve the miser problem, three *token circulation (TC)* strategies are proposed in this paper. The *passive TC strategy* regularly taxes every UE and redistributes the taxed tokens to poor UEs whose tokens are few. Then, the *active TC strategy*

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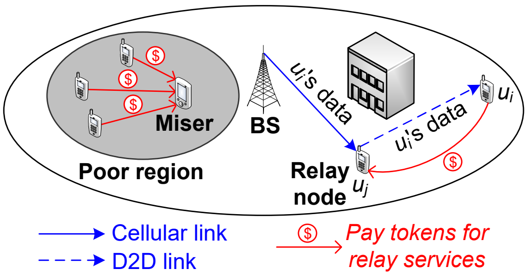

Fig. 1: D2D relay and the miser problem.

taxes only rich UEs with many tokens and then gives these tokens to poor UEs. On the other hand, the *hybrid TC strategy* combines the above two strategies to facilitate the circulation of tokens in the network. Each TC strategy can prevent misers from hoarding tokens, help poor UEs obtain necessary relay services, and keep a constant number of tokens in the network (which means that there will be no inflation of tokens). Our contribution is to point out an inherent deficiency of TBI mechanisms and develop efficient solutions.

The rest of this paper is organized as follows: Section 2 surveys the related work and Section 3 discusses the system model. Then, we propose our TC strategies in Section 4, followed by the performance evaluation in Section 5. Finally, Section 6 concludes this paper.

2 RELATED WORK

2.1 D2D Communication and Relay

In the literature, many schemes are proposed to help D2D links reuse the spectrum resources allocated to *cellular UEs* (*CUEs*, which are UEs talking with the BS). Yu et al. [10] define a maximum matching problem to pair CUEs and D2D links for resource sharing. The Gale-Shapley method is applied in [11] to find matches between CUEs and D2D links to reuse resources, whose result achieves Pareto-optimal [12]. In [13], a distance-based method is proposed to mitigate interference among UEs and minimize the outage ratio of D2D links. The work [14] assigns subchannels to D2D links such that they will not cause significant interference to the CUEs using the same subchannels. The study [15] adopts a graph-coloring approach to let D2D links reuse the resources of CUEs with the aim of eliminating interference. Lai et al. [16] propose a pure D2D model, which allows D2D links sharing resources without involving CUEs. How to improve the *energy efficiency (EE)* is also addressed. The study [17] decides the transmitted power for D2D links and then allocates resources to them, so as to raise their EE. The work [18] finds the communication mode, transmission period, and power allocation for D2D links to save energy and fulfill their demands. Xu et al. [19] allocate subchannels to D2D links and adjust their power to improve the overall EE. Zhou et al. [20] adopt the game-theoretic mechanism to find out the correlation of UEs, and match D2D links with CUEs to maximize EE. As can be seen, the above schemes aim at resource or power allocation for cellular and D2D links. None of them address the issue of D2D relay.

A number of studies consider D2D relay. Wu et al. [21] apply network coding to D2D relay to raise throughput and evaluate the effect of caching at relay nodes on system performance. The work [22] selects relay nodes according to their social relationships, communication ranges, and transmitted power. The study [23] formulates a multi-objective binary integer linear programming problem for relay selection, and solves the problem by both fuzzy and entropy theories. Zhang et al. [24] explore the community relationship between D2D UEs through deep learning to pick the best relay node. In [25], D2D relay is used to transfer services of UEs among different cells, so as to balance the workloads of BSs and turn off idle BSs to support green communication. The work [26] proposes a coordinated relay discovery method to reduce periodic discovery transmissions of D2D UEs to economize their energy. However, these studies assume that UEs are unconditional to act as relay nodes. This assumption may not hold when they are owned by self-interested users.

2.2 Incentive Mechanisms

Most incentive mechanisms can be classified into three categories. In *bandwidth-exchanging mechanisms* [27], [28], after a UE u_j helps relay data for another UE u_i, u_i should give u_j a portion of its bandwidth as compensation. Some variations are also proposed, such as exchanging the transmission time [29] or the relay service [30]. Nevertheless, these mechanisms ask u_i to compensate u_j right after it gets u_j's service, even though u_j does not require u_i's assistance instantly. Thus, they can only obtain suboptimal solutions [31].

In *reputation-based mechanisms* [31], [32], each UE assesses the reputation of others based on its own interaction (i.e., the first-hand information) and also the second-hand information from neighbors. When a UE u_i rejects relaying data for other UEs many times, its reputation will be bad. As punishment, other UEs will not help relay u_i's data. The reputation-based mechanisms rely on the omnidirectional broadcast for UEs to monitor each other's transmission to evaluate reputation. However, since the MIMO and beam-forming techniques are widely used in cellular networks, it is hard to support the omnidirectional broadcast [33].

In *TBI mechanisms* [34], [35], UEs carry out the trade of relay services through virtual currencies, namely, tokens, which are capable of preserving value. Each UE can earn tokens by acting as the relay node for a neighbor, say, u_i and later on ask for the relay service from other UEs (not necessarily u_i) by paying tokens to them. The study [36] investigates the effect of the number of tokens on the profit of UEs. The work [37] employs the Markov decision process to help each UE decide whether to provide the relay service to a requestor in exchange for tokens. As compared with the bandwidth-exchanging and reputation-based mechanisms, TBI mechanisms are more flexible and efficient. However, they are vulnerable to the miser problem, where malicious UEs excessively gather tokens from other UEs to reduce negotiable tokens.

Some studies also propose tax-based methods of tokens. The work [38] considers video streaming from a source to multiple receivers, which requires intermediate nodes to relay the video to receivers. The payment of tokens by receivers depends on the energy spent by senders. Each node also pays a portion of its reward to the parent nodes as tax. However, the objective of taxation in [38] is to let the nodes closer to the source have higher rewards (as they may consume more energy), instead of avoiding some nodes (e.g., misers) to hoard tokens. Yang et al. [39] carry out user-centric *mobile crowdsensing (MCS)* by cooperative D2D communication. The MCS server pays each UE a reward r_x and a monetary transfer t_x, where $t_x > 0$ means to pay a subsidy and $t_x < 0$ means to impose a tax. With the monetary transfer, each UE aims to maximize its net profit (i.e., $r_x - \text{cost}_x + t_x$). Unlike [39], the subsidy in our TC strategies is to help poor UEs get necessary relay services (i.e., avoid them starvation due to misers). To the best of our knowledge, none of the existing studies address the miser problem that TBI mechanisms would encounter. This motivates us to develop TC strategies to conquer the problem and protect a TBI mechanism for D2D relay.

3 SYSTEM MODEL

3.1 Network Architecture

We consider 4G networks or 5G non-standalone networks, where 4G and 5G BSs coexist in the service area. The typical radius of a 4G cell is more than 1 km [40], so the edge effect is non-neglected. Moreover, since there could exist many obstacles and interference sources in indoor environments or urban outdoor environments, penetration losses and blockage effects become more severe. In this case, some UEs may encounter bad channel quality, so they need D2D relay to improve performance.

Modern cellular networks adopt OFDMA (orthogonal frequency division multiple access) for downlink communication, where spectrum resources are divided into *resource blocks (RBs)*. Specifically, one RB spans twelve 15 kHz subcarriers (i.e., totally 180 kHz) and has the duration of 0.5 ms. Our discussion aims at a macrocell that serves a set $\hat{\mathcal{U}}$ of UEs, where each UE is capable of relaying data for other UEs by D2D communication. However, since the UEs in $\hat{\mathcal{U}}$ are owned by self-interested users, an incentive mechanism is essential.

The time axis is divided into fixed *scheduling periods* to facilitate RB allocation and D2D relay. The length T_{S} of a scheduling period should be long enough to let each UE complete three tasks: 1) check if D2D relay is required, 2) find a good relay node (when necessary), and 3) accomplish data transmission. The tasks will be discussed in Sections 3.2 and 3.3. Besides, both channel quality and position of each UE cannot change drastically in a scheduling period. Thus, we suggest setting T_{S} to one frame defined in 5G (i.e., 10 ms).

In each scheduling period, the BS selects a subset $\hat{\mathcal{U}}_{\mathrm{D}} \subseteq \hat{\mathcal{U}}$ of UEs to get downlink data (depending on the scheduling algorithm). When some UEs have bad channel quality, these UEs can request neighbors to relay their data. We adopt the two-hop relaying approach, as shown in Fig. 1. In particular, a UE u_i can select at most one UE, say, u_j to be its relay node. Then, the transmission from the BS to u_i will be substituted by the two-hop transmission "BS → u_j → u_i".

3.2 Choosing between Cellular or Relay Modes

Each UE $u_i \in \hat{\mathcal{U}}_{\mathrm{D}}$ can choose to get its downlink data either directly from the BS (called the *cellular mode*) or via a relay node $u_j \in \hat{\mathcal{U}}_{\mathrm{N}}$ (called the *relay mode*) in a scheduling period t, where $\hat{\mathcal{U}}_{\mathrm{N}}$ is the subset of UEs in $\hat{\mathcal{U}}$ such that they are not scheduled to send uplink data or receive downlink data in period t. Obviously, $\hat{\mathcal{U}}_{\mathrm{D}} \cap \hat{\mathcal{U}}_{\mathrm{N}} = \emptyset$. A crucial factor for the choice is whether u_i's demand can be met by using the cellular mode. Below, our discussion aims at one period, so the variable t is omitted for ease of presentation.

Let $\omega_{b,i}$ be the bandwidth of the cellular link between the BS (as denoted by b) and u_i. According to the Shannon's formula, u_i's data rate in the cellular mode can be estimated by

$$\lambda_{b,i} = \omega_{b,i} \times \log_2(1 + \sigma_{b,i}). \tag{1}$$

In Eq. (1), $\sigma_{b,i}$ is the *signal-to-interference-plus-noise ratio (SINR)* from the BS to u_i, which is calculated as follows:

$$\sigma_{b,i} = \frac{g_{b,i} \times p_{b,i}}{\Psi_i + \omega_{b,i} N_0}, \tag{2}$$

where $g_{b,i}$ and $p_{b,i}$ are the channel gain and the transmitted power for the BS to send data to u_i, respectively, Ψ_i is the amount of interference imposed on u_i, and N_0 is the power spectral density of the environmental noise.

For the relay mode, suppose that u_i obtains its data through u_j's relay, which is denoted by $\langle j \rangle$. Then, u_i's data rate is measured by

$$\lambda_{b,i}^{\langle j \rangle} = \omega_{b,i}^{\langle j \rangle} \times \log_2(1 + \sigma_{b,i}^{\langle j \rangle}). \tag{3}$$

To improve the resource utilization, the cellular link (b, u_j) and the D2D link (u_j, u_i) will share the same RB. In this case, we have $\omega_{b,j} = \omega_{b,i} = \omega_{i,j}$, so $\omega_{b,i}^{\langle j \rangle}$ is equal to $\omega_{b,i}$.

There are two common schemes for D2D relay: *amplify-and-forward (AF)* and *decode-and-forward (DF)*. The AF scheme relays data with a simple amplification stage at the relay node from the source to the destination. On the other hand, the DF scheme makes the relay node decode the data gotten from the source and then retransmit it to the destination. As compared with the DF scheme, the AF scheme is easier to implement and thus widely used. Moreover, there have been some techniques proposed to conquer the problem of poor end-to-end bit-error-rate performance that the AF scheme may encounter [41], [42]. Consequently, we adopt the AF scheme for relay in our work. According to [43], the SINR $\sigma_{b,i}^{\langle j \rangle}$ can be computed by

$$\sigma_{b,i}^{\langle j \rangle} = \frac{\sigma_{b,j} \times \sigma_{j,i}}{\sigma_{b,j} + \sigma_{j,i} + 1}, \tag{4}$$

where $\sigma_{j,i}$ is derived from Eq. (2) by replacing b with j.

Based on Eq. (1), if the SINR $\sigma_{b,i}$ is good enough, u_i chooses the cellular mode, since its demand can be met and the packet latency could reduce (as compared with the two-hop communication in the relay mode). More concretely, let σ_i^Q be the smallest SINR for u_i to suffice its QoS (quality of service) demand. When $\sigma_{b,i} \geq \sigma_i^Q$, u_i receives downlink data in the cellular mode. Otherwise, u_i will select a UE u_j from $\hat{\mathcal{U}}_{\mathrm{N}}$ to be its relay node, as discussed in Section 3.3.

3.3 Selection of Relay Nodes

For a UE $u_i \in \hat{\mathcal{U}}_{\mathrm{D}}$ choosing the relay mode, the problem of selecting u_i's relay node can be formulated as follows:

$$u_j = \arg\min_{u_j \in \hat{\mathcal{U}}_{\mathrm{N}}} p_{j,i} \tag{5}$$

subject to

$$\lambda_{b,i}^{\langle j \rangle} \geq \omega_{b,i} \times \log_2(1 + \sigma_i^Q) \tag{6}$$

$$p_{\min} \leq p_{j,i} \leq p_{\max} \tag{7}$$

The objective function in Eq. (5) is to select a relay node u_j whose transmitted power is the minimum to save energy and reduce interference. The constraint in Eq. (6) means that u_i's demand should be met through u_j's relay, and the constraint in Eq. (7) puts both lower and upper bounds on u_j's transmitted power for the relay.

As for the implementation, u_i sends a *relay request* to each neighbor u_j. If u_j does not send uplink data or receive downlink data in the scheduling period (i.e., $u_j \in \hat{\mathcal{U}}_{\mathrm{N}}$), it judges whether to provide the relay service to u_i (as discussed in Section 3.4). If u_j is willing to serve as a relay node, it sends a *relay reply* to u_i that contains parameters $p_{j,i}$ (i.e., the amount of u_j's transmitted power for relaying data) and $\sigma_{b,j}$ (i.e., u_j's SINR from the BS). When getting the relay reply from u_j, u_i measures its SINR from u_j (i.e., $\sigma_{j,i}$). In this way, u_i can calculate data rate $\lambda_{b,i}^{\langle j\rangle}$ by using Eqs. (3) and (4). Then, among all neighbors that send relay replies, u_i selects a neighbor u_j by Eqs. (5), (6), and (7). After that, u_i sends u_j a *relay confirmation* to tell u_j that u_i chooses it to be the relay node. This confirmation also involves the transfer of a token from u_i to u_j. With the relay confirmation, u_j can notify the BS that it will help relay u_i's data. Thus, the BS transmits u_i's data to u_j by using u_i's RBs. Then, u_j reuses these RBs to forward the data to u_i. However, if no neighbors send relay replies to u_i, u_i switches to the cellular mode to receive its data directly from the BS.

3.4 Judgement on Offering Services

We adopt the judgement method proposed in [37], where a UE $u_j \in \hat{\mathcal{U}}_{\mathrm{N}}$ decides whether to offer the relay service to a requestor $u_i \in \hat{\mathcal{U}}_{\mathrm{D}}$ in exchange for tokens by a Markov decision process. Let (e_j, ζ_j) be the state of u_j, where e_j is the amount of u_j's budget energy and ζ_i is the number of u_j's tokens ($e_j \geq 0$ and $\zeta_j \in \mathbb{N}$). The budget energy only occupies a portion of u_j's energy. In other words, even though u_j uses up its budget energy, it still has energy to perform other jobs (however, u_j will no longer provide relay services). Then, the state transition of both UEs will be

$$\text{Requestor } u_i\text{:}\quad (e_i, \zeta_i) \rightarrow (e_i, \zeta_i - 1), \tag{8}$$

$$\text{Relay node } u_j\text{:}\quad (e_j, \zeta_j) \rightarrow (e_j - e_i^{\mathrm{R}}, \zeta_j + 1). \tag{9}$$

Eq. (8) means that u_i pays one token for the relay service. Eq. (9) indicates that u_j consumes an amount e_i^{R} of energy to relay u_i's data but it can earn one token from u_i.

The action set is defined as a function of the UE's budget energy:

$$\mathcal{A}(e_j) = \begin{cases} \{0, 1\}, & e_j > 0 \\ \{0\}, & \text{otherwise.} \end{cases} \tag{10}$$

For every action $a_j \in \mathcal{A}(e_j)$, $a_j = 1$ implies that u_j is willing to serve as a relay node; otherwise, $a_j = 0$. Afterward, the cooperation policy of u_j, which is denoted by $\varpi_j(e_j, \zeta_j)$, is a function that maps u_j's state (e_j, ζ_j) to its action a_j. Given the probability that u_j is asked to relay data for another UE (as denoted by μ_j), the probability that u_j provides its relay service can be calculated by $\mu_j \varpi_j(e_j, \zeta_j)\tilde{I}_{\{e_j>0\}}$, where $\tilde{I}_{\{x\}}$ is an indicator whose value is set to 1 when the event x occurs and is set to 0 otherwise.

Let $\bar{P}([e'_j, \zeta'_j] \,|\, [e_j, \zeta_j], a_j)$ denote the state transition probability function, which gives the probability that u_j moves from a state (e_j, ζ_j) to another state (e'_j, ζ'_j) after taking an action a_j.

TABLE 1: Summary of notations.

notation	definition
$\hat{\mathcal{U}}, \hat{\mathcal{U}}_{\mathrm{D}}, \hat{\mathcal{U}}_{\mathrm{N}}$	sets of total/downlink/idle UEs
$\hat{\mathcal{U}}_{\mathtt{pr}}, \hat{\mathcal{U}}_{\mathtt{rh}}, \hat{\mathcal{U}}_{\mathtt{mc}}$	sets of poor/rich/middle-class UEs
$\omega_{b,i}$, $\lambda_{b,i}$, $\sigma_{b,i}$	bandwidth, rate, and SINR of a UE u_i from the BS
σ_i^Q	smallest SINR to meet u_i's QoS demand
$\sigma_{\mathtt{th}}$	SINR threshold to check if a UE is poor
$p_{j,i}$	u_j's power to relay data to u_i ($p_{\min} \leq p_{j,i} \leq p_{\max}$)
e_i	amount of budget energy of u_i
ζ_i	number of tokens owned by u_i (initial tokens: ζ_{ini})
$T_{\mathrm{S}}, T_{\mathrm{C}}$	lengths of scheduling/circulating periods ($T_{\mathrm{S}} < T_{\mathrm{C}}$)
Γ	number of tokens taxed from UEs
$\zeta_{\mathtt{pr}}$	token threshold on judging poor UEs ($\zeta_{\mathtt{pr}} \in \mathbb{Z}^+$)
$\alpha_{\mathtt{rh}}$	token threshold on judging rich UEs ($0 < \alpha_{\mathtt{rh}} < 1$)
$\delta_{\mathtt{hi}}$, $\delta_{\mathtt{lo}}$	high/low tax rates ($\delta_{\mathtt{hi}} > \delta_{\mathtt{lo}}$)
Λ	difference between u_i's tokens and initial tokens

Given the probability ν_j that u_j wants help from a relay node, the state transition probability function is defined as follows:

$$\bar{P}([e'_j, \zeta'_j] \,|\, [e_j, \zeta_j], a_j) = \begin{cases} \nu_j e_j \tilde{I}_{\{\zeta_j>0, e_j>0\}}, & \text{if } \zeta'_j = \zeta_j - 1, e'_j = e_j \\ \mu_j a_j \tilde{I}_{\{e_j>0\}}, & \text{if } \zeta'_j = \zeta_j + 1, e'_j = e_j - e_i^{\mathrm{R}} \\ 1 - \nu_j e_j \tilde{I}_{\{\zeta_j>0, e_j>0\}} & \\ \quad - \mu_j a_j \tilde{I}_{\{e_j>0\}}, & \text{if } \zeta'_j = \zeta_j, e'_j = e_j \\ 0, & \text{otherwise.} \end{cases} \tag{11}$$

Due to page limitation, we leave the detail in [37].

In essence, our TC strategies adjust the number of tokens owned by UEs (by taxation and subsidies), so they are independent of the judgement method. In other words, the proposed TC strategies can still work well on different judgement methods.

3.5 The Miser Problem

Normally, UEs will not serve as relay nodes if they run out of budget energy (i.e., $e_j = 0$) or have too many tokens. On the contrary, a miser is very keen to collect tokens, so it *unconditionally* offers relay services to neighboring UEs (i.e., without considering other factors like energy) as long as they can pay tokens. The miser could be equipped with external power supply (e.g., power bank or wire) to have very large budget energy. Moreover, the miser never spends tokens on buying relay services from other UEs. Eventually, most neighbors of the miser will have very few tokens, which forms a poor region as shown in Fig. 1. In this case, these UEs have no choice but using the cellular mode to get data, resulting in low throughput.

Even if there exist only few misers, they can roam in the cell and create many poor regions. In this way, the overall negotiable tokens will become fewer and fewer, until most UEs cannot afford relay services, thereby spoiling a TBI mechanism. One may suggest asking the BS to regularly replenish tokens to UEs. However, this solution has a side effect of *token inflation*, which devaluates tokens and also causes damage to the TBI mechanism.

It is worth noting that misers neither tamper messages (e.g., try to gain free tokens or falsify states of other UEs) nor cheat requestors by giving them fake parameters in relay replies (i.e., $p_{j,i}$ and $\sigma_{b,j}$). In other words, they seek to destroy TBI mechanisms under the guise of legitimate acts. Thus, cryptographic methods (e.g., authentication by the public-key cryptography) cannot solve the miser problem.

Algorithm 1: Passive TC Strategy

```
1  $\Gamma \leftarrow 0$ and $\hat{\mathcal{U}}_{\mathtt{pr}} \leftarrow \emptyset$;
2  foreach $u_i \in \hat{\mathcal{U}}$ do
3      $\zeta_i \leftarrow \zeta_i - \lceil \delta_{\mathtt{hi}} \times \zeta_i \rceil$;
4      $\Gamma \leftarrow \Gamma + \lceil \delta_{\mathtt{hi}} \times \zeta_i \rceil$;
5      if $\sigma_{b,i} < \sigma_{\mathtt{th}}$ and $\zeta_i < \zeta_{\mathtt{pr}}$ then
6          $\hat{\mathcal{U}}_{\mathtt{pr}} \leftarrow \hat{\mathcal{U}}_{\mathtt{pr}} \cup \{u_i\}$;
7  if $\hat{\mathcal{U}}_{\mathtt{pr}} \neq \emptyset$ then
8      Call Subsidy($\hat{\mathcal{U}}_{\mathtt{pr}}$, $\Gamma$) to give taxed tokens to UEs in $\hat{\mathcal{U}}_{\mathtt{pr}}$;
9  else
10     foreach $u_i \in \hat{\mathcal{U}}$ do
11         $\zeta_i \leftarrow \zeta_i + \lceil \delta_{\mathtt{hi}} \times \zeta_i \rceil$;
```

Procedure Subsidy($\hat{\mathcal{U}}_{\mathtt{pr}}$, Γ)

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1  $\zeta_{\mathtt{sub}} \leftarrow \lfloor \Gamma / |\hat{\mathcal{U}}_{\mathtt{pr}}| \rfloor$;
2  if $\zeta_{\mathtt{sub}} > 0$ then
3      foreach $u_i \in \hat{\mathcal{U}}_{\mathtt{pr}}$ do
4          $\zeta_i \leftarrow \zeta_i + \zeta_{\mathtt{sub}}$;
5          $\Gamma \leftarrow \Gamma - \zeta_{\mathtt{sub}}$;
6  if $\Gamma > 0$ then
7      Sort UEs in $\hat{\mathcal{U}}_{\mathtt{pr}}$ by their $\zeta_i$ values increasingly;
8      foreach $u_i \in \hat{\mathcal{U}}_{\mathtt{pr}}$ do
9          $\zeta_i \leftarrow \zeta_i + 1$;
10         $\Gamma \leftarrow \Gamma - 1$;
11         if $\Gamma = 0$ then
12             return;
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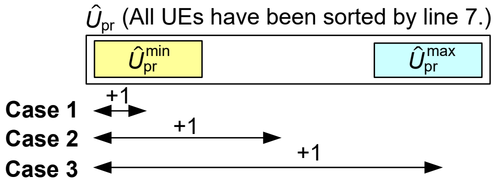

Fig. 2: Three cases considered in the proof of Theorem 1, where double-headed arrows indicate the UEs in $\hat{\mathcal{U}}_{\mathtt{pr}}$ that are given extra tokens by lines 8–12 in the Subsidy procedure.

To conquer the miser problem, we should help the BS efficiently redistribute tokens to UEs with three objectives: 1) preventing misers from hoarding tokens, 2) making most UEs afford to buy relay services, and 3) stabilizing the number of tokens in the cell (to avoid inflation or deflation of tokens). In this way, tokens can be effectively circulated among UEs, thereby protecting TBI mechanisms. Table 1 summarizes our notations.

4 TOKEN CIRCULATION (TC) STRATEGIES

When a UE u_i is newly added to $\hat{\mathcal{U}}$ (e.g., u_i just handovers to the cell, or it is booted up), the BS gives it ζ_{ini} initial tokens as starting. If u_i wants other UEs to relay its data, u_i has to pay tokens to them. Except for the initial tokens, u_i can get extra tokens in two ways: 1) providing the relay service for others and 2) the subsidy from the BS (through a TC strategy). Once u_i uses up tokens, it can only adopt the cellular mode to receive data right from the BS.

To efficiently solve the miser problem, we propose three TC strategies, called *passive*, *active*, and *hybrid* strategies. The idea is to collect a portion of tokens from some UEs as tax and then redistribute these tokens to UEs in need. The BS performs a TC strategy every *circulating period* whose length is T_{C}. Specifically, T_{C} should be a multiple of T_{S} (i.e., the length of a scheduling period) to avoid disturbing the operation of token trade. For example, T_{C} can be set to $10T_{\text{S}}$. Below, we elaborate on each TC strategy. Afterward, we discuss these strategies and also how to deal with the case when a UE leaves the cell.

4.1 Passive TC Strategy

The passive TC strategy taxes every UE with the same rate and uses these taxes to subsidize poor UEs, where Algo. 1 presents its pseudocode. Let Γ be the number of tokens taxed from UEs and $\hat{\mathcal{U}}_{\mathtt{pr}}$ be the set of poor UEs. For each UE u_i in $\hat{\mathcal{U}}$, it has to pay $\lceil \delta_{\mathtt{hi}} \times \zeta_i \rceil$ tokens to the BS, where $\delta_{\mathtt{hi}}$ is the tax rate and $0 < \delta_{\mathtt{hi}} \leq 0.5$, as shown in lines 3–4. Then, line 5 checks if the UE belongs to $\hat{\mathcal{U}}_{\mathtt{pr}}$. More concretely, u_i is viewed as a poor UE if 1) its SINR $\sigma_{b,i}$ from the BS is lower than a threshold $\sigma_{\mathtt{th}}$, where

$$\sigma_{\mathtt{th}} < \min_{\forall u_j \in \hat{\mathcal{U}}} \sigma_j^Q, \tag{12}$$

and 2) it has fewer than $\zeta_{\mathtt{pr}}$ tokens, where $\zeta_{\mathtt{pr}} \in \mathbb{Z}^+$. There are two meanings behind Eq. (12). First, u_i cannot fulfill its QoS demand by using the cellular mode to receive data. In other words, u_i has to choose the relay mode. Second, since u_i's signal quality from the BS is bad, no one will ask u_i to be its relay node. Thus, u_i cannot earn tokens from others. When both conditions are met, u_i thirsts for D2D relay but it does not have enough tokens to buy the service, and this situation will last for a while (until u_i can improve its signal quality and start earning tokens by providing the relay service). Thus, u_i is added to $\hat{\mathcal{U}}_{\mathtt{pr}}$ by line 6. Then, the BS allots the taxed tokens to poor UEs to help them obtain relay services, which is done by the *Subsidy* procedure. However, once $\hat{\mathcal{U}}_{\mathtt{pr}}$ is empty (i.e., no poor UE), the BS gives the taxed tokens back to each UE in $\hat{\mathcal{U}}$, as shown in lines 9–11.

The Subsidy procedure aims to fairly deal out taxed tokens to the UEs in $\hat{\mathcal{U}}_{\mathtt{pr}}$. Since the BS has collected Γ tokens, each poor UE can obtain $\lfloor \Gamma / |\hat{\mathcal{U}}_{\mathtt{pr}}| \rfloor$ ($= \zeta_{\mathtt{sub}}$) tokens, where $|\hat{\mathcal{U}}_{\mathtt{pr}}|$ denotes the number of UEs in $\hat{\mathcal{U}}_{\mathtt{pr}}$. The code is given in lines 1–5. In case that Γ is not dividable by $|\hat{\mathcal{U}}_{\mathtt{pr}}|$, the BS allots residual tokens (after line 5) in a round-robin manner. Specifically, line 7 sorts all poor UEs based on their ζ_i values in ascending order. Then, each UE in $\hat{\mathcal{U}}_{\mathtt{pr}}$ is given one token, until Γ decreases down to zero, as shown in lines 8–12. Let us define the *maximum wealth gap (MWG)* of a set of UEs to be the difference between the number of tokens of the richest UE and that of the poorest UE in the set. Theorem 1 shows that the MWG of $\hat{\mathcal{U}}_{\mathtt{pr}}$ is bounded by a small constant after dealing out taxed tokens by the Subsidy procedure, which implies that no poor UE will be starved. Thus, the gap between rich and poor can be reduced. Lemma 1 then analyzes the time complexity of the Subsidy procedure.

Theorem 1. By using the Subsidy procedure, the MWG of $\hat{\mathcal{U}}_{\mathtt{pr}}$ is no more than $(\zeta_{pr} - 1)$ if $\zeta_{pr} > 1$ or one otherwise.

Proof: Suppose that $\zeta_{\mathtt{pr}} > 1$. Since a necessary condition for poor UEs is $\zeta_i < \zeta_{\mathtt{pr}}$, the number of tokens of any UE in $\hat{\mathcal{U}}_{\mathtt{pr}}$ before running the Subsidy procedure is within the range of $[0, \zeta_{\mathtt{pr}} - 1]$. Then, in lines 3–5 of the Subsidy procedure, each UE in $\hat{\mathcal{U}}_{\mathtt{pr}}$ is given $\zeta_{\mathtt{sub}}$ tokens, so the MWG of $\hat{\mathcal{U}}_{\mathtt{pr}}$ is $\max_{\forall u_i \in \hat{\mathcal{U}}_{\mathtt{pr}}} \zeta_i - \min_{\forall u_i \in \hat{\mathcal{U}}_{\mathtt{pr}}} \zeta_i \leq (\zeta_{\mathtt{pr}} - 1 + \zeta_{\mathtt{sub}}) - \zeta_{\mathtt{sub}} = \zeta_{\mathtt{pr}} - 1$. Let us denote by $\hat{\mathcal{U}}^{\min}_{\mathtt{pr}}$ and $\hat{\mathcal{U}}^{\max}_{\mathtt{pr}}$ the subsets of the poorest UEs and the richest UEs in $\hat{\mathcal{U}}_{\mathtt{pr}}$ right after running lines 1–5, respectively. Then, there are three cases to be discussed for the code in lines 6–12, as shown in Fig. 2.

Case 1: Some (but not all) UEs in $\hat{\mathcal{U}}^{\min}_{\mathtt{pr}}$ are given extra tokens. Since a subset of UEs in $\hat{\mathcal{U}}^{\min}_{\mathtt{pr}}$ do not get extra tokens, the number of tokens owned by the poorest and richest UEs will not change. Thus, the MWG of $\hat{\mathcal{U}}_{\mathtt{pr}}$ is still no more than $\zeta_{\mathtt{pr}} - 1$.

Case 2: All UEs in $\hat{\mathcal{U}}^{\min}_{\mathtt{pr}}$ are given extra tokens but no UE in $\hat{\mathcal{U}}^{\max}_{\mathtt{pr}}$ gets extra tokens. In this case, each UE in $\hat{\mathcal{U}}^{\min}_{\mathtt{pr}}$ can get one extra token, so we have $\max_{\forall u_i \in \hat{\mathcal{U}}_{\mathtt{pr}}} \zeta_i - \min_{\forall u_i \in \hat{\mathcal{U}}_{\mathtt{pr}}} \zeta_i \leq (\zeta_{\mathtt{pr}} - 1 + \zeta_{\mathtt{sub}}) - (\zeta_{\mathtt{sub}} + 1) = \zeta_{\mathtt{pr}} - 2$.

Case 3: Some (but not all) UEs in $\hat{\mathcal{U}}^{\max}_{\mathtt{pr}}$ get extra tokens. As some richest UEs each obtains an extra token, we have $\max_{\forall u_i \in \hat{\mathcal{U}}_{\mathtt{pr}}} \zeta_i - \min_{\forall u_i \in \hat{\mathcal{U}}_{\mathtt{pr}}} \zeta_i \leq (\zeta_{\mathtt{pr}} - 1 + \zeta_{\mathtt{sub}} + 1) - (\zeta_{\mathtt{sub}} + 1) = \zeta_{\mathtt{pr}} - 1$.

By summing up the above three cases, the MWG of $\hat{\mathcal{U}}_{\mathtt{pr}}$ is at most $(\zeta_{\mathtt{pr}} - 1)$ if $\zeta_{\mathtt{pr}} > 1$, so this part is proven.

When $\zeta_{\mathtt{pr}} = 1$, every UE in $\hat{\mathcal{U}}_{\mathtt{pr}}$ has exactly $\zeta_{\mathtt{sub}}$ tokens before running line 6. Since $\Gamma < |\hat{\mathcal{U}}_{\mathtt{pr}}|$, based on lines 8–12, some UEs in $\hat{\mathcal{U}}_{\mathtt{pr}}$ each can obtain one extra token but others cannot. Thus, $\hat{\mathcal{U}}_{\mathtt{pr}}$'s MWG is no more than one, thereby proving the other part. □

Lemma 1. Given ξ_{pr} UEs in $\hat{\mathcal{U}}_{pr}$, the time complexity of the Subsidy procedure is $O(\xi_{pr} \log_2 \xi_{pr})$.

Proof: Lines 1 and 2 require $O(1)$ time. Then, the for-loop in lines 3–5 spends $O(\xi_{\mathtt{pr}})$ time. It takes $O(\xi_{\mathtt{pr}} \log_2 \xi_{\mathtt{pr}})$ time to sort all UEs in $\hat{\mathcal{U}}_{\mathtt{pr}}$ by line 7. After that, the for-loop in lines 8–12 spends no more than $O(\xi_{\mathtt{pr}})$ time. Thus, the total time complexity is $O(1) + O(\xi_{\mathtt{pr}}) + O(\xi_{\mathtt{pr}} \log_2 \xi_{\mathtt{pr}}) + O(\xi_{\mathtt{pr}}) = O(\xi_{\mathtt{pr}} \log_2 \xi_{\mathtt{pr}})$. □

Theorem 2 shows that the passive TC strategy makes the number of tokens in the cell stable. Theorem 3 estimates its time complexity.

Theorem 2. If $\hat{\mathcal{U}}$ does not change, the number of tokens owned by all UEs in $\hat{\mathcal{U}}$ remains constant after running the passive TC strategy.

Proof: In Algo. 1, every UE in $\hat{\mathcal{U}}$ is taxed a number $\lceil \delta_{\mathtt{hi}} \times \zeta_i \rceil$ of tokens. Since the value of $\delta_{\mathtt{hi}}$ is between 0 and 0.5, no UE will pay more tokens than it has (i.e., ζ_i will never become negative for any UE $u_i \in \hat{\mathcal{U}}$). Based on lines 3 and 4, whenever a UE pays $\lceil \delta_{\mathtt{hi}} \times \zeta_i \rceil$ tokens to the BS, the same number of tokens is added to Γ. Thus, Γ must record the total number of tokens collected from all UEs in $\hat{\mathcal{U}}$. Then, there are two cases to be discussed.

Case 1: If-statement in lines 7–8. The Subsidy procedure is used to deal out the taxed tokens to poor UEs. Observing the procedure's code, lines 4–5 and lines 9–10 imply that when the BS gives some tokens to a UE, the same number of tokens will be deducted from Γ. Moreover, the Subsidy procedure will terminate only when $\Gamma = 0$ (i.e., line 11). In other words, the BS must fully allocate the taxed tokens to each UE in $\hat{\mathcal{U}}_{\mathtt{pr}}$ and never reserves any token. Thus, the number of tokens owned by all UEs in the cell can keep constant.

Algorithm 2: Active TC Strategy

```
1  $\Omega \leftarrow 0$;
2  foreach $u_i \in \hat{\mathcal{U}}$ do
3      $\Omega \leftarrow \Omega + \zeta_i$;
4  $\hat{\mathcal{U}}_{\mathtt{rh}} \leftarrow \emptyset$ and $\hat{\mathcal{U}}_{\mathtt{pr}} \leftarrow \emptyset$;
5  foreach $u_i \in \hat{\mathcal{U}}$ do
6      if $\zeta_i / \Omega > \alpha_{\mathtt{rh}}$ then
7          $\hat{\mathcal{U}}_{\mathtt{rh}} \leftarrow \hat{\mathcal{U}}_{\mathtt{rh}} \cup \{u_i\}$;
8      else if $\sigma_{b,i} < \sigma_{\mathtt{th}}$ and $\zeta_i < \zeta_{\mathtt{pr}}$ then
9          $\hat{\mathcal{U}}_{\mathtt{pr}} \leftarrow \hat{\mathcal{U}}_{\mathtt{pr}} \cup \{u_i\}$;
10 if $\hat{\mathcal{U}}_{\mathtt{rh}} \neq \emptyset$ and $\hat{\mathcal{U}}_{\mathtt{pr}} \neq \emptyset$ then
11     $\Gamma \leftarrow 0$;
12     foreach $u_i \in \hat{\mathcal{U}}_{\mathtt{rh}}$ do
13         $\zeta_i \leftarrow \zeta_i - \lceil \delta_{\mathtt{hi}} \times \zeta_i \rceil$;
14         $\Gamma \leftarrow \Gamma + \lceil \delta_{\mathtt{hi}} \times \zeta_i \rceil$;
15     Call Subsidy($\hat{\mathcal{U}}_{\mathtt{pr}}$, $\Gamma$);
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Case 2: Else-statement in lines 9–11. When $\hat{\mathcal{U}}_{\mathtt{pr}} = \emptyset$, the BS returns the taxed tokens to UEs in $\hat{\mathcal{U}}$. Specifically, a UE $u_i \in \hat{\mathcal{U}}$ gives $\lceil \delta_{\mathtt{hi}} \times \zeta_i \rceil$ tokens to the BS in line 3, and it can get back $\lceil \delta_{\mathtt{hi}} \times \zeta_i \rceil$ tokens by line 11. Thus, the number of tokens owned by every UE remains constant in this case.

By summing up the two cases, this theorem is proven. □

Theorem 3. Let $|\hat{\mathcal{U}}| = \xi$ and $|\hat{\mathcal{U}}_{pr}| = \xi_{pr}$. Algo. 1 takes time of $O(\xi) + \max\{O(\xi_{pr} \log_2 \xi_{pr}), O(\xi)\}$ in the worst case.

Proof: Line 1 takes $O(1)$ time to initialize Γ and $\hat{\mathcal{U}}_{\mathtt{pr}}$. In lines 3–6, each statement also takes $O(1)$ time (including line 5, as $\sigma_{\mathtt{th}}$ and $\zeta_{\mathtt{pr}}$ are constants). Thus, this loop spends $O(\xi)$ time. According to Lemma 1, the if-statement in lines 7–8 takes $O(\xi_{\mathtt{pr}} \log_2 \xi_{\mathtt{pr}})$ time. The else-statement in lines 9–11 requires $O(\xi)$ time. Since these two statements are mutually exclusive, the code in lines 7–11 takes time of $\max\{O(\xi_{\mathtt{pr}} \log_2 \xi_{\mathtt{pr}}), O(\xi)\}$. Therefore, the time complexity of Algo. 1 is $O(1) + O(\xi) + \max\{O(\xi_{\mathtt{pr}} \log_2 \xi_{\mathtt{pr}}), O(\xi)\} = O(\xi) + \max\{O(\xi_{\mathtt{pr}} \log_2 \xi_{\mathtt{pr}}), O(\xi)\}$. □

The passive TC strategy is easy to operate, since the BS simply taxes every UE in $\hat{\mathcal{U}}$ with an equal rate $\delta_{\mathtt{hi}}$ and only needs to identify poor UEs (i.e., $\hat{\mathcal{U}}_{\mathtt{pr}}$). However, when $\zeta_{\mathtt{ini}}$ is small, most UEs are given very few initial tokens and thus poor. By collecting taxes from the poor and dealing out the taxed tokens to them, most UEs actually do not get extra tokens and are still poor. In this case, the performance of the passive TC strategy would degrade.

4.2 Active TC Strategy

Instead of taxing every UE, the active TC strategy will tax the rich to subsidize the poor. Algo. 2 presents its pseudocode. In lines 1–3, we count the total number of tokens in the cell, whose result is stored in Ω. Let $\hat{\mathcal{U}}_{\mathtt{rh}} \subseteq \hat{\mathcal{U}}$ be the set of rich UEs. A UE u_i is considered a rich UE if the following condition is met:

$$\zeta_i / \Omega > \alpha_{\mathtt{rh}}, \tag{13}$$

where $0 < \alpha_{\mathtt{rh}} < 1\%$. The meaning behind Eq. (13) is that u_i owns more than $\alpha_{\mathtt{rh}}$ percentages of tokens in the cell, thereby causing wealth inequality. In this case, there is a good possibility that u_i is a miser. Here, an intuitive method to judge whether a UE is rich is to check if the number of its tokens overtakes a threshold. However, finding a good threshold is not easy, as it highly depends on the number of initial tokens (i.e., ζ_{ini}) given to each UE. That is why we choose to adopt the percentage $\alpha_{\mathtt{rh}}$. Then, the for-loop in lines 5–9 classifies UEs in $\hat{\mathcal{U}}$, where the if-statement in lines 6–7 picks rich UEs, while the else-if-statement in lines 8–9 finds poor UEs.

The residual code performs the circulation of tokens between $\hat{\mathcal{U}}_{\mathtt{rh}}$ (i.e., rich UEs) and $\hat{\mathcal{U}}_{\mathtt{pr}}$ (i.e., poor UEs). If any of them is empty, there is no need to do token circulation and this algorithm terminates by line 10. Otherwise, each rich UE in $\hat{\mathcal{U}}_{\mathtt{rh}}$ pays $\lceil \delta_{\mathtt{hi}} \times \zeta_i \rceil$ tokens to the BS as tax (i.e., the same tax rate with the passive TC strategy). The code is given in lines 12–14. Finally, line 15 uses the Subsidy procedure to distribute the taxed tokens among poor UEs in $\hat{\mathcal{U}}_{\mathtt{pr}}$. Theorem 4 proves that the active TC strategy neither increases nor decreases tokens in the cell. Theorem 5 analyzes its time complexity.

Theorem 4. The number of tokens of all UEs in a cell will not change by running the active TC strategy when $\hat{\mathcal{U}}$ stays the same.

Proof: Algo. 2 is composed of two parts. The first part (i.e., lines 1–9) identifies all rich and poor UEs in $\hat{\mathcal{U}}$. Based on the for-loop in lines 5–9, $\hat{\mathcal{U}}_{\mathtt{rh}}$ (i.e., rich UEs) and $\hat{\mathcal{U}}_{\mathtt{pr}}$ (i.e., poor UEs) have no intersection. Thus, any UE u_i can be in exactly one of the three states: 1) paying tax to the BS if $u_i \in \hat{\mathcal{U}}_{\mathtt{rh}}$, 2) getting the subsidy from the BS if $u_i \in \hat{\mathcal{U}}_{\mathtt{pr}}$, and 3) doing nothing if $u_i \in \hat{\mathcal{U}} \setminus (\hat{\mathcal{U}}_{\mathtt{rh}} \cup \hat{\mathcal{U}}_{\mathtt{pr}})$.

The second part (i.e., lines 10–15) transfers tokens from the rich to the poor. Lines 13 and 14 together make sure that Γ will record the total number of tokens collected from all UEs in $\hat{\mathcal{U}}_{\mathtt{rh}}$. As mentioned in Theorem 2, the Subsidy procedure must deal out all taxed tokens to poor UEs in $\hat{\mathcal{U}}_{\mathtt{pr}}$. Thus, no token will be lost (or reserved) in the above circulation, which verifies this theorem. □

Theorem 5. Given ξ UEs in $\hat{\mathcal{U}}$ and ξ_{pr} UEs in $\hat{\mathcal{U}}_{\mathtt{pr}}$, Algo. 2 spends time of $2O(\xi) + O(\xi_{pr} \log_2 \xi_{pr})$.

Proof: In lines 1, 4, and 11, it takes $O(1)$ time to do initialization. The 1st for-loop in lines 2–3 takes $O(\xi)$ time. The 2nd for-loop in lines 5–9 also uses $O(\xi)$ time. Suppose that there are $\xi_{\mathtt{rh}}$ rich UEs in $\hat{\mathcal{U}}_{\mathtt{rh}}$. The 3rd for-loop in lines 12–14 requires $O(\xi_{\mathtt{rh}})$ time. By Lemma 1, the Subsidy procedure takes $O(\xi_{\mathtt{pr}} \log_2 \xi_{\mathtt{pr}})$ time. Since $\xi_{\mathtt{rh}} < \xi$, the overall time complexity is $O(1) + O(\xi) + O(\xi) + O(\xi_{\mathtt{rh}}) + O(\xi_{\mathtt{pr}} \log_2 \xi_{\mathtt{pr}}) = 2O(\xi) + O(\xi_{\mathtt{pr}} \log_2 \xi_{\mathtt{pr}})$. □

Unlike the passive TC strategy that taxes each UE in $\hat{\mathcal{U}}$, the active TC strategy asks only rich UEs, which are likely misers, to be taxpayers. Besides, there is no need to return taxed tokens to their owners when $\hat{\mathcal{U}}_{\mathtt{pr}} = \emptyset$ (i.e., lines 9–11 in Algo. 1). However, this strategy may have poor performance with too many misers, since more misers compete for the tokens of non-misers. In this case, each miser would not collect lots of tokens and pay less tax. Thus, the amount of subsidy (i.e., Γ) reduces, thereby degrading performance.

4.3 Hybrid TC Strategy

The hybrid TC strategy combines both passive and active TC strategies. Algo. 3 gives its pseudocode, which is similar to Algo. 2, except for three differences:

Algorithm 3: Hybrid TC Strategy

```
1  $\Omega \leftarrow 0$;
2  foreach $u_i \in \hat{\mathcal{U}}$ do
3      $\Omega \leftarrow \Omega + \zeta_i$;
4  $\hat{\mathcal{U}}_{\mathtt{rh}} \leftarrow \emptyset$, $\hat{\mathcal{U}}_{\mathtt{pr}} \leftarrow \emptyset$, and $\hat{\mathcal{U}}_{\mathtt{mc}} \leftarrow \emptyset$;
5  foreach $u_i \in \hat{\mathcal{U}}$ do
6      if $\zeta_i / \Omega > \alpha_{\mathtt{rh}}$ then
7          $\hat{\mathcal{U}}_{\mathtt{rh}} \leftarrow \hat{\mathcal{U}}_{\mathtt{rh}} \cup \{u_i\}$;
8      else if $\sigma_{b,i} < \sigma_{\mathtt{th}}$ and $\zeta_i < \zeta_{\mathtt{pr}}$ then
9          $\hat{\mathcal{U}}_{\mathtt{pr}} \leftarrow \hat{\mathcal{U}}_{\mathtt{pr}} \cup \{u_i\}$;
10     else
11         $\hat{\mathcal{U}}_{\mathtt{mc}} \leftarrow \hat{\mathcal{U}}_{\mathtt{mc}} \cup \{u_i\}$;
12 if $\hat{\mathcal{U}}_{\mathtt{pr}} \neq \emptyset$ then
13     $\Gamma \leftarrow 0$;
14     foreach $u_i \in \hat{\mathcal{U}}_{\mathtt{rh}}$ do
15         $\zeta_i \leftarrow \zeta_i - \lceil \delta_{\mathtt{hi}} \times \zeta_i \rceil$;
16         $\Gamma \leftarrow \Gamma + \lceil \delta_{\mathtt{hi}} \times \zeta_i \rceil$;
17     foreach $u_i \in \hat{\mathcal{U}}_{\mathtt{pr}} \cup \hat{\mathcal{U}}_{\mathtt{mc}}$ do
18         $\zeta_i \leftarrow \zeta_i - \lceil \delta_{\mathtt{lo}} \times \zeta_i \rceil$;
19         $\Gamma \leftarrow \Gamma + \lceil \delta_{\mathtt{lo}} \times \zeta_i \rceil$;
20     Call Subsidy($\hat{\mathcal{U}}_{\mathtt{pr}}$, $\Gamma$);
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Lines 4, 10, 11: We introduce one new category of UEs, called *middle-class UEs*. Let $\hat{\mathcal{U}}_{\mathtt{mc}}$ be the set of such UEs. If a UE is neither rich (i.e., checked by line 6) nor poor (i.e., checked by line 8), it is added to $\hat{\mathcal{U}}_{\mathtt{mc}}$ in line 11.

Line 12: As compared with line 10 in Algo. 2, the hybrid TC strategy will perform token circulation by checking only the condition of $\hat{\mathcal{U}}_{\mathtt{pr}} \neq \emptyset$. In other words, even if there is no rich UE (i.e., $\hat{\mathcal{U}}_{\mathtt{rh}} = \emptyset$), this strategy will still perform circulation of tokens.

Lines 17–19: Like the passive TC strategy in Algo. 1, non-rich UEs are also taxed. However, they have a lower tax rate $\delta_{\mathtt{lo}}$, where $0 < \delta_{\mathtt{lo}} < \delta_{\mathtt{hi}}$. Note that we do not differentiate the tax rates of middle-class UEs and poor UEs. The reason is that some middle-class UEs may have a similar number of tokens with poor UEs (i.e., $\zeta_i < \zeta_{\mathtt{pr}}$) but they have better signal quality (i.e., $\sigma_{b,i} \geq \sigma_{\mathtt{th}}$). In this case, using different tax rates for middle-class UEs and poor UEs cannot have significant effect.

Theorem 6 shows that the hybrid TC strategy can keep a fixed number of tokens and Theorem 7 analyzes its time complexity.

Theorem 6. If $\hat{\mathcal{U}}$ is not modified, the number of tokens of all UEs in a cell is maintained constant with the hybrid TC strategy.

Proof: In Algo. 3, the for-loop in lines 5–11 divides $\hat{\mathcal{U}}$ into three disjointed subsets $\hat{\mathcal{U}}_{\mathtt{rh}}$, $\hat{\mathcal{U}}_{\mathtt{pr}}$, and $\hat{\mathcal{U}}_{\mathtt{mc}}$. Thus, each UE can be in only one subset and taxed with a single rate. The for-loop in lines 14–16 makes each rich UE in $\hat{\mathcal{U}}_{\mathtt{rh}}$ pay $\lceil \delta_{\mathtt{hi}} \times \zeta_i \rceil$ tokens to the BS, which is faithfully recorded in Γ. Besides, the for-loop in lines 17–19 makes each poor UE in $\hat{\mathcal{U}}_{\mathtt{pr}}$ and each middle-class UE in $\hat{\mathcal{U}}_{\mathtt{mc}}$ pay $\lceil \delta_{\mathtt{lo}} \times \zeta_i \rceil$ tokens to the BS, and the equal number of tokens are added to Γ. After that, the Subsidy procedure in line 20 deals out the taxed tokens to UEs in $\hat{\mathcal{U}}_{\mathtt{pr}}$.

Since the BS does not add extra tokens to Γ, the total number of tokens remains constant. □

Theorem 7. Suppose that there are ξ UEs in a cell, of which ξ_{pr} UEs are poor. Algo. 3 requires time of $3O(\xi) + O(\xi_{pr}\log_2\xi_{pr})$.

Proof: Doing initialization by lines 1, 4, and 13 takes $O(1)$ time. The 1st for-loop in lines 2–3 consumes $O(\xi)$ time. The 2nd for-loop in lines 5–11 also spends $O(\xi)$ time. Suppose that $\hat{\mathcal{U}}_{\text{rh}}$ contains ξ_{rh} UEs. The 3rd for-loop in lines 14–16 takes $O(\xi_{\text{rh}})$ time, and the 4th for-loop in lines 17–19 requires $O(\xi - \xi_{\text{rh}})$ time. According to Lemma 1, line 20 spends $O(\xi_{\text{pr}}\log_2\xi_{\text{pr}})$ time. To sum up, the total time complexity is $O(1) + O(\xi) + O(\xi) + O(\xi_{\text{rh}}) + O(\xi - \xi_{\text{rh}}) + O(\xi_{\text{pr}}\log_2\xi_{\text{pr}}) = 3O(\xi) + O(\xi_{\text{pr}}\log_2\xi_{\text{pr}})$. □

4.4 Discussion

In the TC strategies, the BS taxes parts of (i.e., active) or all (i.e., passive and hybrid) UEs and deals out the taxed tokens to poor UEs in $\hat{\mathcal{U}}_{\text{pr}}$ by the Subsidy procedure. One may wonder whether some UEs in $\hat{\mathcal{U}}_{\text{pr}}$ will become lazy, where they can get free tokens from the BS without providing relay services to others. The answer is no, because each UE in $\hat{\mathcal{U}}_{\text{pr}}$ is *involuntarily poor*, which is shown in Theorem 8. Thus, the BS does subsidize those UEs in need. When a UE is capable of earning tokens from neighbors (i.e., its channel quality improves), the BS will stop subsidizing that UE.

Theorem 8. Each UE $u_i \in \hat{\mathcal{U}}_{pr}$ is involuntarily poor, since the only way for u_i to get tokens is the subsidy from the BS.

Proof: We prove this theorem by contradiction. Suppose that except for the BS, a UE $u_i \in \hat{\mathcal{U}}_{\text{pr}}$ can acquire tokens from other places. As discussed in Section 4, the only way for u_i to do so is to sell its relay service to another UE u_j. That means u_i's SINR $\sigma_{b,i}$ can fulfill u_j's QoS demand (i.e., $\sigma_{b,i} \geq \sigma_j^Q > \sigma_{\text{th}}$), or u_j will not choose u_i to be its relay node. As Eq. (12) is violated, u_i will never be included in $\hat{\mathcal{U}}_{\text{pr}}$. Thus, a contradiction occurs and the theorem is proven. □

In Theorems 2, 4, and 6, we show that our proposed TC strategies keep a stable number of tokens in a cell. However, when some UEs leave the cell (e.g., handover), they would take away their tokens, which reduces negotiable tokens in the cell. Thus, we propose an amendment to cope with this situation, whose pseudocode is given in Algo. 4. Suppose that a UE u_i leaves the cell. Depending on the TC strategy, we remove it from the corresponding sets (i.e., $\hat{\mathcal{U}}, \hat{\mathcal{U}}_{\text{pr}}, \hat{\mathcal{U}}_{\text{rh}}$, or $\hat{\mathcal{U}}_{\text{mc}}$), as shown in line 2. Then, a timer T_i is set for u_i in line 3. In case that u_i returns to the cell before timeout (i.e., lines 4–6), it is added to $\hat{\mathcal{U}}$ (but not $\hat{\mathcal{U}}_{\text{pr}}, \hat{\mathcal{U}}_{\text{rh}}$, and $\hat{\mathcal{U}}_{\text{mc}}$, since the TC strategy will do so). The BS gives u_i a number ζ_i of tokens (i.e., its original tokens, instead of ζ_{ini} new tokens).

However, once u_i does not come back before T_i expires, the BS redistributes its tokens to stabilize the total number of tokens in the cell. The code is given in lines 7–19. Let Λ be the difference between the number of u_i's tokens (i.e., ζ_i) and the number of initial tokens (i.e., ζ_{ini}), as shown in line 8. There are three cases to be discussed.

Case I: $\Lambda > 0$ (i.e., lines 9–10). UE u_i takes more tokens from others than it pays. Since u_i will never use its surplus (i.e., $\zeta_i - \zeta_{\text{ini}}$), these tokens are distributed among all other UEs by using the Subsidy procedure (where $\hat{\mathcal{U}}_{\text{pr}}$ is replaced by $\hat{\mathcal{U}}$ in its parameter).

Algorithm 4: Amendment

```
1  if UE $u_i$ leaves the cell then
2      Remove $u_i$ from $\hat{\mathcal{U}}, \hat{\mathcal{U}}_{\text{pr}}, \hat{\mathcal{U}}_{\text{rh}}, \hat{\mathcal{U}}_{\text{mc}}$;
3      Start a timer $T_i$ for $u_i$;
4  if $u_i$ comes back before $T_i$ expires then
5      $\hat{\mathcal{U}} \leftarrow \hat{\mathcal{U}} \cup \{u_i\}$;
6      Give $u_i$ a number $\zeta_i$ of tokens;
7  else
8      $\Lambda \leftarrow \zeta_i - \zeta_{\text{ini}}$;
9      if $\Lambda > 0$ then
10         Deal out $u_i$'s surplus to UEs in $\hat{\mathcal{U}}$ by Subsidy($\hat{\mathcal{U}}$, $\Lambda$);
11     else if $\Lambda < 0$ then
12         Sort UEs in $\hat{\mathcal{U}}$ by their $\zeta_j$ values decreasingly;
13         while $\Lambda < 0$ do
14             foreach $u_j \in \hat{\mathcal{U}}$ do
15                 if $\zeta_j > 0$ then
16                     $\zeta_j \leftarrow \zeta_j - 1$;
17                     $\Lambda \leftarrow \Lambda + 1$;
18                     if $\Lambda = 0$ then
19                         break;
```

Case II: $\Lambda < 0$ (i.e., lines 11–19). Since $\zeta_i < \zeta_{\text{ini}}$, u_i leaves a debt in the cell. Thus, the BS levies extra taxes from other UEs to pay off the debt, so as to keep the total number of tokens stable. To avoid making many UEs poor while maintaining fairness, all UEs are sorted from the richest to the poorest in line 12. After that, each UE is asked to pay one token in a round-robin manner, until the debt Λ becomes zero. The code is given in 13–19.

Case III: $\Lambda = 0$. The BS need not redistribute u_i's tokens, as the number of tokens in the cell keeps stable when u_i leaves the cell.

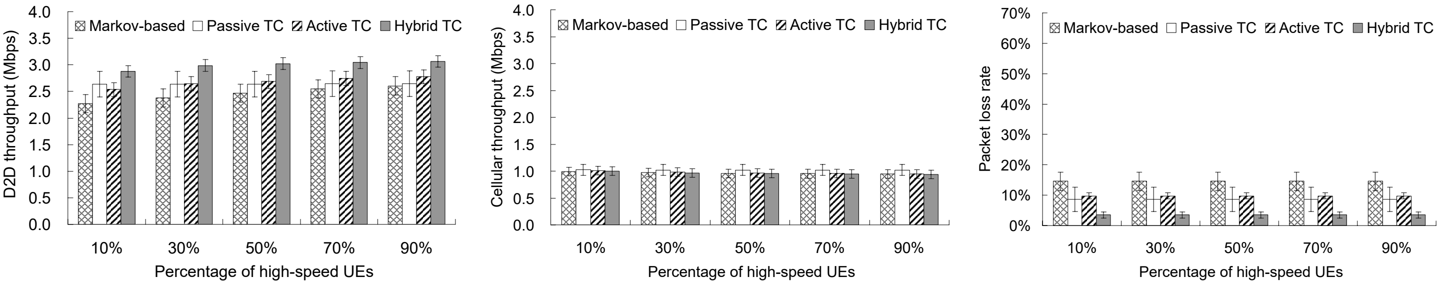
In case II, some UEs may become poor due to the extra tax. However, it does not matter as these UEs will be added to $\hat{\mathcal{U}}_{\text{pr}}$ and compensated by the TC strategies. Theorem 9 shows that the number of tokens in the cell must be stable by using the amendment in Algo. 4. Then, Algo. 10 analyzes its time complexity.

Theorem 9. Given ξ UEs in a cell, the number of tokens owned by them is kept $(\xi \times \zeta_{\text{ini}})$ with Algo. 4 in the long term.

Proof: Suppose that there are $(\xi \times \zeta_{\text{ini}})$ tokens in the cell and one UE u_i that owns ζ_i tokens leaves the cell. If u_i comes back before T_i expires, the BS gives back its original tokens by the code in lines 4–6. In this case, $\hat{\mathcal{U}}$ contains ξ UEs (i.e., including u_i) and the total number of tokens is also $\xi \times \zeta_{\text{ini}}$, which proves this theorem.

Otherwise, $\hat{\mathcal{U}}$ contains $(\xi - 1)$ UEs (i.e., excluding u_i) and the total number of tokens should be reduced to $(\xi - 1) \times \zeta_{\text{ini}}$. Let us observe the three cases. In case I, we have $\Lambda > 0$ and the BS uses the Subsidy procedure to distribute Λ tokens to the UEs in $\hat{\mathcal{U}}$. Thus, the total number of tokens is

$$\sum\nolimits_{\forall u_j \in \hat{\mathcal{U}}} \zeta_j + \Lambda = \sum\nolimits_{\forall u_j \in \hat{\mathcal{U}}} \zeta_j + (\zeta_i - \zeta_{\text{ini}})$$
$$= \sum\nolimits_{\forall u_j \in \hat{\mathcal{U}} \cup \{u_i\}} \zeta_j - \zeta_{\text{ini}} = (\xi \times \zeta_{\text{ini}}) - \zeta_{\text{ini}} = (\xi - 1) \times \zeta_{\text{ini}}.$$



(a) D2D throughput (b) cellular throughput (c) packet loss rate

Fig. 3: System performance under different percentages $\Phi_{\rm h}$ of high-speed UEs.

TABLE 2: Simulation parameters.

parameter	value
General parameters:	
cell radius	2 km
channel bandwidth	10 MHz
number of UEs	3000 (with 100, 600, and 1100 misers)
period length	$T_{\rm S}$ (scheduling): 10 ms, $T_{\rm C}$ (circulating): 100 ms
transmitted power	BS: 46 dBm, UE: 23 dBm
mobility model	random waypoint
Channel-related parameters:	
path loss	BS to UE: $128.1 + 37.6 \log_{10}$ dist(BS, u_i) UE to UE: $148 + 40 \log_{10}$ dist(u_i, u_j)
propagation model	urban macrocell scenario
shadow fading	zero-mean log-normal distribution
thermal noise (N_0)	-174 dBm/Hz
TC-related parameters:	
initial tokens ($\zeta_{\tt ini}$)	1–30
poor UEs	SINR ($\sigma_{\tt th}$): -5.147 dB, token ($\zeta_{\tt pr}$): 2
rich UEs	percentage of tokens ($\alpha_{\tt rh}$): 0.1%
tax rates	high ($\delta_{\tt hi}$): 0.3, low ($\delta_{\tt lo}$): 0.1

In case II, we have $\Lambda < 0$ and the UEs in $\hat{\mathcal{U}}$ are taxed $(\zeta_{\rm ini} - \zeta_i)$ tokens. Thus, the total number of tokens is $\sum_{\forall u_j \in \hat{\mathcal{U}}} \zeta_j - (\zeta_{\rm ini} - \zeta_i) = (\xi - 1) \times \zeta_{\rm ini}$. In case III, we have $\Lambda = 0$, which implies that u_i owns $\zeta_{\rm ini}$ tokens. After u_i leaves the cell, the residual number of tokens in the cell will be $(\xi \times \zeta_{\rm ini}) - \zeta_{\rm ini} = (\xi - 1) \times \zeta_{\rm ini}$. Based on the argument of the three cases, the theorem is proven. □

Theorem 10. Given ξ UEs in $\hat{\mathcal{U}}$, the worst-case time complexity of Algo. 4 is $O(\xi \log_2 \xi) + O(\Lambda)$.

Proof: Each statement in lines 1–8 (except line 2) takes $O(1)$ time. In line 2, removing u_i from $\hat{\mathcal{U}}$ requires $O(\xi)$ time, as we have to search all UEs in $\hat{\mathcal{U}}$ once. Since $\hat{\mathcal{U}}_{\tt pr} \cup \hat{\mathcal{U}}_{\tt rh} \cup \hat{\mathcal{U}}_{\tt mc} = \hat{\mathcal{U}}$, removing u_i from $\hat{\mathcal{U}}_{\tt pr}$, $\hat{\mathcal{U}}_{\tt rh}$, and $\hat{\mathcal{U}}_{\tt mc}$ spends $O(\xi)$ time. The if-statement in lines 9–10 distributes u_i's surplus to the UEs in $\hat{\mathcal{U}}$ by the Subsidy procedure, which takes $O(\xi \log_2 \xi)$ time. The else-if-statement in lines 11–19 sorts $\hat{\mathcal{U}}$ (by line 12) and levies a token from each UE in $\hat{\mathcal{U}}$ in a round-robin manner to pay off debt Λ (by the while-loop in lines 13–19), which takes time of $O(\xi \log_2 \xi) + O(\Lambda)$. Thus, the time complexity is $O(1) + 2O(\xi) + \max\{O(\xi \log_2 \xi), O(\xi \log_2 \xi) + O(\Lambda)\} = O(\xi \log_2 \xi) + O(\Lambda)$. □

5 PERFORMANCE EVALUATION

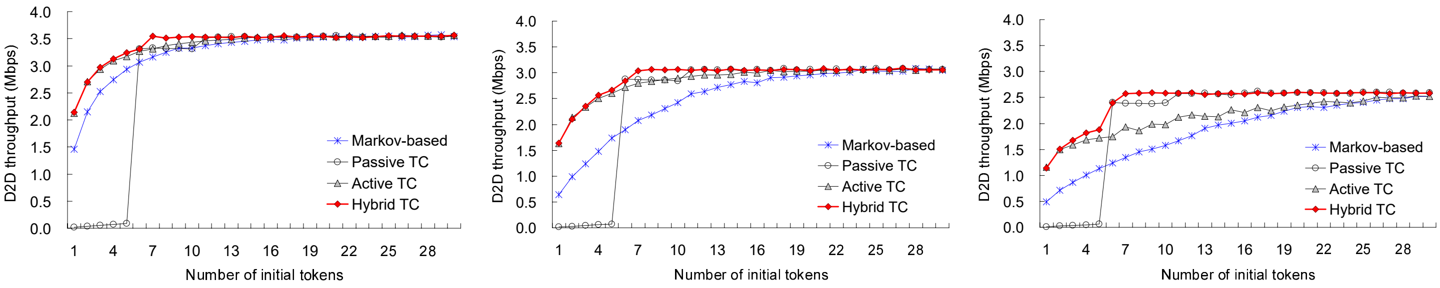
We use the OMNet++ simulator for performance evaluation, which is open-source software and supports many network scenarios [44]. Table 2 lists simulation parameters [37], [45]. We consider a macrocell serving numerous UEs. Some of them are misers, which attempt to hoard tokens and breach the incentive mechanism. The path loss is decided by the distance between a UE u_i and its sender (i.e., the BS or another UE u_j), which is measured in kilometers. Then, the shadow fading is modeled by a log-normal distribution whose standard deviation is set to 10 dB and 3 dB for both cellular and relay links, respectively. In our TC strategies, the SINR threshold $\sigma_{\tt th}$ to judge whether a UE is poor is set to -5.147 dB, which is the minimum required SINR for CQI (channel quality indicator) = 2 [46].

As discussed in Section 3.4, we adopt the Markov-based method in [37] to help each non-miser judge whether to provide the relay service to a requestor. According to the result of token trade, the passive, active, and hybrid TC strategies discussed in Section 4 are used to circulate tokens in each $T_{\rm C}$ period. We measure 1) D2D throughput (i.e., the amount of average throughput of UEs that obtain data through D2D relay), 2) cellular throughput (i.e., the amount of average throughput of UEs which directly get data from the BS), and 3) average packet loss rate. The simulation time is set to 1800 seconds.

5.1 Effect of Mobility

Let us first investigate the effect of UE mobility on the system performance. In particular, there are two types of UEs in the network, namely *high-speed UEs* and *low-speed UEs*, whose velocities are set to [50, 120] km/h and [0, 8] km/h, respectively. The distribution of high-speed UEs is uniform, so they would not congregate in certain regions of the cell. Moreover, we change the percentage of high-speed UEs (denoted by $\Phi_{\rm h}$) from 10% to 30%, 50%, 70%, and 90%. To minimize the effect of other factors, the number of initial tokens is gradually increased from 1 to 30 and the number of misers is set to 100, 600, and 1100. After that, we conduct simulations on these 90 (i.e., 30 × 3) combinations of initial tokens and misers, and Fig. 3 shows their averages together with 95% confidence intervals.

Fig. 3(a) gives the amount of D2D throughput. Generally speaking, D2D throughput rises as $\Phi_{\rm h}$ grows, since the probability that a UE finds out good (and also willing) relay nodes could increase due to high mobility. This result agrees with the observation in the work [37]. Because misers will hoard tokens, making other UEs possess fewer tokens to buy relay services, the Markov-based method results in the lowest D2D throughput. By efficiently circulating tokens, all TC strategies can improve D2D throughput. For the passive TC strategy, its performance is scarcely affected by $\Phi_{\rm h}$, since each UE in $\hat{\mathcal{U}}$ is taxed by the same rate $\delta_{\tt hi}$. For the active TC strategy, because it is easier for misers to roam to collect tokens from UEs when $\Phi_{\rm h}$ grows, the strategy can recognize misers more precisely, thereby increasing D2D throughput. By combining these two



(a) 100 misers (b) 600 misers (c) 1100 misers

Fig. 4: Comparison on the D2D throughput under different numbers of initial tokens and misers.

TABLE 3: Improvement ratios of TC strategies.

performance	passive	active	hybrid
total throughput	7.12%	6.76%	15.85%
packet loss	40.52%	33.26%	76.02%

strategies, the hybrid TC strategy can substantially raise D2D throughput.

Fig. 3(b) presents the amount of cellular throughput. As mentioned in Section 3.3, a UE u_i whose SINR $\sigma_{b,i}$ is good must get data directly from the BS. Otherwise, it will choose the relay mode to improve throughput (on the premise that u_i has tokens to buy the relay service). That explains why the amount of cellular throughput of every method is similar and also the effect of mobility is not significant. Interestingly, the passive TC strategy has slightly higher cellular throughput than the rest. The reason is that it makes many UEs poor when the number $\zeta_{\texttt{ini}}$ of initial tokens is set too small. In this case, they have to use the cellular mode to receive data with bad channel quality. We will further discuss this issue in Section 5.2.

Fig. 3(c) compares the packet loss rate. Without token circulation, misers will make their neighbors poor, which forces these UEs to get data from the BS under bad channel conditions. Thus, the Markov-based method has the highest packet loss rate (i.e., above 14.5%). Both passive and active TC strategies keep the rate below 10%. The hybrid TC strategy can further reduce the packet loss rate to 3.5%, which verifies its effectiveness.

Table 3 lists the improvement ratio of each TC strategy as compared with the Markov-based method. Let Υ_{MB} and Υ_x denote the amount of performance of the Markov-based method and a TC strategy x, respectively. This ratio is defined by $((\Upsilon_x - \Upsilon_{\mathrm{MB}})/\Upsilon_{\mathrm{MB}}) \times 100\%$ for throughput and $((\Upsilon_{\mathrm{MB}} - \Upsilon_x)/\Upsilon_{\mathrm{MB}}) \times 100\%$ for packet loss. Evidently, the hybrid TC strategy performs better than both passive and active strategies.

5.2 Effect of Initial Tokens and Misers

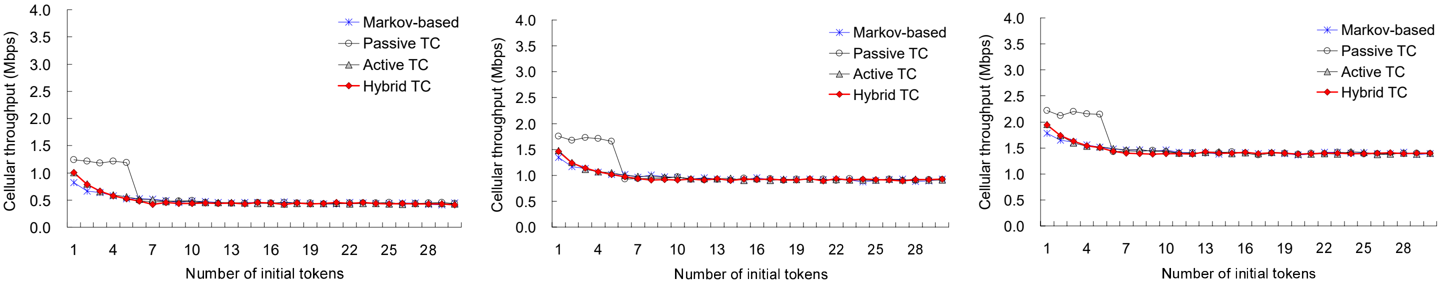
Then, we assess the effect of the number of initial tokens (i.e., $\zeta_{\texttt{ini}}$) and the number of misers. To do so, beginning from one, $\zeta_{\texttt{ini}}$ is iteratively increased by one, until $\zeta_{\texttt{ini}} = 30$. There will be 100, 600, and 1100 misers in the network. Moreover, we set $\Phi_{\mathrm{h}} = 50\%$, which means that one half of UEs in $\hat{\mathcal{U}}$ are high speed.

Fig. 4 shows the amount of D2D throughput. As a whole, D2D throughput improves when $\zeta_{\texttt{ini}}$ grows, since each UE has more tokens to buy relay services. Because misers will gather tokens, more misers lead to lower D2D throughput. These phenomenons are especially obvious in the Markov-based method, which means that this method is easily affected by $\zeta_{\texttt{ini}}$ and misers. The passive TC strategy does not work well when $\zeta_{\texttt{ini}} \leq 5$, since most UEs own just few tokens but pay a heavy tax (i.e., $\delta_{\texttt{hi}}$). For some UEs, the subsidy received may be less than the tax paid, thereby making them poor. This problem can be efficiently solved by enlarging $\zeta_{\texttt{ini}}$. In particular, the D2D throughput of the passive TC strategy will reach the peak when $\zeta_{\texttt{ini}} = 10$. On the other hand, the active TC strategy penalizes merely rich UEs, so it still wins the Markov-based method even though $\zeta_{\texttt{ini}}$ is small. However, its D2D throughput significantly drops when there exist more misers. In this case, some misers may not collect many tokens, so they would not be treated as rich UEs and pay no tax. The hybrid TC strategy taxes rich UEs and non-rich UEs with different rates (i.e., $\delta_{\texttt{hi}}$ and $\delta_{\texttt{lo}}$), so it avoids the problems of both passive and active ones. Therefore, the hybrid TC strategy always has the highest D2D throughput among all methods.

Fig. 5 gives the amount of cellular throughput. As discussed in Section 3.3, a UE chooses the cellular mode when 1) its SINR $\sigma_{b,i}$ with the BS is good enough or 2) it has no token to buy the relay service. Thus, the result in Fig. 5 is complementary to that in Fig. 4. In other words, the higher the D2D throughput is, the lower the cellular throughput is, and vice versa. However, cellular throughput is much lower than D2D throughput due to the second condition (i.e., the UE has bad channel quality from the BS but it has to get data by using the cellular mode). Observing in Fig. 5, the amount of cellular throughput of the passive TC strategy is higher than others when $\zeta_{\texttt{ini}} \leq 5$. Besides, all methods have similar cellular throughput as $\zeta_{\texttt{ini}} \geq 6$. This result explains why the passive TC strategy has the highest cellular throughput in Fig. 3(b), as mentioned in Section 5.1.

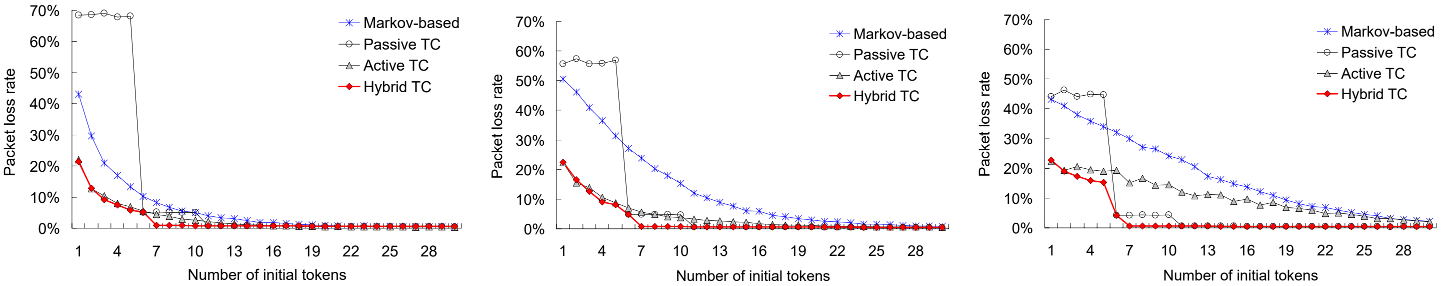
Fig. 6 presents the packet loss rate. In general, increasing throughput can mitigate packet loss. Thus, the packet loss rate reduces as $\zeta_{\texttt{ini}}$ raises. Without token circulation, the Markov-based method encounters serious packet loss, especially when $\zeta_{\texttt{ini}}$ is not large and there are more misers. For the passive TC strategy, the packet loss rate can greatly reduce when $\zeta_{\texttt{ini}} \geq 6$. The hybrid TC strategy can keep the lowest packet loss rate, which shows its high efficiency.

Through the above verification, we arrive at the following conclusions: 1) The Markov-based method is susceptible to misers. If there are more misers, we have to significantly increase initial tokens (i.e., $\zeta_{\texttt{ini}}$) to keep its performance. However, doing so will increase the risk of token inflation. 2) For the passive TC strategy, its performance can be greatly improved by setting $\zeta_{\texttt{ini}} \geq 6$. 3) The active TC strategy performs better in the case of fewer misers. 4) The hybrid TC strategy has the



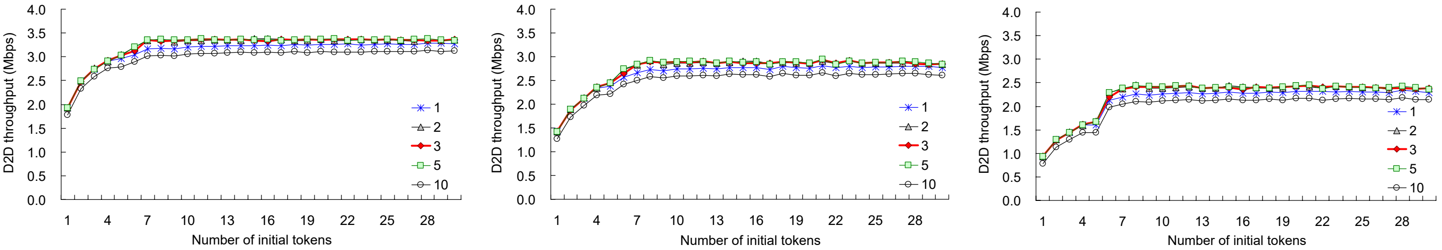
(a) 100 misers (b) 600 misers (c) 1100 misers

Fig. 5: Comparison on the cellular throughput under different numbers of initial tokens and misers.



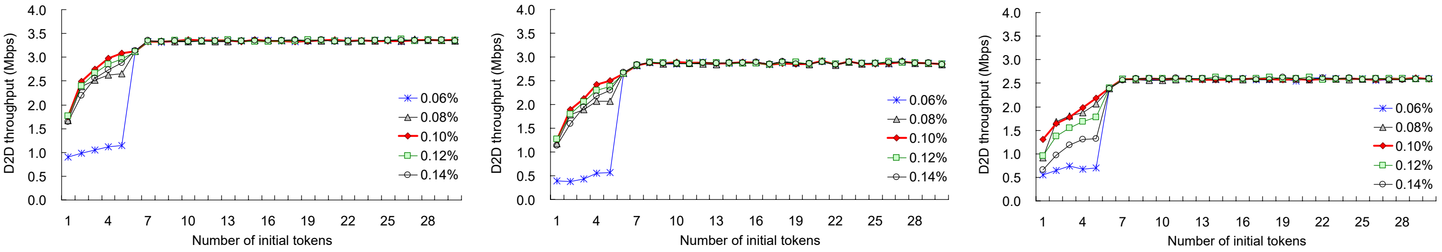
(a) 100 misers (b) 600 misers (c) 1100 misers

Fig. 6: Comparison on the packet loss rate under different numbers of initial tokens and misers.



(a) 100 misers (b) 600 misers (c) 1100 misers

Fig. 7: Effect of ζ_{pr} (for poor UEs) on the D2D throughput in the hybrid TC strategy.



(a) 100 misers (b) 600 misers (c) 1100 misers

Fig. 8: Effect of α_{rh} (for rich UEs) on the D2D throughput in the hybrid TC strategy.

highest performance in any circumstance.

5.3 Effect of Poor and Rich UEs

As discussed in Sections 5.1 and 5.2, the hybrid TC strategy always has the highest D2D throughput, since it combines the advantages of both passive and active TC strategies. More concretely, the hybrid TC strategy asks rich UEs to pay a heavier tax (i.e., δ_{hi}). Moreover, it gives relief to poor UEs by the Subsidy procedure. Thus, how to find out poor and rich UEs is important in the hybrid TC strategy.

Recall that a condition to check if a UE is poor is whether it has fewer than ζ_{pr} tokens, where $\zeta_{\mathrm{pr}} \in \mathbb{Z}^{+}$. Fig. 7 shows the amount of D2D throughput in the hybrid TC strategy, where $\Phi_{\mathrm{h}} = 50\%$ and $\zeta_{\mathrm{pr}} = 1, 2, 3, 5, 10$. When ζ_{pr} is set to 1, only if a UE has no token will it be viewed as a poor UE. Since the condition is relatively strict, D2D throughput will decrease. On the other hand, when ζ_{pr} is set to 10, the BS may also subsidize some non-poor UEs, making poor UEs get fewer extra tokens. In this case, they would not afford relay services, which reduces D2D throughput. Based on the result in Fig. 7,

TABLE 4: Average time delay of each TC strategy.

misers	passive	active	hybrid
100	16 ms	20 ms	26 ms
600	151 ms	158 ms	163 ms
1100	504 ms	510 ms	514 ms

the suitable range for $\zeta_{\mathtt{pr}}$ is within [2, 5].

To judge whether a UE is rich, we check if it has more than $\alpha_{\mathtt{rh}}$ percentage of tokens in the cell. Fig. 8 gives the amount of D2D throughput in the hybrid TC strategy, where $\Phi_{\mathrm{h}} = 50\%$ and $\alpha_{\mathtt{rh}} = 0.06\%, 0.08\%, 0.10\%, 0.12\%, 0.14\%$. If $\alpha_{\mathtt{rh}}$ is set too small (e.g., $\alpha_{\mathtt{rh}} = 0.06\%$), some non-misers may be included in $\hat{\mathcal{U}}_{\mathtt{rh}}$ (i.e., the set of rich UEs), which causes false alarms and lowers D2D throughput. On the contrary, when $\alpha_{\mathtt{rh}}$ is set too large for the case of 1100 misers (e.g., $\alpha_{\mathtt{rh}} \geq 0.12\%$), there will be fewer taxpayers. Thus, the amount of subsidy given to poor UEs reduces, thereby lowering D2D throughput. Based on Fig. 8, we suggest setting $\alpha_{\mathtt{rh}}$ to 0.10%.

5.4 Time Delay

Finally, let us measure the time delay incurred by each TC strategy. We execute our simulations on a desktop computer with an AMD Ryzen 3.6 GHz processor and 32 GB of memory, running Windows 10. Table 4 shows the average time delays of passive, active, and hybrid TC strategies. Evidently, the time delay increases as the number of misers increases. The reason is that more misers hoard tokens, making more non-misers become poor. Since each TC strategy adopts the Subsidy procedure to deal out the taxed tokens to all poor UEs in $\hat{\mathcal{U}}_{\mathtt{pr}}$, according to Lemma 1, it takes more time to execute the Subsidy procedure. On the other hand, the passive TC strategy only finds poor UEs (as it taxes every UE in $\hat{\mathcal{U}}$). The active TC strategy has to differentiate between rich and poor UEs. The hybrid TC strategy combines both passive and active strategies. Thus, the passive TC strategy has the lowest time delay, followed by the active and hybrid TC strategies. From Table 4, we can observe that each TC strategy requires not much time for execution, which shows that our proposed TC strategies are low-complexity.

6 CONCLUSION

D2D relay provides an alternative way for UEs to efficiently receive data when their signal quality from the BS is bad. Since the owners of most UEs are self-interested, TBI mechanisms are developed to encourage UEs to act as relay nodes. In this paper, we point out that these mechanisms are vulnerable to the miser problem, and thus propose three TC strategies to conquer it. The passive TC strategy taxes every UE, whereas the active TC strategy asks only rich UEs to be taxpayers. The hybrid TC strategy combines both of them, which taxes rich and non-rich UEs with different rates. Through the Subsidy procedure, the taxed tokens are efficiently dealt out to poor UEs. Simulation results show that the passive TC strategy can work well by giving UEs more initial tokens, and the active TC strategy performs better when there are fewer misers. By combining the advantages of both strategies, the hybrid TC strategy can keep the highest D2D throughput and the lowest packet loss rate.

REFERENCES

[1] ETSI, "Study on system enhancement for Proximity based Services (ProSe) in the 5G System (5GS)," 3GPP TR 23.752 V17.0.0, 2021.

[2] K. Vasudevan, A.P.K. Reddy, G.K. Pathak, and M.A.M. Albreem, "Turbo coded single user massive MIMO," *Sensors & Transducers Journal*, vol. 252, no. 5, pp. 65–75, 2021.

[3] K. Vasudevan, A.P.K. Reddy, G.K. Pathak, and M.A.M. Albreem, "Scilab code for turbo coded single user massive MIMO," https://doi.org/10.24433/CO.8218725.v1.

[4] S. Bachtobji, K. Hassan, A. Omri, K. Raoof, and R. Bouallegue, "3-D modeling and analysis of blockage effects on the performance of urban wireless communication systems," *Proc. Int'l Conf. Information and Comm. Technology Convergence*, 2018, pp. 332–336.

[5] H. Zhang, Y. Zhang, J. Cosmas, N. Jawad, W. Li, R. Muller, and T. Jiang, "mmWave indoor channel measurement campaign for 5G New Radio indoor broadcasting," *IEEE Trans. Broadcasting*, pp. 1–14, 2022.

[6] Q. Shen, W. Shao, and X. Fu, "D2D relay incenting and charging modes that are commercially compatible with B2D services," *IEEE Access*, vol. 7, pp. 36446–36458, 2019.

[7] M. Wu, Y. Xiao, Y. Gao, and M. Xiao, "Dynamic socially-motivated D2D relay selection with uniform QoE criterion for multi-demands," *IEEE Trans. Comm.*, vol. 68, no. 6, pp. 3355–3368, 2020.

[8] C.V. Anamuro, N. Varsier, J. Schwoerer, and X. Lagrange, "Distance-aware relay selection in an energy-efficient discovery protocol for 5G D2D communication," *IEEE Trans. Wireless Comm.*, vol. 20, no. 7, pp. 4379–4391, 2021.

[9] O.A. Amodu, M. Othman, N.K. Noordin, and I. Ahmad, "Relay-assisted D2D underlay cellular network analysis using stochastic geometry: Overview and future directions," *IEEE Access*, vol. 7, pp. 115023–115051, 2019.

[10] G. Yu, L. Xu, D. Feng, R. Yin, G.Y. Li, and Y. Jiang, "Joint mode selection and resource allocation for device-to-device communications," *IEEE Trans. Wireless Comm.*, vol. 62, no. 11, pp. 3814–3824, 2014.

[11] W. Chang, Y.T. Jau, S.L. Su, and Y. Lee, "Gale-Shapley-algorithm based resource allocation scheme for device-to-device communications underlaying downlink cellular networks," *Proc. IEEE Wireless Comm. and Networking Conf.*, 2016, pp. 1–6.

[12] Y.C. Wang, "A two-phase dispatch heuristic to schedule the movement of multi-attribute mobile sensors in a hybrid wireless sensor network," *IEEE Trans. Mobile Computing*, vol. 13, no. 4, pp. 709–722, 2014.

[13] Q. Duong, Y. Shin, and O.S. Shin, "Distance-based resource allocation scheme for device-to-device communications underlaying cellular networks," *Int'l J. Electronics and Comm.*, vol. 69, no. 10, pp. 1437–1444, 2015.

[14] W. Zhao and S. Wang, "Resource sharing scheme for device-to-device communication underlaying cellular networks," *IEEE Trans. Comm.*, vol. 63, no. 12, pp. 4838–4848, 2015.

[15] T. Yang, R. Zhang, X. Cheng, and L. Yang, "Graph coloring based resource sharing (GCRS) scheme for D2D communications underlaying full-duplex cellular networks," *IEEE Trans. Vehicular Technology*, vol. 66, no. 8, pp. 7506–7517, 2017.

[16] W.K. Lai, Y.C. Wang, H.C. Lin, and J.W. Li, "Efficient resource allocation and power control for LTE-A D2D communication with pure D2D model," *IEEE Trans. Vehicular Technology*, vol. 69, no. 3, pp. 3202–3216, 2020.

[17] Y. Jiang, Q. Liu, F. Zheng, X. Gao, and X. You, "Energy-efficient joint resource allocation and power control for D2D communications," *IEEE Trans. Vehicular Technology*, vol. 65, no. 8, pp. 6119–6127, 2016.

[18] D.D. Penda, L. Fu, and M. Johansson, "Energy efficient D2D communications in dynamic TDD systems," *IEEE Trans. Comm.*, vol. 65, no. 3, pp. 1260–1273, 2017.

[19] H. Xu, W. Xu, Z. Yang, Y. Pan, J. Shi, and M. Chen, "Energy-efficient resource allocation in D2D underlaid cellular uplinks," *IEEE Comm. Letters*, vol. 21, no. 3, pp. 560–563, 2017.

[20] Z. Zhou, K. Ota, M. Dong, and C. Xu, "Energy-efficient matching for resource allocation in D2D enabled cellular networks," *IEEE Trans. Vehicular Technology*, vol. 66, no. 6, pp. 5256–5268, 2017.

[21] Y. Wu, W. Liu, S. Wang, W. Guo, and X. Chu, "Network coding in device-to-device (D2D) communications underlaying cellular networks," *Proc. IEEE Int'l Conf. Comm.*, 2015, pp. 2072–2077.

[22] B. Ying and A. Nayak, "A power-efficient and social-aware relay selection method for multi-hop D2D communications," *IEEE Comm. Letters*, vol. 22, no. 7, pp. 1450–1453, 2018.

[23] K. Wu, M. Jiang, and H.Z. Tan, "D2D relay selection based on joint fuzzy and entropy theories with social similarity," *IEEE Trans. Vehicular Technology*, vol. 67, no. 9, pp. 8796–8807, 2018.

[24] P. Zhang, X. Kang, X. Li, Y. Liu, D. Wu, and R. Wang, “Overlapping community deep exploring-based relay selection method toward multi-hop D2D communication,” *IEEE Wireless Comm. Letters*, vol. 8, no. 5, pp. 1357–1360, 2019.

[25] Y.C. Wang and Z.H. Lin, “Efficient load rearrangement of small cells with D2D relay for energy saving and QoS support,” *Proc. IEEE Wireless Comm. and Networking Conf.*, 2020, pp. 1–6.

[26] A. Chaudhari, J. Gandikota, A. Sen, and S. Narayan, “A realistic approach to enhance the battery performance of device-to-device (D2D) relay UEs,” *Proc. IEEE Consumer Comm. and Networking Conf.*, 2020, pp. 1–2.

[27] D. Zhang, R. Shinkuma, and N.B. Mandayam, “Bandwidth exchange: An energy conserving incentive mechanism for cooperation,” *IEEE Trans. Wireless Comm.*, vol. 9, no. 6, pp. 2055–2065, 2010.

[28] S.H. Lee and I. Sohn, “Distributed relay pairing for bandwidth exchange based cooperative forwarding,” *IEEE Comm. Letters*, vol. 19, no. 3, pp. 459–462, 2015.

[29] T. Nadkar, V. Thumar, U.B. Desai, and S.N. Merchant, “Distributed execution of cognitive relaying with time incentive: Multiple PU scenario,” *EURASIP J. Wireless Comm. and Networking*, vol. 2012, no. 1, pp. 1–19, 2012.

[30] G. Zhang, K. Yang, Q. Hu, P. Liu, and E. Ding, “Bargaining game theoretic framework for stimulating cooperation in wireless cooperative multicast networks,” *IEEE Comm. Letters*, vol. 16, no. 2, pp. 208–211, 2012.

[31] Y. Chen and K.J.R. Liu, “Indirect reciprocity game modelling for cooperation stimulation in cognitive networks,” *IEEE Trans. Comm.*, vol. 59, no. 1, pp. 159–168, 2011.

[32] B. Zhang, Y. Chen, and K.J.R. Liu, “An indirect-reciprocity reputation game for cooperation in dynamic spectrum access networks,” *IEEE Trans. Wireless Comm.*, vol. 11, no. 12, pp. 4328–4341, 2012.

[33] Q. Nadeem, A. Kammoun, and M. Alouini, “Elevation beamforming with full dimension MIMO architectures in 5G systems: A tutorial,” *IEEE Comm. Surveys & Tutorials*, vol. 21, no. 4, pp. 3238–3273, 2019.

[34] J. Xu and M. van der Schaar, “Token system design for autonomic wireless relay networks,” *IEEE Trans. Comm.*, vol. 61, no. 7, pp. 2924–2935, 2013.

[35] N. Mastronarde, V. Patel, and L. Liu, “Device-to-device relay assisted cellular networks with token-based incentives,” *Proc. IEEE Int'l Conf. Comm. Workshop*, 2015, pp. 698–704.

[36] M. van der Schaar, J. Xu, and W. Zame, “Efficient online exchange via fiat money,” *Economic Theory*, vol. 54, no. 2, pp. 211–248, 2013.

[37] N. Mastronarde, V. Patel, J. Xu, L. Liu, and M. van der Schaar, “To relay or not to relay: Learning device-to-device relaying strategies in cellular networks,” *IEEE Trans. Mobile Computing*, vol. 15, no. 6, pp. 1569–1585, 2016.

[38] M. Mousavi and A. Klein, “Decentralized video streaming in multi-hop wireless networks: Incentive mechanism and energy efficiency,” *IEEE Access*, vol. 7, pp. 51329–51345, 2019.

[39] S. Yang, X. Wang, U. Adeel, C. Zhao, J. Hu, X. Yang, and J. McCann, “The design of user-centric mobile crowdsensing with cooperative D2D communications,” *IEEE Wireless Comm.*, pp. 1–9, 2022.

[40] Y.C. Wang and S. Lee, “Small-cell planning in LTE HetNet to improve energy efficiency,” *Int'l J. Comm. Systems*, vol. 31, no. 5, pp. 1–18, 2018.

[41] A. Gouissem, L. Samara, R. Hamila, N. Al-Dhahir, and S. Foufou, “Multiple relay selection and beamforming in dual-hop amplify-and-forward relay networks,” *IEEE Systems J.*, vol. 13, no. 2, pp. 1534–1545, 2019.

[42] R. Lopez-Valcarce and M. Martinez-Cotelo, “Robustness analysis of beamforming based designs for mmWave full-duplex amplify-and-forward relays,” *Proc. Int'l Conf. Signal Processing and Comm. Systems*, 2020, pp. 1–5.

[43] Y. Zhao, R. Adve, and T.J. Lim, “Improving amplify-and-forward relay networks: Optimal power allocation versus selection,” *IEEE Trans. Wireless Comm.*, vol. 6, no. 8, pp. 3114–3123, 2007.

[44] OMNet++, “Discrete event simulator,” https://omnetpp.org/.

[45] Y.C. Wang and C.A. Chuang, “Efficient eNB deployment strategy for heterogeneous cells in 4G LTE systems,” *Computer Networks*, vol. 79, pp. 297–312, 2015.

[46] Y.C. Wang and D.R. Jhong, “Efficient allocation of LTE downlink spectral resource to improve fairness and throughput,” *Int'l J. Comm. Systems*, vol. 30, no. 14, pp. 1–13, 2017.