Stackelberg Game Based Cooperative User Relay Assisted Load Balancing in Cellular Networks

Dantong Liu, Yue Chen, Tiankui Zhang, Kok Keong Chai, Jonathan Loo, and Alexey Vinel

***Abstract*—We propose a Stackelberg game based cooperative user relay assisted load balancing (LB) scheme to tackle SNR degradation problem of shifted cell-edge users which commonly occurs in a conventional direct handover LB scheme. In the proposed scheme, users from a lightly loaded cell can be selected as cooperative user-relays and will be paid by the shifted cell-edge users. Stackelberg game theory is applied to optimize the strategies of both the user relays and shifted cell-edge users, in order to maximize both of their utilities in terms of SNR and payment. Theoretical analysis and simulation study are undertaken to show the effectiveness of the proposed scheme.**

***Index Terms*—Cooperative user relay, load balancing, Stackelberg game.**

I. Introduction

LOAD balancing (LB) scheme is well suited to tackle the hotspot problems caused by bursty and unevenly distributed traffic. However, in the conventional direct handover based LB, the SNR of the shifted cell-edge users will decrease when the channel condition at the cell-edge is poor [1]. Cooperative transmission [2] is a promising candidate to overcome the above problems due to its inherent spatial diversity gain. In [3] and [4], fixed relay in cooperative networks have been studied, which utilized spatial diversity technique. In this letter, user relay is adopted, compared to the fixed relay, it can eliminate the deployment and infrastructure problems as well as benefiting from spatial diversity gains.

In this letter, we propose a cooperative user relay assisted LB scheme, where the cell-edge users of the heavily loaded hotspot cell can be handed over to a lightly loaded neighbour cell via a user in the lightly loaded cell as the relay for cooperative transmission. In turn, the user relays ask for the payment from the shifted cell-edge users as a reward for their cooperation.

In order to ensure the user relay cooperative transmission benefiting both heavily and lightly loaded cells, several concerning problems should be resolved such as which user node should be selected as a user relay for a certain shifted cell-edge user, what power level should the user relay adopt for the cooperative transmission and how to maximize the utility of all the selected user relay in terms of payment.

In [5], a form of user cooperation diversity formulated with a 2-person bargaining cooperative game theory was studied. In such game, two agents in an equal status are bargaining how resources should be shared for cooperation.

Stackelberg game theory [6], on the other hand, is more suitable for our study as it is a leader-follower (or seller-buyer) sequential game, and modelling the user relay and shifted cell-edge user by leader and follower relationship is much closer to the practical system operation. The work [7] applies the Stackelberg game to help the source select relays and improve the system performance in cooperative transmission. However this work does not address the load balance issue between heavy-load and light-loaded cells. The main contribution of this letter is the Stackelberg game theory based analysis for the user cooperation in the user relays assisted LB scheme, between cells, in order to maximize the average SNR of all the shifted cell-edge users and optimize the utility of each selected user relay in terms of payment.

The paper is organized as follows. In Section II the system model and the studied problem are formulated. In Section III, the optimal strategies of both the user relays and shifted cell-edge users are analyzed via Stackelberg game. Simulation results and conclusions are in Sections IV and V, respectively.

II. Problem Formulation

A. System model

The downlink transmission in cellular networks is considered with the assumption that orthogonal channels are allocated to different users.

Assuming there are M cell-edge user equipments in the heavily loaded cell h, donated as UE_m ($m = 1, 2, \ldots, M$), and they need to be handed over to the neighbour lightly loaded cell l. There are N user nodes in cell l, which all have the potential to act as user relay which facilitates handover to help the UE_m achieve higher data rate than the corresponding data rate during the direct handover, and they are donated as UR_n ($n = 1, 2, \ldots, N$). The downlink transmission in this handover model is shown in Figure 1. BS_l is the base station in cell l.

The transmission in this system model is based on frame-by-frame basis. The first time slot is for the transmission from BS_l to UR_n and the transmission from BS_l to UE_m directly, the other one is for the transmission from UR_n to UE_m. In this letter, an amplify-and-forward [4] relay is considered since it has the advantages of simple implementation and low computation load for UR_n.

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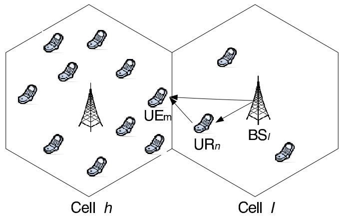

Fig. 1. Direct handover and user relay assisted handover.

At the end of slot t, the signals received in UR$_n$ and UE$_m$ are expressed as $y_{bn}[t] = \alpha_{bn}x_b[t] + z_n[t]$ and $y_{bm}[t] = \alpha_{bm}x_b[t] + z_m[t]$, respectively, where $x_b[t]$ is the information sent from BS$_l$ at t-th frame, $z_n[t]$ and $z_m[t]$ are the background noise at UR$_n$ and UE$_m$, which are independent identically distributed (i.i.d) complex Gaussian random variables with a common variance σ^2, α_{bn} and α_{bm} are the channel gains from BS$_l$ to UR$_n$ and from BS$_l$ to UE$_m$ respectively.

At the end of time slot $t+1$, the signal received in UE$_m$ is $y_{nm}[t+1] = \alpha_{nm}\lambda y_{bn}[t] + z_m[t+1]$, where α_{nm} is the channel gain from UR$_n$ to UE$_m$, λ is the amplification factor of relay, which is related to the transmission power of UR$_n$. It satisfies $\lambda^2(|\alpha_{bn}|^2 P_b + \sigma^2) = P_n$, that is $\lambda^2 = P_n/(|\alpha_{bn}|^2 P_b + \sigma^2)$, where P_b and P_n are the transmission powers of BS$_l$ and UR$_n$.

The following gives the data rate for different way of transmission.

B. Direct transmission without user relay

To establish baseline performance under direct transmission, we consider the case when the BS$_l$ transmit signal to UE$_m$ directly. The data rate between input and output is achieved by i.i.d. zero-mean, circularly symmetric complex Gaussian inputs [8]:

$$R^d = \log(1 + SNR|\alpha_{bm}|^2),$$

where SNR is the ratio of signal to noise power in the source node (here is BS$_l$). In this model, the data rate of direct transmission between BS$_l$ and UE$_m$ is expressed as follows:

$$R_m^d = \log(1 + \frac{\beta_{bm} P_b}{\sigma^2}), \tag{1}$$

where $\beta_{bm} = |\alpha_{bm}|^2$.

C. Cooperative transmission via user relay

When considering the transmission via user relay, the amplify-and-forward protocol produces an equivalent one-input, two-output complex Gaussian noise channel. The data rate between the input and the two outputs, achieved by i.i.d. complex Gaussian inputs, is given by [8]:

$$R^r = \frac{\log(1 + SNR|\alpha_{bm}|^2 + \frac{SNR|\alpha_{bn}|^2 SNR|\alpha_{nm}|^2}{1+SNR|\alpha_{bn}|^2+SNR|\alpha_{nm}|^2})}{2}.$$

In this model the data rate of transmission between BS$_l$ and UE$_m$ via UR$_n$ is expressed as the following:

$$R_{mn}^r = \frac{1}{2}\log(1 + \frac{P_b}{\sigma^2}(\beta_{bm} + \frac{\beta_{bn}\beta_{nm}P_{mn}}{\beta_{bn}P_b + \sigma^2 + \beta_{nm}P_{mn}})), \tag{2}$$

where $\beta_{bn} = |\alpha_{bn}|^2$, $\beta_{bm} = |\alpha_{bm}|^2$, $\beta_{nm} = |\alpha_{nm}|^2$, P_{mn} is the power UR$_n$ used for UE$_m$'s cooperative transmission, when UR$_n$ acts as relay for UE$_m$.

D. User relay selection criterion

Only when the shifted cell edge users' data rate in user relay assisted handover is higher than the data rate through direct handover, the user relay UR$_n$ will be selected for UE$_m$'s cooperative transmission. Thus the respective criterion is

$$R_m^d < R_{mn}^r. \tag{3}$$

The matrix $K = \{k_{mn}\}_{M\times N}$, $k_{mn} = \{0, 1\}$ is used to denote the relationship between the potential user relays and shifted cell-edge users:

$$k_{mn} = \begin{cases} 1, & \text{UR}_n \text{ is selected as a user relay for UE}_m \\ 0, & \text{otherwise} \end{cases}, \tag{4}$$

then the data rate of the shifted cell-edge user is:

$$R_m = \begin{cases} R_{mn}^r, & \text{when } \sum_n k_{mn} = 1 \\ R_m^d, & \text{otherwise} \end{cases}. \tag{5}$$

To ensure the cooperative user relay assisted LB scheme benefiting both the heavily and lightly loaded cells, three problems should be resolved. First is which user relay n should be selected to serve shifted cell-edge user m. Second is what power level should each selected user relay use for the cooperative transmission. Third one is how much the payment/revenue should the user relays get as a reward for the cooperation. To solve the above problems, Stackelberg game is used to optimize the behaviors of shifted cell-edge users and user relays.

III. STACKELBERG GAME THEORY ANALYSIS

A. Shifted cell-edge user's/ buyers' utility function

The shifted cell-edge users can be modelled as followers, since they need buy the user relays' resource for cooperative transmission, so they can be also called buyers. One of the aims of the proposed scheme is to maximize the cell's overall utility, so they intend to maximize the overall utility of all the shifted cell-edge users. The overall utility can be formulated as:

$$U^e = \sum_{m=1}^{M} R_m - \sum_{n=1}^{N} Q_n, \tag{6}$$

where R_m is the data rate of the shifted cell-edge user UE$_m$, Q_n is the payment for UR$_n$, which is defined as following:

$$Q_n = \sum_{m=1}^{M} k_{mn}\rho_{mn}P_{mn}, \tag{7}$$

where ρ_{mn} is the unit power price UR$_n$ charge for UE$_m$'s cooperative transmission when UR$_n$ acts as user relay for UE$_m$.

The optimization problem for all the buyers game can be formulated as:

$$\max U^e, \tag{8}$$

$$\text{s.t.} \quad \textstyle\sum_m k_{mn} \le 1, \tag{9}$$

$$\textstyle\sum_n k_{mn} \le 1, \tag{10}$$

$$k_{mn} = \{0, 1\}, 1 \le m \le M \text{ and } 1 \le n \le N. \tag{11}$$

The constraint in (9) means that one potential user relay can serve at most one shifted cell-edge user. Although in theory, one user relay is able to serve multiple shifted cell-edge users, considering the implementation complexity in practice, one user relay is constrained to serve one shifted cell-edge user. The constraint in (10) indicates that one shifted cell-edge user can only select at most one user relay, because one relay is capable to achieve full diversity of cooperation [9].

B. User relays'/ sellers' utility function

The user relays can be modelled as leaders, since they own the available resource for cooperative transmission; user relays are also called sellers as they sell their power to the shifted cell-edge users for the cooperative transmission. The utility function of each user relay UR_n when serving UE_m can be formulated as:

$$\mu_{mn}^r = (\rho_{mn} - c_n)P_{mn}, \tag{12}$$

where c_n is the cost of UR_n's unit power for relaying data.

Each user relay aim to earn the payment which not only covers their forwarding cost but also obtain as much net profit as possible. Then optimization problem for each user relay UR_n when serving UE_m can be formulated as:

$$\max_{\rho_{mn}>0} \mu_{mn}^r, \ \forall n, m. \tag{13}$$

C. Optimal strategy analysis

1) Shifted cell-edge user's/ buyers' strategy analysis: The shifted cell-edge users aim to maximize their utility. Substituting (4), (5) and (7) into function (6), the utility of the shifted-cell edge users can be written as:

$$U^e = \sum_{m=1}^{M} (R_m^d + \sum_{n=1}^{N} k_{mn} I_{mn}), \tag{14}$$

where

$$I_{mn} \triangleq R_{mn}^r - R_m^d - P_{mn}\rho_{mn}. \tag{15}$$

The optimization problem of the shifted cell-edge users' game is a mixed integer problem. Fortunately, as shown in equation (14), the utility function U^e increases as the function I_{mn} grows. Furthermore, it is found that I_{mn} is independent of K. Thus, this optimization problem can be solved in two linear parts. First of all, optimal amount of cooperative transmission power P_{mn} is determined to maximize I_{mn}. Secondly, based on the result of the first part, relay selection K is decided to maximize the overall utility of all the shifted cell-edge users.

Therefore, we analyze to maximize I_{mn} firstly. Depending on (15), by first order of I_{mn}, it follows that:

$$\frac{dI_{mn}}{dP_{mn}} = \frac{dR_{mn}^r}{dP_{mn}} - \rho_{mn}. \tag{16}$$

When $P_{mn} \neq 0$, if $\rho_{mn} < dR_{mn}^r/dP_{mn}$, we have $dI_{mn}/dP_{mn} > 0$, which means UE_m can increase U^e by purchasing larger power from UR_n. Thus, the price ρ_{mn} determines the amount of power UE_m will purchase from UR_n. It is easy to understand that UR_n will set low initial price (such as c_n) to attract UE_m, and then UR_n may increase the price ρ_{mn} to make more profit. When $\rho_{mn} > dR_{mn}^r/dP_{mn}$, UE_m will decrease its utility when purchasing more power from UR_n, so UE_m will buy less power from UR_n.

Therefore, the optimal condition to maximize I_{mn} is expressed:

$$\frac{dI_{mn}}{dP_{mn}} = 0. \tag{17}$$

Solving (17), the optimal power amount P_{mn}^*, which UE_m buy from UR_n is:

$$P_{mn}^*(\rho_{mn}) = \frac{-\rho_{mn}B(2+A)+\sqrt{4AB\rho_{mn}W+A^2B^2\rho_{mn}^2+4\rho_{mn}A^2BW}}{2\rho_{mn}(1+A)}, \tag{18}$$

where $A = P_b\beta_{bn}/(\sigma^2 + P_b\beta_{bm})$, $B = (\sigma^2 + P_b\beta_{bn})/\beta_{nm}$, $W = 1/(2\ln 10)$.

Furthermore, we can prove that when UR_m announce the price ρ_{mn}, I_{mn} is the concave function of P_{mn}, since $\partial^2 I_{mn}/\partial P_{mn}^2 < 0$. In turn, this justifies the way to maximize I_{mn} by its first order.

2) User relays'/ sellers' strategy analysis: Every user relay wants to maximize their utility. Substituting (18) into function (13), we obtain:

$$\max \mu_{mn}^r = (\rho_{mn} - c_n)P_{mn}^*. \tag{19}$$

We can prove that μ_{mn}^r is a concave function of ρ_{mn}, since $\partial^2\mu_{mn}^r/\partial\rho_{mn}^2 < 0$. Thus, the optimal ρ_{mn} to maximize μ_{mn}^r can be derived from:

$$\frac{d\mu_{mn}^r}{d\rho_{mn}} = P_{mn}^* + (\rho_{mn} - c_n)\frac{dP_{mn}^*}{d\rho_{mn}} = 0. \tag{20}$$

Finally the optimal unit power price ρ_{mn}^* is derived and subsequently through (18), the corresponding optimal power P_{mn}^* is obtained. Based on the above ρ_{mn}^* and P_{mn}^*, user relay selection K will be determined to maximize the overall utility of all the shifted cell-edge users and K can be computed by Hungarian method with computation complexity $O((M+N)^3)$ [10].

IV. Simulation Results

A. Simulation settings

A two-hop cellular network system-level simulation platform is developed for the simulation. In this simulation, two adjacent cells are considered, one is heavily loaded, and the other is lightly loaded. 25 users are randomly distributed in the heavily loaded cell-edge area (farther than 0.8×radius of cell from BS). N users are randomly distributed in the lightly loaded cell, and they all located in the intermediate area between the BS_l and shifted cell-edge users in the heavily loaded cell, N=10, 15, 20, and 25.

B. Simulation results

We compare the results of the proposed scheme with the conventional direct handover based LB and the user relay assisted LB without the proposed game theory approach. In the simulation, the conventional direct handover based LB is arranged that the edge users are shifted to the target lightly loaded cell without any relay. Meanwhile in the user relay assisted LB without game theory, we have set the shifted cell-edge user with worst channel condition to have the highest priority in user relay selection, and all the shifted cell-edge users are selfish and aim to maximise their own SNR without considering the cell's overall utility maximization.

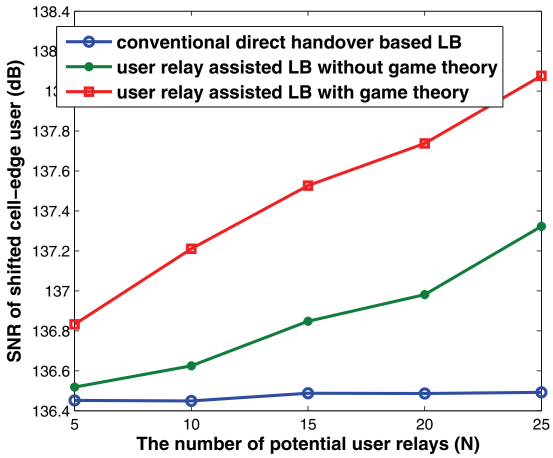

Fig. 2. SNR of shifted cell-edge user with different LB scheme.

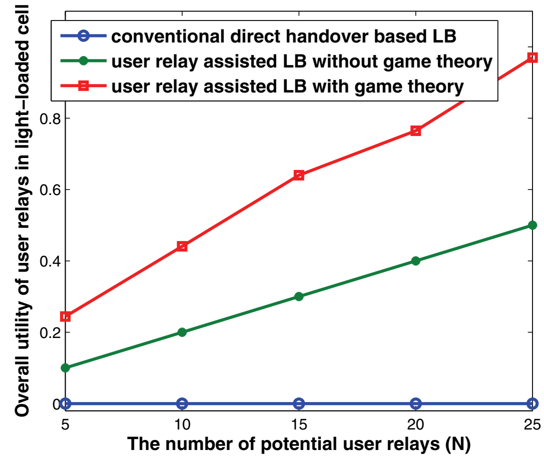

Fig. 3. Overall utility of user relays in lightly loaded cell.

1) Average SNR of every shifted cell-edge users: Figure 2 shows that in case of conventional direct handover based LB the shifted cell-edge users' SNR in the heavily loaded cell doesn't change much with the increasing number of potential user relay. This is due to the fact that the direct handover does not utilize user relay in the lightly loaded cell.

On the other hand, in case of the user relay assisted LB with or without game theory, the shifted cell-edge users' SNR is increasing linearly proportional to the increasing number of potential user relay. This improvement is due to the diversity gain achieved by the cooperative user relays.

As shown in Figure 2, the proposed user relay assisted LB with game theory is superior to the LB without game theory with the increasing number of potential user relays, since it is aimed at achieving global optimum by efficiently distributing user relays to shifted cell-edge users and help enhancing their average SNR.

2) Overall utility of user relays in lightly loaded cell: Figure 3 shows the overall utility of user relays in lightly loaded cell (which is the sum of all the selected user relay's utility) versus the number of potential user relays. Obviously, in the proposed user relay assisted LB with game theory, the user relays obtain the most payment (utility). The utility grows as number of relay increases, which will stimulate more potential user relays into the cooperative transmission. In the conventional direct handover based LB, the lightly loaded cell will gain nothing from the cooperation.

V. Conclusion

In this letter, a Stackelberg game based cooperative user relay assisted load balancing scheme is proposed. In this scheme, both heavily and lightly loaded cell can benefit, where the users from the lightly loaded cell are selected as relays for the shifted cell-edge users' cooperative transmission and the cell-edge users will pay the selected user relays. The Stackelberg game theory, which is a leader-follower sequential game, enables all the shifted cell-edge users and user relays adopt optimal strategies, resulting in efficiently distributing user relays to shifted cell-edge users. Simulation results indicate the proposed scheme achieves a global optimum in all the shifted cell-edge users' average SNR improvement and the selected user relay's utility maximization.

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