Silence is Gold: Strategic Small Cell Interference Management Using Tokens

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***Abstract*—**

Electronic tokens have been proved as an effective incentive scheme in stimulating self-interested network nodes to transmit other nodes' traffic. In other words, tokens are paid to *buy transmission*. In this work, we propose a novel token framework in a distributed small cell network and design the token system for improved interference mitigation. Contrary to the traditional role of tokens for buying transmission, they are exchanged between users to *buy "silence"*. We focus on designing the optimal token system that minimizes the system outage probability. We first analyze the optimal strategies of individual users, which only consider their own utility maximization and do not care about the system-wise performance. We show that under some mild conditions the optimal strategy has a simple threshold structure. We then analytically derive the optimal token supply that minimizes the network outage probability. Simulation results show that not only does the proposed token system design greatly improve the network outage probability (by up to 75%), it also improves the overall small cell network QoS, particularly when the deployment density is high.

I. Introduction

Dense deployment of distributed low-cost small cells (e.g., femtocells) has been viewed as one of the most promising solutions to meet the challenge of exploding wireless traffic [1]. Small cells are attractive because they can not only extend the service coverage but also boost the network capacity by shortening the access distance (cell splitting gain) and offloading traffic from the macro network (offloading gain). However, as the density of small cells increases, interference has become the bottleneck of the overall system performance, which has motivated a lot of research in recent years. On the physical layer, advanced technologies such as interference cancellation [2], multi-user MIMO [3], Coordinated Multi-point transmission/reception (CoMP) [4], and large scale antenna system (LSAS) [5] have been proposed and extensively studied. In the upper layers, novel techniques such as power control [6], fractional frequency reuse (FFR) [7], and spatial techniques [3] have been pursued. While these advanced techniques provide promising solutions for interference mitigation in conventional wireless networks, the densely deployed small cell networks impose unique challenges that are yet to be well addressed.

As the density becomes much higher and the devices become more heterogeneous with different capabilities, centralized solutions or distributed techniques that require extensive coordination or information exchange between cells/users may not be feasible in practice. Furthermore, the majority of the existing research on interference problems focuses on optimizing the performance of either individual users or the overall system, assuming all users follow the established system-level solution. This may not work well as users become increasingly cognitive and self-interested. In certain scenarios, if users can improve their individual performance by unilaterally deviating from the prescribed actions, previous approaches may fail to provide efficient coordination among users to mitigate interference.

These challenges call for an efficient interference mitigation method for the dense small cell networks that is simple, scales easily with the volume of small cells and end users, involves minimal information exchange, and works with cognitive and self-interested devices. In this paper, we address these design challenges for the dense small cell interference problem and propose a novel framework using *tokens* to stimulate user cooperation by exploiting the long-term nature of the system states. In our design, users are assumed to be self-interested but rational, meaning that they aim to maximize only their own utilities and do not care about the system-wise performance. Minimal information exchanges between users is required so that it can accommodate a mixture of different self-interested devices. Unlike previous solutions, we attack the problem of lack of incentives by utilizing the long term nature of the network states and providing insurance to the self-interested user that by temporarily sacrificing its own performance it can potentially achieve a better utility in the long term. This is accomplished by the introduction of tokens, which allows the users to exchange the current utility decrease for future utility increase with a minimal information exchange.

Token is not a new concept. Two types of token applications have been extensively studied: relay networks [8], [9] and peer-to-peer networks [10], [11]. Monetary pricing schemes are proposed in [8] to stimulate relay cooperation in wireless networks. In [9], tokens are used to provide incentive for the self-interested transceivers to provide relay services. For peer-to-peer systems, a general economic framework for avoiding free-riders is provided in [10], using a single scalar value called *KARMA*. Payment-based incentives are proposed in [11], also targeting the free-riders.

To the best of the authors' knowledge, this paper is the first to introduce tokens in a distributed small cell network. It is also the first to utilize tokens for the purpose of interference avoidance. Moreover, our work differs from the previous token/virtual currency schemes in several important aspects. Firstly, the functionality of tokens in our work is different. Tokens used to be paid to the recipient to "buy transmission" [9]. In this work, however, tokens are exchanged to "buy silence" – the recipient gets paid to stop talking. This is a much less severe cost incurred to the recipients comparing to the "buy transmission" application, where the target node not only needs to sacrifice its own transmission, but also has to actively spend its resources for others. Secondly, we use the *repeated game theory* [12] to model the token exchanges. In our model, UEs are players who hold the tokens; the game that is played among the players is to buy and sell "silence" services for tokens; and the *repeated* game setting fully captures the long term characteristic of tokens that can stimulate cooperation even for selfish users. Last but not the least, the performance gain increases with the network density (see Section V), which makes the proposed token scheme particularly suitable for hyper-dense small cell networks.

The rest of this paper is organized as follows. Section II presents the system model. In Section III we introduce tokens in the small cell network, and discuss the proposed scheme and the system design problem. The general theory that guides the system design is presented in Section IV. Simulation results are presented in Section V, using QoS optimization as an exemplary objective. Finally, Section VI concludes the paper.

II. System Model

We study a small cell (SC) network with N cells. We consider N to be large and the density of the small cells is high, and hence the inter-site distance (ISD) is small. In such dense small cell deployment, due to the short access distance, signal-to-noise ratio (SNR) is typically very high, and the most important element that limits the system capacity is the interference from neighboring small cells (downlink interference) and their active users (uplink interference). We use g_{ij} to denote the channel power between transmitter (SC) i and receiver (User Equipment: UE) j. Note that g_{ij} takes into account both large-scale and small-scale fading.

Fig. 1 depicts the typical downlink interference problem between two neighboring cells: when a user is in the coverage intersection of these two cells, it will experience strong downlink interference from the neighboring cell and hence its signal-to-interference-plus-noise ratio (SINR) may reduce significantly, resulting in low throughput and even call drop. This problem becomes worse when the user is receiving high priority packets, since the interference issue causes more significant performance impact than the less important packets.

We denote the transmit power of SC i as P_i. Consider the two-cell example in Fig. 1 where both cells have active users to serve. For UE i, its downlink SINR can be written as:

$$SINR_i^{ON} = \frac{P_i g_{ii}}{N_0 + P_j g_{ji}}, \tag{1}$$

where the interference term $P_j g_{ji}$ comes from the neighboring small cell j's downlink transmission, and N_0 incorporates both

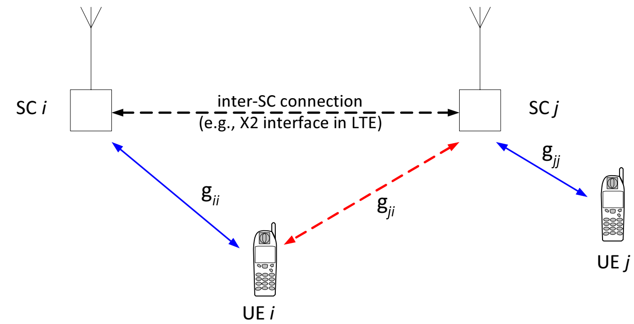

Fig. 1. A two-user example illustrating the small cell downlink interference problem.

the thermal noise and the residual interference. The superscript "ON" indicates that the neighboring cell j is transmitting.

We consider a time slotted system, where the network topology is fixed at one time slot and changes in the next (due to user movement, cell power-on/off, etc). All small cells are assumed to be synchronized (e.g., a TDD network). Due to the randomness of user traffic, a small cell does not always have an active user to serve. We capture the user random activity by γ_i, which is the probability that user i has active downlink traffic in a time slot. Note that for individual users, their traffic activity can be different, meaning that γ_i is user-specific. Lastly, we assume that the network has degree M, i.e., a user has M neighboring users on average.

We assume that each small cell serves at most a single user with active traffic. We thus denote the SC/UE association by assigning the same index to the SC and UE, e.g., UE i is associated with SC i as its serving cell. This assumption is made so that we can focus exclusively on the *inter-cell* interference problem. This is also a reasonable approximation, particularly in the *hyper-dense* small cell deployment model where each small cell's coverage area is very limited. For example, this assumption has been used in the 3GPP study for Home eNodeBs (HeNB) [13]. Finally, we only consider the dominant source of interference which typically causes the majority of the performance degradation [14]. It should be emphasized that these assumptions are made to simplify the discussions, as the proposed token design can be easily extended to accommodate for multiple users and multiple interfering neighbors.

III. Token Design for Interference Mitigation

For the interference scenario in Fig. 1, an efficient and simple solution is for SC/UE j to shut down transmission to eliminate its interference to UE i. If the interference can be eliminated, the SINR of UE i becomes

$$SINR_i^{OFF} = \frac{P_i g_{ii}}{N_0}, \tag{2}$$

where the superscript "OFF" indicates that the neighboring cell j is not transmitting. Note that (2) can be a significant improvement over (1) in an interference-limited network. However, shutting down the transmission of SC/UE j may lead to its performance loss, and hence it may refuse to do so without any incentives.

We now formally model the user interactions as a game. Suppose that at time slot t, SC i is actively serving UE i. A neighboring SC j also actively serves UE j, but due to its proximity to UE i it causes significant interference. In this setting, SC/UE j can take one action from the binary action space $\mathcal{A} = \{0, 1\}$, where action 1 means that the user decides to power off downlink transmission and action 0 means otherwise. If SC/UE j decides to power off transmission to eliminate its interference to UE i, UE i enjoys a benefit $b_i(t)$, which depends on the decrease of the interference. UE j, on the other hand, incurs a cost $c_j(t)$ in order to accommodate UE i's transmission. This cost can be a lost opportunity for its own transmission, or other performance measures such as delay and QoS reduction. Formally, UE i and j are playing an *interference elimination game* $G = \langle\{i, j\}, \mathcal{A}, \{u_i, u_j\}\rangle$. In this game, the players are UE i and UE j. The requester UE i has no action; the interferer UE j can choose an action from $\mathcal{A}$. The utilities of both players depend on UE j's action, i.e.

$$u_i(a_j, t) = a_j(t) b_i(t), \tag{3}$$
$$u_j(a_j, t) = -a_j(t) c_j(t). \tag{4}$$

It is easy to see that the dominant strategy of UE j is $a_j(t) = 0, \forall t$, since powering off its own transmission only brings a cost but no immediate benefit.

Clearly, in a distributed and autonomous small cell network where nodes care about their own utilities, if the *instantaneous* benefit is the only metric for the users, UE j will be reluctant to help UE i, since this incurs a performance degradation to UE j but provides no reward. In this work, we introduce tokens into the network, which provides incentives to shut down downlink transmission to eliminate interference. We denote the total amount of tokens circulating in the entire network by W. These tokens are equally assigned to all the users when they first enter the network, and they can be exchanged among users to "buy" and "sell" power-off services. In the aforementioned game involving two UEs i and j, UE i needs to decide whether to initiate a token exchange with UE j, based on the interference level and its QoS requirement. If UE i decides to "buy silence" and UE j accepts the proposal, then UE i sends one token (possibly via its serving cell SC i) to UE j (possibly via its serving cell SC j). UE i enjoys a benefit $b_i(t)$ while losing one token; UE j incurs a cost $c_j(t)$ but gains one token which can be used in the future for better utility. In this paper, we focus on the *static* policy design in which the user strategy σ_i is set prior to the system operation, where off-line computation of the optimal solution is performed and no run-time benefit/cost adjustment is done. Hence for the remainder of this paper we will use the expected benefit $b_i = \mathbb{E}[b_i(t)]$ and $c_i = \mathbb{E}[c_i(t)]$.

We capture the need for power-off services by λ_i, which is the probability that user i suffers from severe interference that it requires the dominant interfering SC/UE to power off its downlink transmission. For example, if SINR is the performance metric, then λ_i can be derived from (1) as

$$\lambda_i = \Pr\left\{\frac{P_i g_{ii}}{N_0 + \sum_{j=i_1,\cdots,i_{M_i}} I_j P_j g_{ji}} < \mathsf{SINR}_{\mathsf{th}}\right\} \tag{5}$$

where $j = i_1, \cdots, i_{M_i}$ are the M_i neighbors of user i with $\mathbb{E}[M_i] = M$, I_j is a random variable which takes value 1 with probability γ_j and 0 otherwise, and $\mathsf{SINR}_{\mathsf{th}}$ is a threshold below which the link quality becomes intolerable, e.g., the SINR decoding threshold.

IV. Optimal Token System Design: General Theory

A. Repeated Games

The key observation that motivates the proposed approach is that even with the system dynamics, users are active in the network for a long period of time, and proper incentives can be provided to them so that they are willing to take a (relatively smaller) loss at the moment to eliminate the interference to other cells, in exchange to get the same treatment to obtain a (relatively larger) benefit in the future. Correspondingly, we model the proposed token system in a small cell network using *repeated games* [12] in which the one-shot "interference elimination" game defined in Section IV-A is repeatedly played by the users. Repeated game models the long-term nature of the token system, and captures the essence that each player needs to take into account the impact of the current decision on the future actions of other players. In a small cell network, each user acts as a player, while the game being played is to exchange tokens for silence services. This game can be repeated since the users exist in the network for a long period of time. We also assume that the users discount the future utility at a constant rate $\beta \in (0, 1]$. Discounting is a main method to model the preference relation in an infinitely repeated game [12].

In the repeated "interference elimination" game, different users may choose different strategies. We thus denote user i's strategy as $\sigma_i : \mathcal{S}_i \to \mathcal{A}$, which is a mapping from the system state space $\mathcal{S}_i$ to the user action space $\mathcal{A}$. Each system state $s \in \mathcal{S}_i$ captures a combination of channel states and token holding that is known to user i.

For the considered repeated game problem, a user cares about its long-term utility which is defined as follows. Suppose the user already has k tokens and is asked for silence service. If it decides to power off to eliminate the interference to a neighboring user, it will gain one more token and has $k + 1$ tokens in the next time slot; otherwise it remains k tokens in the next time slot. We define $V_i(s|\sigma_i)$ as the long-term utility of user i when it is in a system state $s \in \mathcal{S}_i$ and adopts strategy σ_i. It should be emphasized that user i only knows the system state s of itself, including channel states to user i and its token holding. Since we consider static polices in this paper, the impact of dynamic channel states to the utility of user i is reflected by the power-off demand rate λ_i, and by fixing the expected cost c_i and benefit b_i, the utility function only depends on the token holding k, and the state equations can be written as

$$
\begin{aligned}
V_i(0|\sigma_i) &= (1-\lambda_i(1-\rho_0)\sigma_i(0))\beta V_i(0|\sigma_i) \\
&\quad +\lambda_i(1-\rho_0)\sigma_i(0)(-c_i+\beta_i V_i(1|\sigma_i)) \qquad (6)\\
V_i(k|\sigma_i) &= \lambda_i(1-\rho_r)(b_i+\beta V_i(k-1|\sigma_i)) \\
&\quad +\lambda_i(1-\rho_0)\sigma_i(k)(-c_i+\beta V_i(k+1|\sigma_i)) \\
&\quad +(1-\lambda_i(1-\rho_r)-\lambda_i(1-\rho_0)\sigma_i(k))\beta V_i(k|\sigma_i) \qquad (7)
\end{aligned}
$$

where ρ_0 is the probability that a different user is in need of the power-off service but does not request and ρ_r is the probability that a different user rejects the power-off service when requested. The first item in (7) comes from when the user needs to send a silence request. In this case, it will spend one token and receive a benefit b_i. The second and part of the third items correspond to when the user is at the receiving end of a silence request. Depending on the strategy $\sigma_i(k)$, it can either increase a token by accepting the request, or remain with the same amount of tokens by rejecting the request. The remaining of the third items corresponds to when the user neither needs to send a silence request nor receives one.

B. Problem formulation

Ultimately the system designer is interested in maximizing the overall system performance, subject to that all users act in their own best interests by adopting the optimal user strategies. In order to achieve this goal, we need to understand the following hierarchical problems.

- **User-level Problem**. We need to derive each user's optimal strategy, i.e., the one that maximizes user utilities. This problem is solved at the user level: find the optimal strategy σ_i such that $\forall s \in \mathcal{S}$, we have $V_i\left(s|\sigma_i\right) \geq V_i\left(s|\sigma_i^{'}\right)$, if $\sigma_i^{'} \neq \sigma_i$.
- **System-level Problem**. Assuming that each individual user adopts the strategy that maximizes its own utility, the system-level problem seeks to maximize the overall system performance by issuing an optimal amount of tokens into the system. This problem is solved by the system designer, e.g., Home eNodeB Management System (HeMS).

There can be various system metrics applied to the above system-level problem. In this paper, we focus on minimizing the *network outage probability*, which is the probability that an active user cannot meet the requested QoS due to interference. This is a useful performance metric as it captures the impact of inter-cell interference in the entire network, and also isolates the interference problem from others, e.g., scheduling or physical layer issues. We denote the network outage probability as

$$\bar{\mathsf{P}}_{\mathsf{out}} \doteq \mathbb{E}_{\mathcal{S}}\left\{\mathsf{P}_{\mathsf{out}}\left(\{\sigma_i\}_{i=1}^{N}, s|W\right)\right\} \qquad (8)$$

where $\mathsf{P}_{\mathsf{out}}\left(\{\sigma_i\}_{i=1}^{N}, s|W\right)$ is the network outage probability when the overall system state is s and UE i uses strategy σ_i. Hence, by issuing an optimal amount of tokens to the system, the system designer can optimize the outage probability from the network perspective, when individual users choose the optimal strategies that maximize their own utilities. We can formally cast the design problem as:

$$
\begin{aligned}
\underset{W}{\text{minimize}} \quad & \mathbb{E}_{\mathcal{S}}\left\{\mathsf{P}_{\mathsf{out}}\left(\{\sigma_i\}_{i=1}^{N}, s|W\right)\right\} \\
\text{subject to} \quad & V_i\left(s|\sigma_i\right) \geq V_i\left(s|\sigma_i^{'}\right) \text{ if } \sigma_i^{'} \neq \sigma_i, \forall s \in \mathcal{S}.
\end{aligned} \qquad (9)
$$

In the following section, a general solution to Problem (9) is developed, where we first solve the *user-level problem* by presenting a threshold-based strategy for individual users and proving its optimality, and then solve the ultimate *system-level problem* that minimizes the network outage probability.

C. Optimal User Strategy

Let us consider a representative SC/UE i that has been asked to "silence" its downlink transmission to help out a neighboring user. Suppose a user already has k tokens. If it decides to power off its transmission, it will gain one more token to have a total of $k+1$ tokens in the next time slot; otherwise, it rejects the power off request and remains with k tokens in the next time slot. Since powering off its own transmission incurs a cost c_i, the concerning user needs to compare the utility improvement from accumulating one more token with the cost c_i to make a utility maximization decision. In fact, with some mild conditions, we can prove that the optimal σ is a threshold strategy. To simplify notation we write $V_i\left(k\right)$ instead of $V_i\left(k|\sigma\right)$.

Proposition 1: If the long-term utility function $V_i\left(k\right)$ is monotonically increasing and concave in k, then an optimal user strategy σ_i is a threshold strategy, i.e., there exists a threshold $K_{th,i}$ for user i such that

$$\sigma_i(k) = 1, \text{if } k \leq K_{th,i} \qquad (10)$$

$$\sigma_i(k) = 0, \text{if } k > K_{th,i} \qquad (11)$$

Proof: See Appendix A. ■

D. Optimal Token System Design

In this section, we focus on QoS failures that are caused by inter-cell interference, which captures the dominant outage event in small cell networks as they are interference-limited rather than thermal-limited. Let us use $\rho_k(i)$ to denote the percentage of users that possess k tokens and the optimal user strategy is a threshold strategy with threshold $K_{th} = i$, as in Proposition 1. Since N is large, we use a continuous model to approximate the discrete distribution. The percentage of the users who would reject a power-off request can be calculated as

$$\rho_{\mathsf{r}} = \sum_{i=0}^{\infty}\sum_{k=i+1}^{\infty}\rho_k(i). \qquad (12)$$

Note that ρ_{r} represents the probability that a user's power-off request to an interfering neighbor is rejected.

On the other hand, an outage can also happen when a user would like to pay one token to the interfering neighboring user for power-off, but has zero token in its possession to do so. This is captured by calculating the percentage of the small cells who have zero token and hence they cannot request power-off service when needed:

$$\rho_0 = \sum_{i=0}^{\infty} \rho_0(i). \tag{13}$$

The network outage probability can be expressed as

$$\begin{aligned}\bar{\mathsf{P}}_{\mathsf{out}} = & \Pr\{\text{User with zero token needs to use a token}\} \\ & + \Pr\{\text{User receives a token request and rejects it}\}.\end{aligned} \tag{14}$$

We focus on homogeneous cost c and demand rate λ , which suggests that all the users will use the same threshold strategy $K_{th,i} = K$. This is a valid assumption for static designs since the designer does not have the complete knowledge of benefits and costs of all users. Hence, we can then drop index i in $\rho_k(i)$ and only consider ρ_k, which is the percentage of UEs that possess k tokens. Obviously we have $\sum_{k=0}^{K} \rho_k = 1$. Moreover, we have $\rho_{\mathsf{r}} = \rho_K$. With all these conditions, the network outage probability can be computed as

$$\begin{aligned}\bar{\mathsf{P}}_{\mathsf{out}} &= \Pr\{\text{UE needs to use a token}\}\Pr\{\text{UE has 0 token}\} \\ &\quad + \Pr\{\text{UE receives a REQ}\}\Pr\{\text{UE has K tokens}\} \qquad (15) \\ &= \lambda\rho_0 + \left(1 - \left(1 - \frac{\lambda}{M}\right)^M\right)\rho_K. \qquad (16)\end{aligned}$$

Proposition 2: Assume users hold tokens and they can move arbitrarily within the small cell network. If all users in the network follow the threshold strategy in Proposition 1, and use the same optimal threshold K, then the optimal token supply per UE, $\frac{W^*}{N}$, that minimizes the network outage probability $\bar{\mathsf{P}}_{\mathsf{out}}$ in (16) is

$$\begin{cases} \dfrac{K}{2}, \text{ if } M = 1 \\ \dfrac{((K-1)\rho_K + \rho_0)(1-\rho_0)(1-\rho_K) - K\rho_K(1-\rho_K)^2}{(\rho_0 - \rho_K)^2}, \text{ else} \end{cases} \tag{17}$$

where $\{\rho_0, \rho_K\}$ satisfies:

$$\begin{cases} 0 \le \rho_K \le \dfrac{1}{K+1} \le \rho_0 \le 1 \\ \dfrac{\rho_0(1-\rho_0)(1-(K+1)\rho_K)}{\rho_K(1-\rho_K)(1-(K+1)\rho_0)} = \dfrac{(1-\lambda)^M - 1}{\lambda} \\ \rho_0(1-\rho_0)^K = \rho_K(1-\rho_K)^K \end{cases} \tag{18}$$

Proof: See Appendix B. ∎

V. Simulation Results

A. Simulation Setup

In order to verify the general theory that guides the optimal token system design, we resort to numerical simulations to demonstrate the effectiveness of the proposed design. In particular, an LTE-based system level simulator was developed in which the geometry of UEs and SCs is explicitly taken into account. We consider a large square area in which 2500 small cells and 2500 UEs are dropped. The entire area is divided into 50×50 small squares. At the center of each small square there is a SC base station whose location does not change over time. UEs, on the other hand, can move freely from time to time and be served by different SCs. The UE movement follows the random waypoint mobility model. Various values of the ISD are considered, ranging from 125 meters to 200 meters, where the former represents a hyper-dense small cell network while the latter corresponds to a sparse deployment. Some other system simulation parameters are summarized in Table I.

We consider the 3GPP pathloss model that is recommended for system simulations of small cells and heterogeneous networks. Particularly, we use the pathloss model in [13]:

$$PL(d)[dB] = 15.3 + 37.6 \times \log_{10}(d) + L_{ow}, d > d_0. \tag{19}$$

Shadowing is not explicitly considered mainly for simplicity, as in this case the outage event is entirely decided by the system geometry.

In the simulations, we study a specific system design by considering both *average QoS* and *outage probability* as the design objectives, to illustrate the effectiveness of the proposed design. Particularly, we consider a downlink small cell system with two different QoS classes: QoS class 1 which is a high-priority class, and QoS class 2 which is a low-priority one. We assume a linear QoS-to-Rate model for both classes $i = 1, 2$:

$$Q_i(R_i) = \begin{cases} 0, & R_i < R_{i,min} \\ Q_{i,min} + \alpha_i(R_i - R_{i,min}), & R_i \ge R_{i,min} \end{cases} \tag{20}$$

where $\alpha_1 > \alpha_2$ reflecting the higher priority of QoS class 1. It is worth mentioning that linear approximation of the QoS-to-Rate relationship is widely used in operational models [15], [16]. We use ξ to denote the probability of QoS class 1 packets, and $(1-\xi)$ to denote the probability of QoS class 2 packets. We define system outage as the decoding failure of QoS class 1 due to strong interference, which is captured by the received SINR of packets associated with QoS class 1 falls below the SINR threshold $\mathsf{SINR}_{\mathsf{th}}$ that corresponds to $R_{1,min}$. Furthermore, we assume full-buffer traffic for all UEs, i.e., $\gamma = 1$. Note that this is the worst case scenario as users will always incur a non-zero cost when accepting a token.

B. Performance

At initialization, we assign an equal amount of tokens to each UE, and then simulate the overall network for a total of 500 time slots. We first investigate whether the proposed token exchange schedule can improve the overall system performance by reducing the outage probability. Fig. 2 plots

TABLE I
SIMULATION PARAMETERS

Parameters	Value	Parameters	Value
SCs	2500	ISD	115m to 200m
UEs	2500	Noise density	-174dBm/Hz
Bandwidth	20MHz	Carrier freq.	2.1GHz
Tx power	10dBm	UE noise figure	5.5dB
PL model	3GPP [13]	Penetration loss	10dB
$\mathsf{SINR}_{\mathsf{th}}$	varies	d_0	1m

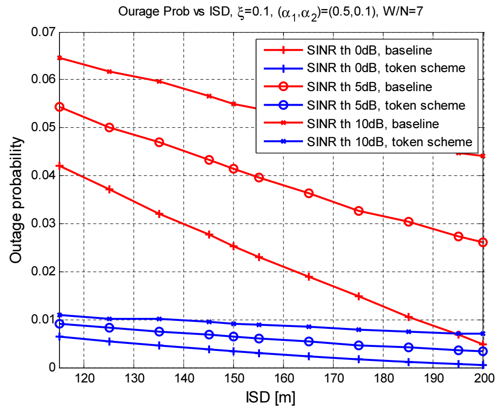

Fig. 2. System outage probability versus SC/UE density with different SINR thresholds. $(\alpha_1, \alpha_2) = (0.5, 0.1)$ and $\xi = 0.10$.

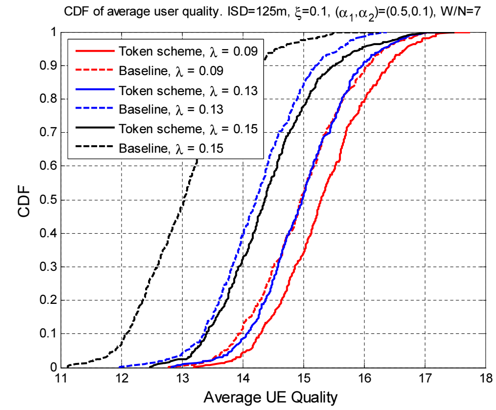

Fig. 3. CDF of user quality comparison: Baseline versus Token scheme. ISD = 125 meters, $(\alpha_1, \alpha_2) = (0.5, 0.1)$ and $\xi = 0.10$.

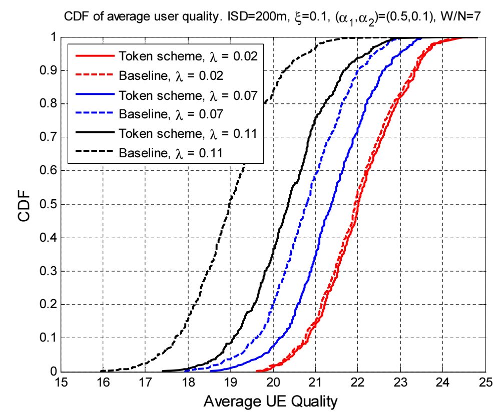

Fig. 4. CDF of user quality comparison: Baseline versus Token scheme. ISD = 200 meters, $(\alpha_1, \alpha_2) = (0.5, 0.1)$ and $\xi = 0.10$.

the system outage probability versus ISD with different SINR thresholds. We can see that the system outage probability with the proposed token exchange scheme is much lower than the baseline system performance, which allows all self-interested users to maximize the individual outage probability without any incentive to stimulate cooperations. Up to 75% performance improvement can be observed. Importantly, the improvement holds for various ISD values, which demonstrates the effectiveness of the proposed token scheme. Moreover, the performance gain decreases as the ISD increases. This is mainly because it is less likely to have significant inter-cell interference when the ISD is large. When ISD becomes very large, the neighboring cells are essentially isolated and hence no inter-cell interference exists. The proposed token system has no benefit in such scenario.

In addition to studying the system outage performance, we also compare the UE QoS of both schemes, using the same simulation parameters and geometry. Fig. 3 shows the CDF of the average UE quality for $ISD = 125$ meters (hyper-dense deployment), while Fig. 4 illustrates the same for $ISD = 200$ meters (sparse deployment). From the CDF curves, it is clear that the token scheme can also improve the average user quality. This is mainly due to the imbalance between QoS class 1 and class 2, and the gain comes largely from saving QoS class 1 failures due to strong interference at the price of sacrificing neighboring user's class 2 transmission, made possible by the token exchanges. Finally, we can see that the quality gain is more significant in the hyper-dense deployment than in the normal or sparse deployment. This observation, combined with the conclusion from Fig. 2, proves the importance of the proposed token scheme in the hyper-dense small cell deployment, which has been hailed as a key option for 5G wireless systems.

VI. Conclusions

We have proposed a novel token framework to address the inter-cell interference problem in a dense small cell network with self-interested users. Different from the previous approaches, tokens were introduced as an incentive to cease small cell transmissions for improved interference mitigation. Optimal token system design that minimizes the network outage probability was developed. We first provided a complete solution to the optimal user strategy that only aims at individual utility maximization. We proved that with some mild conditions, the optimal user strategy has a simple threshold structure. We then derived the optimal token supply that minimizes the network outage probability, assuming each user adopts its utility-optimal strategy. Numerical results were provided to prove the effectiveness of the token system. The proposed token design can compliment the existing interference management techniques, scale well with the volume of users, require minimal information exchange, work with cognitive and self-interested devices, and can be implemented with some enhancements to the existing LTE protocol. All these advantages render the token design a strong candidate for the 5G ultra-dense small cell networks.

Appendix A
Proof of Proposition 1

We drop the user index i for notation convenience. Since $V(k)$ is monotonically increasing, we have $V(k+1) -$

$V(k) > 0$. Using the definition of concavity, $V(k)$ must satisfy

$$V(\alpha k_1 + (1-\alpha)k_2) \geq \alpha V(k_1) + (1-\alpha)V(k_2), \forall k \leq W. \tag{21}$$

Choosing $\alpha = 1/2$, $k_1 = k$, $k_2 = k+2$, we have

$$V(k+1) - V(k) \geq V(k+2) - V(k+1), \forall k \leq W. \tag{22}$$

From inequality (22) we can prove that

Case 1: If $\exists k \in \mathbb{N}$ such that $V(k+1) - V(k) \geq \frac{c}{\beta}$ and hence $\sigma(k) = 1$, then $\forall k' \leq k$, we have

$$V\left(k'+1\right) - V\left(k'\right) \geq V(k+1) - V(k) \geq \frac{c}{\beta}. \tag{23}$$

Thus $\sigma(k') = 1, \forall k' \leq k$.

Case 2: If $\exists k \in \mathbb{N}$ such that $V(k+1) - V(k) < \frac{c}{\beta}$ and hence $\sigma(k) = 0$, then $\forall k' \geq k$, we have

$$V\left(k'+1\right) - V\left(k'\right) \leq V(k+1) - V(k) < \frac{c}{\beta}. \tag{24}$$

Thus $\sigma(k') = 0, \forall k' \geq k$.

Putting both cases together proves Proposition 1.

Appendix B
Proof of Proposition 2

Due to the space limitation, only the sketch of the full proof is provided. We already have an expression of $\bar{\mathsf{P}}_{\mathsf{out}}$ in (16):

$$\bar{\mathsf{P}}_{\mathsf{out}} = \lambda\rho_0 + \left(1 - \left(1 - \frac{\lambda}{M}\right)^M\right)\rho_K. \tag{25}$$

If we denote $\alpha_1 \doteq \lambda$ and $\alpha_2 \doteq 1 - \left(1 - \frac{\lambda}{M}\right)^M$, the objective function becomes

$$\bar{\mathsf{P}}_{\mathsf{out}} = \alpha_1\rho_0 + \alpha_2\rho_K, \tag{26}$$

with $\alpha_1 \leq \alpha_2$. Applying Proposition 4 in [9], we have that $\forall k = 0, 1, \cdots, K$,

$$\rho_k = \left(\frac{1-\rho_0}{1-\rho_K}\right)^k \rho_0. \tag{27}$$

It can be shown that the solution to the following optimization problem

$$\begin{array}{ll} \underset{\{\mathbf{x_1}, \mathbf{x_2}\}}{\text{minimize}} & \alpha_1 x_1 + \alpha_2 x_2 \\ \text{subject to} & x_1(1-x_1)^K = x_2(1-x_2)^K \\ & 0 \leq x_1, x_2 \leq 1 \end{array} \tag{28}$$

satisfies

$$\begin{cases} 0 \leq x_2^* \leq \dfrac{1}{K+1} \leq x_1^* \leq 1 \\ \dfrac{x_1^*(1-x_1^*)(1-(K+1)x_2^*)}{x_2^*(1-x_2^*)(1-(K+1)x_1^*)} = -\dfrac{\alpha_2}{\alpha_1} \\ x_1^*(1-x_1^*)^K = x_2^*(1-x_2^*)^K \end{cases} \tag{29}$$

Using (27), we have

$$\rho_k^* = \left(\frac{1-\rho_0^*}{1-\rho_K^*}\right)^k \rho_0^*. \tag{30}$$

The optimal token supply can be derived as

$$\begin{aligned} \frac{W^*}{N} &= \sum_{k=0}^{K} k\rho_k^* &(31)\\ &= \rho_0^* \sum_{k=0}^{K} k\left(\frac{1-\rho_0^*}{1-\rho_K^*}\right)^k &(32)\\ &= (17). &(33) \end{aligned}$$

where $\{\rho_0^*, \rho_K^*\}$ satisfy:

$$\begin{cases} 0 \leq \rho_K^* \leq \dfrac{1}{K+1} \leq \rho_0^* \leq 1 \\ \dfrac{\rho_0^*(1-\rho_0^*)(1-(K+1)\rho_K^*)}{\rho_K^*(1-\rho_K^*)(1-(K+1)\rho_0^*)} = -\dfrac{\alpha_2}{\alpha_1} \\ \rho_0^*(1-\rho_0^*)^K = \rho_K^*(1-\rho_K^*)^K \end{cases} \tag{34}$$

Note that $\alpha_1 = \alpha_2 = \frac{1}{2}$ is equivalent to $M = 1$, which completes the proof.

References

[1] A. Ghosh *et al.*, "Heterogeneous cellular networks: From theory to practice," *IEEE Commun. Mag.*, vol. 50, no. 6, pp. 54–64, June 2012.

[2] J. G. Andrews, "Interference cancellation for cellular systems: a contemporary overview," *IEEE Commun. Mag.*, vol. 12, no. 2, pp. 19–29, Apr. 2005.

[3] D. Gesbert, M. Kountouris, R. Heath, C.-B. Chae, and T. Salzer, "Shifting the MIMO paradigm," *IEEE Signal Processing Magazine*, vol. 24, no. 5, pp. 36–46, Sept. 2007.

[4] D. Lee *et al.*, "Coordinated multipoint transmission and reception in LTE-Advanced: deployment scenarios and operational challenges," *IEEE Commun. Mag.*, vol. 50, no. 2, pp. 148–155, Feb. 2012.

[5] E. Larsson, O. Edfors, F. Tufvesson, and T. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 186–195, Feb. 2014.

[6] M. Pischella and J. C. Belfiore, "Power control in distributed cooperative OFDMA cellular networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 5, pp. 1900–1906, May 2008.

[7] A. Simonsson, "Frequency reuse and intercell interference co-ordination in E-UTRA," in *Proc. IEEE VTC 2007 Spring*, pp. 3091–3095.

[8] J. Huang, Z. Han, M. Chiang, and H. Poor, "Auction-based resource allocation for cooperative communications," *IEEE J. Select. Areas Commun.*, vol. 26, no. 7, pp. 1226–1237, Sept. 2008.

[9] J. Xu and M. van der Schaar, "Token system design for autonomic wireless relay networks," *IEEE Trans. Commun.*, vol. 61, no. 7, pp. 2924–2935, July 2013.

[10] V. Vishnumurthy, S. Chandrakumar, and E. G. Sirer, "KARMA: A secure economic framework for peer-to-peer resource sharing," in *Workshop on the Economics of Peer-to-Peer Systems*, Berkeley, California, June 2003.

[11] D. R. Figueiredo, J. K. Shapiro, and D. Towsley, "Payment-based incentives for anonymous peer-to-peer systems," University of Massachusetts Computer Science, Tech. Rep. 04-62, July 2004.

[12] G. Mailath and L. Samuelson, Eds., *Repeated games and reputations: long-run relationships*. New York, USA: Oxford University Press, 2006.

[13] 3GPP, "Simulation assumptions and parameters for FDD HeNB RF requirements," Tech. Rep. TSG RAN WG4 R4-092042, May 2009.

[14] D. Lopez-Perez, I. Guvenc, G. de la Roche, M. Kountouris, T. Quek, and J. Zhang, "Coordinated multipoint transmission and reception in LTE-Advanced: deployment scenarios and operational challenges," *IEEE Wireless Communications*, vol. 18, no. 3, pp. 22–30, June 2011.

[15] C. Shen and M. van der Schaar, "Optimal resource allocation for multimedia applications over multiaccess fading channels," *IEEE Trans. Wireless Commun.*, vol. 7, no. 9, pp. 3546–3557, September 2008.

[16] M. van der Schaar and P. Chou, Eds., *Multimedia over IP and Wireless Networks: Compression, Networking, and Systems*. Elsevier, Mar. 2007.