Adaptive Token Circulation to Avoid Malicious UEs Hoarding Tokens and Assure D2D Relay Efficiency

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***Abstract*—Device-to-device (D2D) relay can be used to expand the service coverage of a *base station (BS)* and improve network throughput. In D2D relay, when a *user equipment (UE)* has bad channel quality, it solicits a neighbor to relay its data from the BS. In view that UEs are usually owned by self-interested users, token-based incentive methods adopt tokens as virtual currencies to let UEs sell and buy relay services, which encourages UEs to help relay data for other UEs. However, malicious UEs may keep gathering tokens from others but never spend tokens, which we call *hoarders*. Hence, negotiable tokens would reduce gradually, and many UEs cannot afford relay services due to lack of tokens. In this case, these token-based incentive methods will incur bad performance or even collapse. To this end, we propose an *adaptive token circulation (ATC)* scheme to tax the UEs that have ample tokens and subsidize the UEs in need of tokens. ATC works well in a multi-cell environment and does not cause the inflation of tokens. Simulation results reveal that the ATC scheme keeps high D2D throughput when there exist hoarders, thereby assuring the efficiency of D2D relay.**

***Keywords*—circulation, device-to-device (D2D), hoarder, incentive, relay service, token.**

I. Introduction

Device-to-device (D2D) communication lets two *user equipments (UEs)* close to each other exchange messages directly, without requiring a *base station (BS)* to act as an intermediary. Since cellular and D2D links are permitted to share spectrum resources, the network capacity can be thus improved [1]. D2D communication is also a key technique in 5G systems [2].

A UE may have bad channel quality with the BS as it moves near the cell edge. Moreover, the densely located buildings in an urban area worsen penetration loss and make slow fading (e.g., shadowing) significant [3], [4]. Hence, even if some UEs are not far away from the BS, their channel quality could be bad. This problem can be efficiently solved by D2D relay [5], as shown in Fig. 1. Suppose that a UE u_i wants to receive data from the BS, but it is obstructed by a building (i.e., incurring bad channel quality). Thus, u_i asks a neighbor u_j whose signal quality is good to obtain its data from the BS and send the data to u_i by D2D communication. Here, u_j is known as u_i's *relay node*. As compared with the case that u_i gets data directly from the BS, using D2D relay through u_j can improve throughput.

In effect, UEs may be mobile phones or laptops possessed by self-interested people, so it is too ideal to assume that these UEs can provide gratuitous relay services [6]. Therefore, many

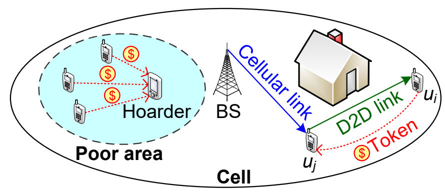


Fig. 1. D2D relay with a token-based incentive method and the token hoarding problem caused by malicious UEs.

token-based incentive methods are proposed to let tokens be circulated among UEs to implement the trade of relay services. As Fig. 1 shows, if u_i wants u_j to be its relay node, u_i pays a token to u_j. Here, we say that u_j sells the relay service and u_i buys the service. This helps raise the willingness of UEs to provide relay services, as UEs can earn tokens for later use.

However, malicious UEs could spoil the above methods by collecting tokens intentionally. They are active to peddle relay services to gather tokens from nearby UEs, but spend no token to buy relay services from other UEs. We call such malicious UEs *hoarders*. Inevitably, some neighbors of each hoarder will have fewer and fewer tokens. Therefore, a *poor area* is created surrounding the hoarder, where many UEs cannot buy relay services due to lack of tokens, as shown in Fig. 1. Even with merely a few hoarders, they can still move around to generate many poor areas and greatly reduce circulating tokens in the network. One may suggest regularly issuing additional tokens to UEs, but this solution brings about the inflation of tokens. In this case, the value of tokens may substantially reduce, making most UEs unwilling to offer relay services to earn tokens [7].

This paper proposes an *adaptive token circulation (ATC)* scheme to tax UEs with many tokens (i.e., potential hoarders) and give taxed tokens to poor UEs that require tokens to buy relay services. In addition to taxing UEs periodically, ATC also imposes taxes on some UEs when they gather too many tokens or move to other cells. Instead of adopting fixed tax rates, ATC adjusts the tax rate for a UE based on the quantitative ratio of its tokens and the average tokens owned by others. Since no extra tokens are added to the network, the inflation of tokens never occurs in ATC. Through simulations, we show that even with hoarders, the ATC scheme can well sustain the circulation of tokens and assure the efficiency of D2D relay.

II. Related Work

A. D2D Communication and D2D Relay

How to make cellular and D2D links share a BS's resource is a key issue in D2D communication [8]. The Gale-Shapley method is used in [9] to match cellular UEs with D2D links for resource sharing, whose result is Pareto optimal [10]. Xu et al. [11] formulate a mixed integer nonlinear programming problem to give cellular and D2D links resources to maximize the energy efficiency [12]. Some studies model resource allocation for D2D communication by games, like Stackelberg game [13] and coalition formation game [14]. A two-stage mechanism is proposed in [15] to allocate channels for D2D links and adjust their power. The work [16] applies graph coloring to resource allocation, which allows D2D pairs to solely share resources. Both reinforcement learning [17] and deep neural network [18] are also adopted to select channels and decide power for D2D UEs. Lai et al. [19] handle resource and power management for D2D communication with network sharing, where multiple operators collocate in a BS and share its resource.

Regarding D2D relay, a relay discovery method is proposed in [20] to minimize periodic discovery transmissions of D2D UEs. The work [21] transfers the service of UEs between cells through D2D relay to balance the loads of BSs and turn off idle BSs for power saving. Various solutions are developed for the D2D relay selection problem, like fuzzy and entropy [22], deep learning [23], Q-learning [24], and the social relationship [25]. However, these studies assume that UEs are willing to provide free relay services, which may not be feasible in some applications (e.g., UEs are owned by self-interested people).

B. Token-based Incentive for D2D Relay

Token-based incentive methods work up self-interested UEs to provide relay services to others in exchange for tokens. The work [26] discusses the relation between the number of tokens and the profit obtained from D2D relay, while the study [27] indicates that the efficiency of D2D relay will rely on issuing a proper number of tokens. In [7], UEs check whether to sell relay services via a supervised learning approach. Yuan et al. [28] employ a Markov decision process to model the trade of relay services, whose objective is to maximize the difference between the benefit that a UE gets from D2D relay and the cost that it pays for relay services. Then, the work [29] applies the law of supply and demand in economics to token transactions to promote D2D relay use. However, the above studies do not consider that there could exist malicious UEs to spoil token-based incentive methods.

Some weaknesses of the incentive mechanism by tokens are also discussed. Mach et al. [30] point out that a token-based incentive method would lead to deadlocks, unless the channel quality and traffic demand can be uniformly distributed among all UEs over time. To avoid malicious UEs hoarding tokens, three circulation methods for tokens are proposed in [31]. The passive method taxes all UEs. The active method taxes only rich UEs with many tokens. The hybrid method taxes rich UEs with a high rate and other UEs with a low rate. Then, they give the taxed tokens to poor UEs with very few tokens. However, the study [31] taxes UEs regularly only with fixed rates. On the contrary, our work dynamically taxes some UEs if they gather many tokens or handover to other cells, and adjusts tax rates based on the network condition. Doing so can not only add more flexibility, but also facilitate the circulation of tokens, thereby solving the token hoarding problem more efficiently.

III. System Model

A. Network Model

Let us consider a cellular network using OFDMA for downlink communication. The basic unit of spectrum resources is called a *resource block (RB)*, whose duration is 0.5 ms and bandwidth is 180 kHz (with 12 subcarriers) [32]. To facilitate both resource allocation and D2D relay, we slice the time axis into periods. Each period is long enough to make a UE check whether D2D relay is needed, find a relay node if required, and complete data transmission. Moreover, the channel quality and locations of UEs shall not drastically change within a period. A good choice of period length is one frame in 5G (i.e., 10 ms).

In every period, the BS chooses a set of UEs from its cell to receive downlink data based on the scheduling algorithm [33], [34]. If some UEs incur bad channel quality, these UEs will solicit neighbors to help relay their data from the BS. Here, we employ the two-hop relaying mechanism, as Fig. 1 shows. More concretely, a UE u_i can pick at most one neighbor u_j as the relay node. The transmission from the BS to u_i is then replaced by the two-hop transmission BS $\rightarrow u_j \rightarrow u_i$.

B. Rate Estimation and Mode Selection

For performance concern, the data rate is the key metric for a UE u_i to choose between the *cellular mode* (i.e., forthright obtaining data from the BS) or the *relaying mode* (i.e., getting data via a relay node). Specifically, u_i's data rate in the cellular mode is calculated by [35]

$$R_{\mathrm{BS},i} = B_{\mathrm{BS},i} \times \log_2(1 + S_{\mathrm{BS},i}), \tag{1}$$

where $B_{\mathrm{BS},i}$ is the bandwidth of the cellular link between the BS and u_i, and $S_{\mathrm{BS},i}$ is the SINR from the BS to u_i [36]:

$$S_{\mathrm{BS},i} = (G_{\mathrm{BS},i} \times P_{\mathrm{BS},i} - \Psi)/(I_i + \sigma), \tag{2}$$

where $G_{\mathrm{BS},i}$ and $P_{\mathrm{BS},i}$ denote the channel gain and transmitted power for the BS to transmit data to u_i, respectively, Ψ is the amount of signal attenuation (caused by path loss, shadowing, and fading), I_i is the amount of interference that u_i encounters, and σ is the thermal noise. Regarding the relaying mode, let u_j be u_i's relay node. Then, u_i's data rate is estimated by

$$R^{(j)}_{\mathrm{BS},i} = B^{(j)}_{\mathrm{BS},i} \times \log_2(1 + S^{(j)}_{\mathrm{BS},i}), \tag{3}$$

where superscript '(j)' signifies the relay via u_j. Both cellular link $(\mathtt{BS}, u_j)$ and D2D link (u_j, u_i) can share the same RB to improve the utilization of RBs, so we have $B_{\mathrm{BS},j} = B_{\mathrm{BS},i} = B_{i,j}$. Hence, $B^{(j)}_{\mathrm{BS},i}$ is equal to $B_{\mathrm{BS},i}$. When we use the amplify-and-forward method for D2D relay [37], SINR $S^{(j)}_{\mathrm{BS},i}$ is

$$S^{(j)}_{\mathrm{BS},i} = (S_{\mathrm{BS},j} \times S_{j,i})/(S_{\mathrm{BS},j} + S_{j,i} + 1). \tag{4}$$

By replacing $\texttt{BS}$ with j in Eq. (2), we can obtain $S_{j,i}$.

According to Eq. (1), when SINR $S_{\texttt{BS},i}$ is good enough to meet its traffic demand, u_i prefers the cellular mode to reduce the packet delay (as the two-hop transmission in the relaying mode may increase the delay). In particular, let $S_i^{\min}$ be the minimum SINR to satisfy u_i's demand. When $S_{\texttt{BS},i} \geq S_i^{\min}$, u_i directly gets data from the BS (i.e., using the cellular mode). Otherwise, u_i adopts the relaying mode to receive data. In this case, how to select u_i's relay node can be expressed as follows:

$$u_j = \arg\min_{u_j \in \hat{\mathcal{N}}_i} P_{j,i}, \quad (5)$$

where $\hat{\mathcal{N}}_i$ is the set of u_i's neighbors, subject to

$$R^{(j)}_{\texttt{BS},i} \geq B_{\texttt{BS},i} \times \log_2(1 + S_i^{\min}) \quad (6)$$

$$P_{\min} \leq P_{j,i} \leq P_{\max} \quad (7)$$

Specifically, Eq. (5) picks a relay node u_j with the minimum transmitted power for energy saving and interference mitigation. Regarding constraints, Eq. (6) indicates that u_i's demand can be met via u_j's relay, and Eq. (7) imposes lower and upper bounds on u_j's transmitted power for the relay.

C. Service Trade via Token Transaction

When u_i chooses the relaying mode and finds a relay node u_j by Eq. (5), u_i sends a *relay request* to u_j. Then, u_j decides whether to accept the request based on some algorithm (here, we adopt the algorithm in [7] for the decision). If u_j accepts the request, it replies a confirmation to u_i and notifies the BS that it will help relay u_i's data. In this case, the BS sends u_i's data to u_j through u_i's RBs. Afterward, u_j will reuse these RBs to forward data to u_i.

Let E_j be the amount of u_j's budget energy for relay, where E_j occupies just a portion of u_j's total energy. Hence, even if u_j runs out of budget energy, u_j still has energy to perform other tasks, but it will no longer offer relay services. Moreover, we denote by τ_i the number of tokens owned by u_i, where $\tau_i \in \mathbb{N}$. The state transition of u_i and u_j can be expressed by

$$\text{UE } u_i\text{:} \quad (E_i, \tau_i) \Rightarrow (E_i, \tau_i - 1), \quad (8)$$

$$\text{Relay node } u_j\text{:} \quad (E_j, \tau_j) \Rightarrow (E_j - \lambda_i, \tau_j + 1). \quad (9)$$

Here, Eq. (8) implies that u_i pays a token for the relay service, and Eq. (9) means that u_j gets one token from u_i and spends an amount λ_i of energy to relay u_i's data. Two conditions must obtain before conducting the state transition: 1) $\tau_i > 0$ (i.e., u_i has tokens) and 2) $E_j > \lambda_i$ (i.e., u_j's energy is enough to do the relay). Like [7], we assume that all messages used for the token transaction are protected by some secure mechanisms (e.g., authentication via the public-key cryptography). Hence, no UE can acquire free tokens or fabricate the states of other UEs by tampering the corresponding messages.

D. Token Hoarding Problem

Though malicious UEs may not profit from message modification, they can cause damage to the token transaction (i.e., the core of token-based incentive methods), under the guise of legitimate acts. Specifically, normal UEs do not serve as relay nodes if they use up budget energy or have too many tokens. By contrast, a hoarder is very active to collect tokens. It usually has external power supply (e.g., power bank), so the hoarder can "unconditionally" provide relay services to other UEs (i.e., without considering the energy factor) as long as they can pay tokens. On the other hand, the hoarder never spends tokens on buying relay services from others. Eventually, most neighbors of the hoarder would be broke, which forms a poor area shown in Fig. 1. In this situation, these UEs can receive their data only via the cellular mode, which results in low performance.

A token-based incentive method could be spoiled by merely a few hoarders, as they can move around to form many poor areas. In this way, the circulating tokens will be gradually reduced, until most UEs cannot afford relay services (due to lack of tokens). A naive solution is to periodically issue extra tokens to UEs. Nevertheless, this solution will lead to the inflation of tokens, making most UEs unwilling to provide relay services for earning tokens. To conquer the toke hoarding problem, we should make tokens be efficiently circulated among UEs by 1) preventing hoarders from amassing tokens, 2) letting most UEs afford to purchase relay services, and 3) keeping the number of tokens stable (to avoid the inflation/deflation of tokens).

TABLE I
SUMMARY OF NOTATIONS.

notations	definitions
$\hat{\mathcal{U}}_k$	set of UEs in a cell whose BS is b_k
$\hat{\mathcal{U}}_k^{\mathrm{R}}, \hat{\mathcal{U}}_k^{\mathrm{P}}, \hat{\mathcal{U}}_k^{\mathrm{O}}$	subsets of rich, poor, and other UEs in $\hat{\mathcal{U}}_k$
Ω_k, T_k	the number of tokens in b_k's token bank and cell
τ_i	the number of tokens owned by a UE u_i (initial: τ_{ini})
$r_{\mathrm{H}}, r_{\mathrm{M}}, r_{\mathrm{L}}$	high, medium, low tax rates ($r_{\mathrm{H}} > r_{\mathrm{M}} > r_{\mathrm{L}}$)
$\delta_{\mathrm{H}}, \delta_{\mathrm{M}}, \delta_{\mathrm{L}}$	high, medium, low thresholds ($\delta_{\mathrm{H}} > \delta_{\mathrm{M}} > \delta_{\mathrm{L}}$)
$\tilde{p}_{\mathrm{H}}, \tilde{p}_{\mathrm{M}}, \tilde{p}_{\mathrm{L}}$	probabilities used in the ANI module ($\tilde{p}_{\mathrm{H}} > \tilde{p}_{\mathrm{M}} > \tilde{p}_{\mathrm{L}}$)

IV. The Proposed ATC Scheme

The ATC scheme contains three modules. The *regular token circulation (RTC)* module taxes UEs and subsidizes poor UEs periodically. If a UE gathers many tokens or uses up tokens, the *anomaly inspection (ANI)* module adaptively performs the circulation of tokens. Then, the *border taxation (BOT)* module deals with the situation where a UE handovers to another cell. For management, each BS b_k has a *token bank* to hold tokens taxed from the UEs in its cell, where Ω_k denotes the number of tokens in b_k's token bank. Next, we elaborate on each module. Table I summarizes our notations.

A. Regular Token Circulation (RTC) Module

The RTC module performs the following tasks periodically: 1) classifying UEs into *rich*, *poor*, and *other* UEs, 2) collecting taxes from non-poor UEs, and 3) subsidizing poor UEs.

Algorithm 1 presents the pseudocode of UE classification, where $\hat{\mathcal{U}}_k$ is the set of UEs in a cell whose BS is b_k. Let $\hat{\mathcal{U}}_k^{\mathrm{R}}$, $\hat{\mathcal{U}}_k^{\mathrm{P}}$, and $\hat{\mathcal{U}}_k^{\mathrm{O}}$ be the subsets of rich, poor, and other UEs in $\hat{\mathcal{U}}_k$, respectively. Line 2 checks if a UE u_i is rich, where u_i has τ_i tokens and T_k is the total number of tokens in the cell. If u_i has more than $\rho_{\mathbf{R}}$ percentages of tokens in the cell (e.g., $\rho_{\mathbf{R}} = 0.1\%$), u_i is viewed as rich and added to $\hat{\mathcal{U}}_k^{\mathrm{R}}$. On the

Algorithm 1: RTC–Classification

1 **foreach** $u_i \in \hat{\mathcal{U}}_k$ **do**
2   **if** $\tau_i/T_k > \rho_{\mathbf{R}}$ **then**
3     $\hat{\mathcal{U}}_k^{\mathrm{R}} \leftarrow \hat{\mathcal{U}}_k^{\mathrm{R}} \cup \{u_i\}$;
4   **else if** $\tau_i < \tau_{\mathbf{P}}$ *and* $S_{\mathrm{BS},i} < S_{\mathtt{th}}$ **then**
5     $\hat{\mathcal{U}}_k^{\mathrm{P}} \leftarrow \hat{\mathcal{U}}_k^{\mathrm{P}} \cup \{u_i\}$;
6   **else**
7     $\hat{\mathcal{U}}_k^{\mathrm{O}} \leftarrow \hat{\mathcal{U}}_k^{\mathrm{O}} \cup \{u_i\}$;

Algorithm 2: RTC–Taxation

1 **foreach** $u_i \in \hat{\mathcal{U}}_k^{\mathrm{R}}$ **do**
2   **if** $\tau_i/(T_k/|\hat{\mathcal{U}}_k|) > \delta_{\mathrm{M}}$ **then**
3     $\tau_i \leftarrow \tau_i - \lfloor r_{\mathrm{H}} \times \tau_i \rfloor$ and $\Omega_k \leftarrow \Omega_k + \lfloor r_{\mathrm{H}} \times \tau_i \rfloor$;
4   **else**
5     $\tau_i \leftarrow \tau_i - \lfloor r_{\mathrm{M}} \times \tau_i \rfloor$ and $\Omega_k \leftarrow \Omega_k + \lfloor r_{\mathrm{M}} \times \tau_i \rfloor$;
6 **foreach** $u_i \in \hat{\mathcal{U}}_k^{\mathrm{O}}$ **do**
7   **if** $(\tau_i/(T_k/|\hat{\mathcal{U}}_k|) > \delta_{\mathrm{M}}$ **then**
8     $\tau_i \leftarrow \tau_i - \lfloor r_{\mathrm{M}} \times \tau_i \rfloor$ and $\Omega_k \leftarrow \Omega_k + \lfloor r_{\mathrm{M}} \times \tau_i \rfloor$;
9   **else**
10     $\tau_i \leftarrow \tau_i - \lfloor r_{\mathrm{L}} \times \tau_i \rfloor$ and $\Omega_k \leftarrow \Omega_k + \lfloor r_{\mathrm{L}} \times \tau_i \rfloor$;

other hand, line 4 checks whether a UE u_i is poor. There are two conditions for checking: 1) u_i has fewer than $\tau_{\mathbf{P}}$ tokens, and 2) u_i's SINR $S_{\mathrm{BS},i}$ from the BS is below $S_{\mathtt{th}}$, where

$$S_{\mathtt{th}} < \min_{\forall u_j \in \hat{\mathcal{U}}_k} S_j^{\min}. \tag{10}$$

Eq. (10) implies that u_i must take the relaying mode, since u_i cannot satisfy its demand by employing the cellular mode to get data. Besides, u_i's signal quality from the BS is bad, so no UE will ask u_i to be its relay node. Hence, u_i cannot earn tokens from others. In this case, we add u_i to $\hat{\mathcal{U}}_k^{\mathrm{P}}$. When u_i is neither rich nor poor, it will be added to $\hat{\mathcal{U}}_k^{\mathrm{O}}$ by line 7.

The remaining two tasks (i.e., taxation and subsidization) will be carried out only when $\hat{\mathcal{U}}_k^{\mathrm{P}} \neq \emptyset$ (i.e., there exist poor UEs). Algorithm 2 gives the pseudocode of taxation. Lines 1–5 shows the code used to tax rich UEs. For a rich UE u_i, if the proportion of its tokens (i.e., τ_i) to the average number of tokens owned by all UEs (i.e., $T_k/|\hat{\mathcal{U}}_k|$) overtakes a threshold δ_{M}, we will tax u_i with a high rate r_{H}. In this case, u_i has to give $\lfloor r_{\mathrm{H}} \times \tau_i \rfloor$ tokens to the BS (which is added to b_k's token bank Ω_k). Otherwise, u_i will be taxed with a medium rate r_{M}, where $r_{\mathrm{H}} > r_{\mathrm{M}}$. On the other hand, lines 6–10 gives the code to tax other UEs. For a UE $u_i \in \hat{\mathcal{U}}_k^{\mathrm{O}}$, if the proportion of τ_i to $T_k/|\hat{\mathcal{U}}_k|$ exceeds δ_{M}, it is taxed with rate r_{M}; otherwise, u_i is taxed with a low rate r_{L}, where $r_{\mathrm{M}} > r_{\mathrm{L}}$. Regarding tax rates, we can set $r_{\mathrm{H}} = 0.5$, $r_{\mathrm{M}} = 0.3$, and $r_{\mathrm{L}} = 0.1$.

Algorithm 3 shows the pseudocode of subsidization. There are two cases to be discussed:

Algorithm 3: RTC–Subsidization

1 **if** $\lfloor \Omega_k/|\hat{\mathcal{U}}_k^{\mathrm{P}}| \rfloor > 0$ **then**
2   **foreach** $u_i \in \hat{\mathcal{U}}_k^{\mathrm{P}}$ **do**
3     $\tau_i \leftarrow \tau_i + \lfloor \Omega_k/|\hat{\mathcal{U}}_k^{\mathrm{P}}| \rfloor$;
4   $\Omega_k \leftarrow \Omega_k - \lfloor \Omega_k/|\hat{\mathcal{U}}_k^{\mathrm{P}}| \rfloor \times |\hat{\mathcal{U}}_k^{\mathrm{P}}|$;
5 **else**
6   Sort UEs in $\hat{\mathcal{U}}_k^{\mathrm{P}}$ by their τ_i values increasingly;
7   **foreach** $u_i \in \hat{\mathcal{U}}_k^{\mathrm{P}}$ **do**
8     $\tau_i \leftarrow \tau_i + 1$ and $\Omega_k \leftarrow \Omega_k - 1$;
9   **if** $\Omega_k = 0$ **then**
10   break;

Case 1 (lines 1–4): BS b_k has enough tokens to let each poor UE get at least one token (i.e., $\lfloor \Omega_k/|\hat{\mathcal{U}}_k^{\mathrm{P}}| \rfloor > 0$). Thus, b_k allots $\lfloor \Omega_k/|\hat{\mathcal{U}}_k^{\mathrm{P}}| \rfloor$ tokens to each poor UE. The residual tokens are kept in b_k's token bank for later use, as shown in line 4.

Case 2 (lines 5–10): Poor UEs are more than the available tokens in token bank Ω_k. Hence, we sort all UEs in $\hat{\mathcal{U}}_k^{\mathrm{P}}$ based on the number of tokens owned by them (i.e., τ_i), and give tokens to poor UEs in a round-robin manner, where each poor UE can get at most one token. In this case, all tokens in the token bank will be distributed (i.e., $\Omega_k = 0$).

B. Anomaly Inspection (ANI) Module

Due to the long interval when the RTC module is triggered, D2D relay may have occurred many times in the interval. Since token circulation cannot be performed (by RTC) in time, two anomalies could occur. First, some UEs (e.g., hoarders) would collect many tokens, thereby creating poor areas. Hence, the token hoarding problem emerges briefly. Second, some UEs may use up their tokens and become poor. Since they cannot obtain subsidies during the interval, these poor UEs have to use the cellular mode, leading to low throughput. To this end, we propose the ANI module to deal with the above two anomalies.

As for the first anomaly, suppose that a UE u_j is serving as the relay node for another UE (i.e., selling its relay service). There is a probability $\tilde{p}$ that u_j's income from this transaction will be taken away and then deposited into the token bank of its BS b_k (i.e., $\tau_j = \tau_j - 1$ and $\Omega_k = \Omega_k + 1$). The probability is adjusted based on the number of tokens owned by u_j:

$$\tilde{p} = \begin{cases} \tilde{p}_{\mathrm{H}} & \text{if } \tau_j/(T_k/|\hat{\mathcal{U}}_k|) \geq \delta_{\mathrm{H}} \\ \tilde{p}_{\mathrm{M}} & \text{if } \delta_{\mathrm{M}} \leq \tau_j/(T_k/|\hat{\mathcal{U}}_k|) < \delta_{\mathrm{H}} \\ \tilde{p}_{\mathrm{L}} & \text{if } \delta_{\mathrm{L}} \leq \tau_j/(T_k/|\hat{\mathcal{U}}_k|) < \delta_{\mathrm{M}} \\ 0 & \text{otherwise,} \end{cases} \tag{11}$$

where $0 < \tilde{p}_{\mathrm{L}} < \tilde{p}_{\mathrm{M}} < \tilde{p}_{\mathrm{H}} < 1$ and $1 < \delta_{\mathrm{L}} < \delta_{\mathrm{M}} < \delta_{\mathrm{H}}$. Here, $\tilde{p}$ rises as u_j has more tokens, and vice versa. If u_j's tokens are not much more than the average number of tokens owned by UEs (i.e., $T_k/|\hat{\mathcal{U}}_k|$), we set $\tilde{p} = 0$ to let u_j keep its income. For probabilities and thresholds, we suggest setting $\tilde{p}_{\mathrm{H}} = 0.9$, $\tilde{p}_{\mathrm{M}} = 0.8$, $\tilde{p}_{\mathrm{L}} = 0.5$, $\delta_{\mathrm{H}} = 2$, $\delta_{\mathrm{M}} = 1.5$, and $\delta_{\mathrm{L}} = 1.2$.

Regarding the second anomaly, suppose that a UE u_i needs D2D relay, but it has no tokens. When BS b_k's token bank has tokens (i.e., $\Omega_k > 0$), b_k can give u_i one token (from Ω_k) to

TABLE II
COMMUNICATION PARAMETERS FOR BSS AND UES.

parameters	BS	UE
transmitted power	46 dBm	23 dBm
noise figure	5 dB	7 dB
antenna gain	18 dB	0 dB
cable loss	2 dB	2 dB

help u_i purchase the relay service for improving throughput. In this case, we have $\Omega_k = \Omega_k - 1$.

C. Border Taxation (BOT) Module

This module is executed only when the handoff case occurs. In this case, a UE leaves its original cell and moves to another cell, which changes the number of UEs (and also their tokens) in the two cells. To avoid occurring token inflation or deflation, we need to guarantee the stability of the number of tokens in a cell. More concretely, given the number τ_{ini} of tokens initially assigned to each UE (when it joins the network), the objective is to keep the number of tokens in a cell at around $\tau_{\text{ini}} \times |\hat{\mathcal{U}}_k|$.

Suppose that a UE u_i handovers from a BS b_x's cell to another BS b_y's cell. There are two cases needed to be handled to keep the number of tokens stable in both cells:

Case 1 ($\tau_i > \tau_{\text{ini}}$)**:** In b_x's cell, u_i gets more tokens from other UEs than u_i pays to them. Hence, b_x takes u_i's surplus (i.e., $\tau_i - \tau_{\text{ini}}$ tokens) and stores the tokens in its token bank. In this case, we can obtain that $\tau_i = \tau_{\text{ini}}$ and $\Omega_x = \Omega_x + (\tau_i - \tau_{\text{ini}})$. On the other hand, u_i will bring the residual tokens for usage in b_y's cell. Doing so can prevent u_i from bringing too many tokens from b_x's cell to b_y's cell, which causes token deflation in b_x's cell and token inflation in b_y's cell.

Case 2 ($\tau_i < \tau_{\text{ini}}$)**:** In b_x's cell, u_i leaves a debt with $\tau_{\text{ini}} - \tau_i$ tokens. Thus, b_x uses the tokens in its token bank to repay u_i's debt. When the debt cannot be paid off in full (i.e., $\Omega_x < \tau_{\text{ini}} - \tau_i$), b_x levies taxes from other UEs in its cell to pay off the debt (with $\tau_{\text{ini}} - \tau_i - \Omega_x$ tokens). To ensure fairness, all UEs are sorted from the richest to the poorest. Each UE donates a token to b_x in turn (i.e., round-robin), until the debt is zero. Then, b_x pays $\tau_{\text{ini}} - \tau_i$ tokens to b_y, which are stored in b_y's token bank. Hence, we can derive that $\Omega_x = \max\{\Omega_x - (\tau_{\text{ini}} - \tau_i), 0\}$ and $\Omega_y = \Omega_y + (\tau_{\text{ini}} - \tau_i)$. In this way, we can keep the number of tokens stable in both cells.

V. PERFORMANCE EVALUATION

We use OMNet++ [38], an open-source and discrete-event simulator, to evaluate system performance. In the simulation, there are 9 cells deployed, where the cell range is 2 km. The channel bandwidth is 10 MHz. There are 4500 UEs distributed over these cells, which move following the random waypoint model [39]. Besides, the velocities of 1/3 UEs are within [0, 8] km/h (i.e., low-speed UEs), and the velocities of others are within [50, 120] km/h (i.e., high-speed UEs). Table II lists the communication parameters for BSs and UEs. Furthermore, the amount of path loss for each link is estimated as follows [40]:

$$\text{Celluar link (i.e., BS to UE):} \quad 128.1 + 37.6 \log_{10} L, \quad (12)$$

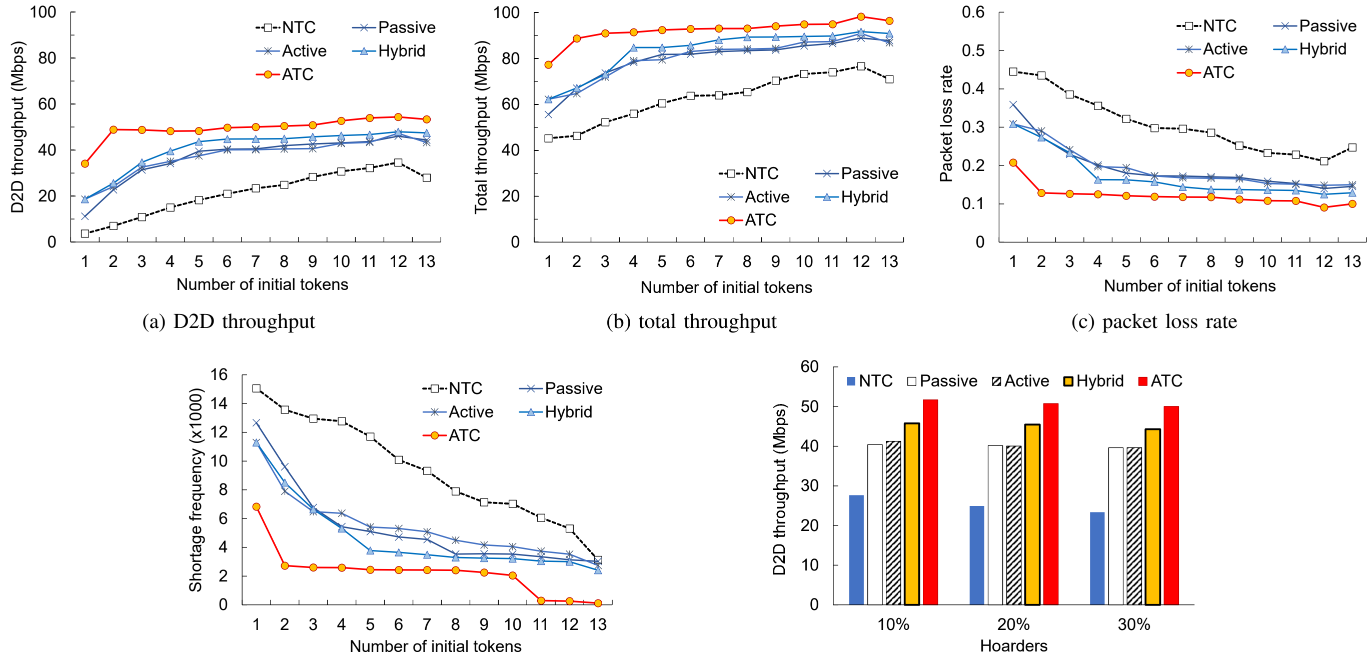
$$\text{D2D link (i.e., UE to UE):} \quad 148 + 40 \log_{10} L, \quad (13)$$

where L is the Euclidean distance between two end-points of the link (e.g., a BS or UE), which is measured in kilometers. The shadowing fading is modeled by a zero-mean log-normal distribution [41], whose standard deviation is 4 dB. To simulate the situation where some UEs encounter bad channel quality, we arbitrarily place some small circular areas, called *non-line-of-sight (NLOS) areas*, in every cell. Each NLOS area has a radius of 50 m and the standard deviation (for the shadowing fading) is set to 6 dB. In addition, we also add 30 dB of signal attenuation in these NLOS areas [42]. When a UE enters an NLOS area, its channel quality becomes bad. In this case, the UE prefers using the relaying mode to improve throughput. Regarding the fast fading, we adopt the Rayleigh fading model.

The supervised learning method [7] is used as the underlying token-based incentive method for UEs to judge whether to offer relay services to neighbors. The minimum SINR $S_i^{\min}$ to meet a UE u_i's demand in Eq. (6) is 0.761, corresponding to CQI (channel quality indicator) = 5 [43]. A method called *no token circulation (NTC)* is taken as the baseline to show how hoarders affect the token-based incentive method. Besides, we compare our ATC scheme with three token circulation methods in [31]. As discussed in Section II, the passive method taxes all UEs, the active method taxes just rich UEs, and the hybrid method taxes rich UEs with a high rate and non-rich UEs with a low rate. To check if a UE is poor, we set $\tau_{\mathbf{P}} = 2$.

Let us evaluate system performance under different numbers τ_{ini} of initial tokens, where we arbitrarily select 30% UEs to be hoarders. Fig. 2(a) gives the amount of D2D throughput in all cells, where D2D throughput of UEs is defined by the amount of throughput when they employ the relaying mode to get data. Overall, D2D throughput rises as the value of τ_{ini} grows. As indicated in [7], when a UE possesses more than 12 tokens, its willingness to help relay data will drop substantially. That is why D2D throughput falls when τ_{ini} is 13. Since NTC does not carry out token circulation, its D2D throughput is much lower than other methods. As discussed in [31], the passive method will incur bad performance when UEs are given fewer initial tokens (i.e., they are poor). Thus, the passive method has lower D2D throughput than the active method when $\tau_{\text{ini}} \leq 4$. Since the hybrid method is a combination of the two methods, it can outperform both passive and active methods. Our ATC scheme not only adaptively adjusts tax rates of UEs, but also asks a BS to perform token circulation when some UEs collect many tokens or use up tokens. Hence, ATC can significantly improve D2D throughput, as compared with all other methods.

Fig. 2(b) shows the amount of total throughput in all cells. As discussed in Section III-B, if SINR $S_{\text{BS},i}$ is good enough, a UE u_i receives data forthright from the BS (i.e., the cellular mode). Otherwise, u_i would like to adopt the relaying mode to increase throughput (on the premise that u_i has tokens to purchase relay services). In this case, the amount of cellular throughput of every method will be alike. Hence, the trend in Fig. 2(b) is similar to that in Fig. 2(a). Then, Fig. 2(c) gives the average packet loss rate of UEs. Evidently, the higher the total throughput is, the lower the packet loss rate will be. Therefore, the trend in Fig. 2(c) will be inverse to that in Fig. 2(b).



(a) D2D throughput (b) total throughput (c) packet loss rate (d) token shortage frequency (e) effect of the percentage of hoarders

Fig. 2. Experimental results.

Fig. 2(d) shows the token shortage frequency. If a UE wants to use the relaying mode, but the UE has no token to buy the relay service, it is credited with one time of token shortage. Obviously, when UEs are given more initial tokens, the token shortage frequency can reduce. Without circulation of tokens, hoarders will gather many tokens from their neighbors, making other UEs lack of tokens. Hence, the NTC method has a much higher token shortage frequency than other methods. On the other hand, the hybrid method can have a lower token shortage frequency than both passive and active methods. Because the ATC scheme allows each BS to give relief to poor UEs in time, it has the lowest token shortage frequency. This result reveals that our ATC scheme can efficiently sustain the circulation of tokens, thereby assuring the efficiency of D2D relay.

Finally, we evaluate the effect of the percentage of hoarders on D2D throughput, where Fig. 2(e) presents the experimental result by setting $\tau_{\text{ini}} = 7$. Since hoarders attempt to decrease negotiable tokens in the network, D2D throughput drops as the percentage of hoarders rises. When there exist fewer hoarders (i.e., 10%), the active method can have higher D2D throughput than the passive method. The reason is that the concentration of wealth (i.e., tokens) becomes more pronounced. Hence, it is easier for the active method to find out hoarders and tax them accordingly. Our ATC scheme always keeps the highest D2D throughput, which verifies its effectiveness on conquering the token hoarding problem.

VI. Conclusion

D2D relay helps a UE efficiently receive data if it incurs bad channel quality from the BS. Since the owners of most UEs could be self-interested, token-based incentive methods make UEs sell and buy relay services by exchanging tokens, thereby stirring them to offering D2D relay. However, malicious UEs called hoarders will cause damage to these incentive methods by deliberately gathering tokens and reducing circulating tokens. In this paper, we thus propose the ATC scheme with three modules to sustain token circulation and mitigate the damage caused by hoarders. The RTC module periodically taxes non-poor UEs and subsidizes poor UEs. The ANI module enforces token circulation once a UE collects many tokens or uses up tokens. The BOT module handles the handoff case to let ATC perform well in a multi-cell environment. Through simulations by OMNET++, we show that the ATC scheme can significantly improve D2D throughput and reduce packet loss, as compared with the NTC, passive, active, and hybrid methods.

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