User Cooperation Solution of Multipath Streaming Application Using Auction Theory

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***Abstract*—Cooperation among network devices is a promising solution to improve network throughput and network service quality. In addition, it can be used to enhance network survivability against failures. In this paper, we study the user cooperation solution of multipath streaming application on wireless user equipments (UEs) using auction theory. We assume that UEs use multipath transport layer service, and establish two paths for streaming events, one path goes through its cellular link, another path is established using a Wi-Fi connection with a neighbor UE. We propose two user cooperation schemes (LCF and EAC) for UEs to participate in the user cooperation system. We compare the performance of using LCF and EAC schemes to the scheme without cooperation, and the simulation results show that applying the proposed user cooperation scheme and establishing multipath connections for the streaming event can reduce up to 60% of total energy consumed. LCF scheme can also help balance the energy consumption among UEs in the system.**

***Index Terms*—User cooperation, multipath communication, auction theory.**

I. Introduction

In modern cellular networks, mobile traffic is exponentially growing because of the broad use of smartphones, tablets together with the 'data hungry' applications, such as wireless high definition video application, location navigation service, online gaming etc. Network cooperation and user cooperation are two promising solutions to use current network resources to increase bit rate, improve service reliability, and meet the users quality of service requirements. Network cooperation solution [1], [2] allows cooperation among base stations to provide service to UEs using signal coding and beam forming techniques. This approach can reduce intercell interference greatly and increase service rate. The disadvantage is that not all wireless networks have coverage over the mobile devices. Wifi networks have disjoint coverage, and most mobile devices only have one subscriber identity module (SIM) card and can only connect to one wireless network at one time. User cooperation approach [3]–[6] allows mobile devices in the vicinity to cooperate providing mobile users with stable quality of service. It's advantages over network cooperation approach is that:1) power consumption of the UE is balanced by nearby UEs that relay packets for it; 2) if the UE can only connect to cellular network or Wi-Fi network, it can still enhance its bandwidth by connecting to relay UEs using its other available wireless interfaces [7].

There is a number of technologies that can be used for user cooperation purpose [8]:

- Bluetooth: most energy efficient, and only supports point-to-point connections. But it can be difficult to create large groups of devices and has relatively low speeds.
- Wifi hotspot: one device acts as the access point, and the others as clients. It is widely supported and offers high speeds. However, the device acting as access point will consume more energy.
- Wi-Fi Direct: allows true peer-to-peer operation and offers high speeds.
- LTE Direct: emerging technology that uses the LTE band for energy-efficient device-to-device communication and discovery.

What's more, multipath transport layer protocols like Multipath Transmission Control Protocol (MPTCP) [9] and Multipath Real-time Transport Protocol (MPRTP) [10] provide multipath functionality that increase both service rate and service reliability. In this paper, we assume UEs are enabled with device to device (D2D) communication technology and multipath transport layer service, and can establish two paths for streaming applications, where one path goes through its cellular link, other path is established using a Wi-Fi Direct connection with a neighbor UE.

In this paper, we study user cooperation solutions of streaming applications using auction theory approach. References [3]–[6] are some of the recent related research works. Their works are mainly focused on resource allocation, route selection and interference cancelation in cooperative communications. [3] studied a scenario where a D2D transmitter acts as an in-band relay for a cellular link and at the same time transmits its own data by employing superposition coding in the downlink. They formulated an optimization problem to minimize the assigned power for cooperation while achieve the direct link capacity for the D2D transmitter. [4] and [5] both studied the scenario where the UEs closer to BS acting as relays for UEs which are far away from the BS. In this two step forwarding scenario, they formulated the problem into joint optimization of power allocation, subcarrier pairing and relay selection such that the total throughput in the system is maximized. The major difference is between [4] and [5] is that [5] studied a wireless powered communication network (WPCN) where UEs transfer information using the energy harvested. [6] studied network resource allocation problem among users that manage multiple connections. They studied this problem from the data flow level and assume the system has a given number of links and end-to-end connections. They formulated problems to optimize the end-to-end connections such that the given utility objectives are optimized. All of these works did not provide incentives to UEs serving as the relay. In this study, we treat all users in the system as selfish users. The incentive for participating in user cooperation is that relay UEs must be paid by the traffic UEs which they relays traffic for. Relay UEs can choose to work with traffic UEs whoever provide them with maximum utility. We form the user cooperation negotiation process as an auction game, and design rules for UEs to follow such that the system performance are greatly improved compared to the non-cooperation scheme. The simulation study shows that our proposed user cooperation schemes improve system performance by reducing total energy consumption down to $50-60\%$ of the energy consumption of the non-cooperation scheme. The relay UEs are motivated in participating in the auction game with positive utility. In addition, one of the proposed user cooperation scheme shows potential in balancing the UE's remaining energy.

The rest of the paper is organized as follows. Section II introduces the system model. The problem formulation of streaming traffic allocation optimization is given in Section III. Section IV explains the proposed solution of the streaming traffic allocation problem. The participation rules of the auction are provided in Section V. The numerical results are discussed in Section VI. Finally, the paper is concluded in Section VII.

II. System Model

We study a wireless network environment as shown in Fig.1. A Macro Base Station (MBS) locates in the center of the cell, and a number of User Equipments (UE) are deployed within the transmission range of the MBS. For a UE i with streaming event, the neighbor UEs within i's transmission range participate in a auction, and the winning neighbor UE receives traffic from UE i through Wi-Fi device to device connection and forward the traffic to BS using its cellular link. We assume UEs belong to different users, therefore they have no obligation in forwarding other UEs' traffic unless they enjoy positive utility with the payment made to them.

We denote UEs with streaming event as auctioneers, and their neighbor UEs that within auctioneers' transmission range as bidders. The bidders report their transmission cost related information to the auctioneers, as if the bidders report their bids to auctioneers. We assume information is not known to other UEs and only auctioneer receives it (sealed bid). Auctioneers then run the auction following the rules proposed in Section V. Our objective is to design the auction operation rules such that the streaming event is supported with the highest bit rate that can be achieved, and the power consumption is minimized.

At the beginning of the auction, every bidder reports bid to the auctioneers. For example, bidder i reports $Info_i$ to the auctioneer o, where $Info_i = \{d_i, d_{io}, k_i, \alpha_{i0}, \alpha_{i1}, E_{iFull}, \theta_i, E_i\}$. The symbols of the $Info_i$ are explained below:

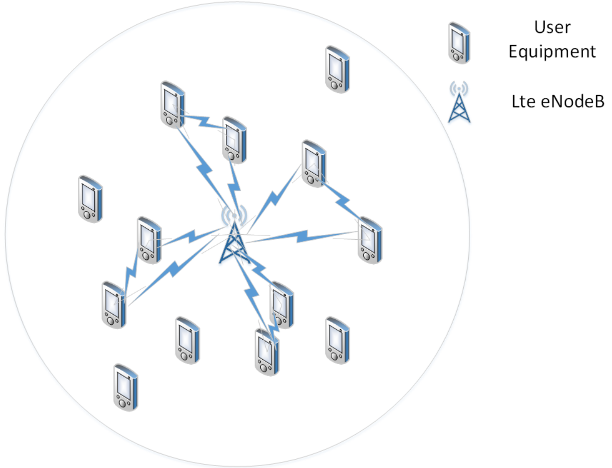

Fig. 1: Network model

- d_i, d_{io}: d_i is the distance in meters between bidder i and MBS. d_{io} is the distance in meters between bidder i and auctioneer o.
- $k_i, \alpha_{i0}, \alpha_{i1}, \theta_i, E_{iFull}$: we assume the energy price of every UE is a linear function of its current energy balance. $\alpha_i = \mathbb{I}_{\{e_i>\theta_i E_{iFull}\}}\alpha_{i0} + (1-\mathbb{I}_{\{e_i>\theta_i E_{iFull}\}})\alpha_{i1} + k_i e_i$, where $k_i < 0$, and

  $$\mathbb{I}_{\{e_i>\theta_i E_{iFull}\}} = \begin{cases} 1 & e_i > \theta_i E_{iFull} \\ 0 & e_i \le \theta_i E_{iFull} \end{cases}$$

  e_i is UE i's current energy balance, E_{iFull} is the energy balance when UE i is fully charged, θ_i is a threshold $\in (0,1)$ and α_{i1} is a very large number close to infinity. The cost function suggests when UE i has energy balance below θE_{iFull}, it will not participate in the Auction as bidders. k_i is the slope of the linear function. The total energy cost when e_i of UE i drops from energy balance E_1 to energy balance E_2 is as follows:

  $$Cost = \int_{e_i=E_2}^{E_1} \Big(\mathbb{I}_{\{e_i>\theta_i E_{iFull}\}}\alpha_{i0} + (1-\mathbb{I}_{\{e_i>\theta_i E_{iFull}\}})\alpha_{i1} + k_i e_i\Big) de_i \qquad (1)$$

- E_i: bidder i's current remaining energy.

with $Info_i$, auctioneer calculates the minimal total energy cost of the cooperation between itself and bidder i by optimizing the streaming traffic allocation. The minimized energy cost is bidder i's bid. The formulation of this optimization problem is described in the next Section.

III. Problem Formulation

In this section, we formulate the problem to calculate the bid given bidder's reported information. The actual bid can be optimized by choosing the optimal portion $\beta \in [0,1]$ of the total streaming traffic to be relayed by the bidder. $1-\beta$ is the portion of streaming traffic transmitted through the auctioneer's cellular link.

Let $r_{imax} = \min\{R_{oimaxWifi}, R_{imaxLte}\}$ be the maximum transmission rate supported by bidder i, where $R_{oimaxWifi}$ is the maximum transmission rate through the Wi-Fi connection between bidder i and auctioneer o and $R_{imaxLte}$ is the maximum transmission rate through i's cellular connection to MBS. Given the maximum transmission rate $R_{omaxLte}$ supported by auctioneer o's cellular connection to MBS, the maximum transmission rate supported by the cooperative transmission of auctioneer o and bidder i: $TP_i = r_{imax} + R_{omaxLte}$. Applying Shannon-Hartley theorem, $R_{imaxLte}$, $R_{oimaxWifi}$ and $R_{omaxLte}$ is calculated using following equations:

$$R_{imaxLte} = W_{iLte} \log_2 \left(1 + \frac{Pt_{imaxLte} \cdot H_{lte}(d_i)}{N_0 W_{iLte}}\right) \quad (2)$$

$$R_{oimaxWifi} = W_{wifi} \log_2 \left(1 + \frac{Pt_{maxWifi} \cdot H_{wifi}(d_{io})}{N_0 W_{wifi} + I_{wifi}}\right) \quad (3)$$

$$R_{omaxLte} = W_{oLte} \log_2 \left(1 + \frac{Pt_{omaxLte} \cdot H_{lte}(d_o)}{N_0 W_{oLte}}\right) \quad (4)$$

W_{iLte}, W_{wifi} and W_{oLte} are the spectrum bandwidth assigned to bidder i's cellular connection, Wi-Fi connection between bidder i and auctioneer o and auctioneer o's cellular connection, respectively. H_{wifi} and H_{lte} are the channel gain of Wi-Fi channel and cellular channel, respectively. $Pt_{imaxLte}$, $Pt_{maxWifi}$ and $Pt_{omaxLte}$ are the maximum transmission power of cellular interface of bidder i, Wi-Fi interface of auctioneer o and celular interface of auctioneer o, respectively. N_0 is noise power spectrum density. d_o is the distance in meters between auctioneer o and MBS. I_{wifi} is the interference towards the Wi-Fi receiver. We ignore the interference on the cellular receiver in MBS, since the spectrum assigned to UEs is in the form of nonoverlapping resource blocks.

We assume the streaming application generates traffic with three different constant bit rates: $\{B_{low}, B_{med}, B_{high}\}$, and the auctioneer always choose the highest streaming bit rate restricted by the maximum channel capacity TP_i:

- $TP_i < B_{low} \rightarrow$ the streaming event is not supported.
- $B_{low} \leq TP_i < B_{med} \rightarrow B_o = B_{low}$.
- $B_{med} \leq TP_i < B_{high} \rightarrow B_o = B_{med}$.
- $B_{high} \leq TP_i \rightarrow B_o = B_{high}$.

The resulted optimization problem is formulated as follows:

$$\underset{\beta}{\text{Minimize}} \quad Cost_o + Cost_i \quad (5)$$

$$\text{s.t.} \quad \beta B_o <= \min\{R_{oimaxWifi}, R_{imaxLte}\} \quad (6)$$

$$(1-\beta) B_o <= R_{omaxLte} \quad (7)$$

$$0 \leq \beta \leq 1 \quad (8)$$

$$\beta B_o = w_{iLte} \log_2 \left(1 + \frac{Pt_{iLte} \cdot H_{lte}(d_i)}{N_0 w_{iLte}}\right) \quad (9)$$

$$\beta B_o = w_{wifi} \log_2 \left(1 + \frac{Pt_{oWifi} \cdot H_{wifi}(d_{io})}{N_0 w_{wifi} + w_{wifi} \frac{I_{wifi}}{W_{wifi}}}\right) \quad (10)$$

$$(1-\beta) B_o = w_{oLte} \log_2 \left(1 + \frac{Pt_{oLte} \cdot H_{lte}(d_o)}{N_0 w_{oLte}}\right) \quad (11)$$

$Cost_o$ is the energy cost on auctioneer o, and $Cost_i$ is the energy cost on bidder i. w_{iLte}, w_{wifi} and w_{oLte} are the actual bandwidth used by bidder i's cellular link, Wi-Fi link between bidder i and auctioneer o and auctioneer o's cellular link, respectively. Pt_{iLte}, Pt_{oWifi} and Pt_{oLte} are the transmission power of bidder i's cellular interface, auctioneer o's Wi-Fi interface and auctioneer o's cellular interface, respectively. Constraint (6) and (7) state that the data rates go through bidder i and auctioneer o should not exceed their corresponding transmission capacity. Constraints (9) to (11) state the relations between the transmission power Pt_{iLte}, Pt_{oWifi} and Pt_{oLte} and their supported data rates.

We consider two different approaches to design the energy cost function. The first one is the linear cost function (LCF) we proposed in Section II, and the second one uses consumed energy as the energy cost (EAC). The closed form expressions for $Cost_o$ and $Cost_i$ are as follows when using LCF approach:

$$\begin{aligned} Cost_i = & \int_{e_i=E_i-Pt_{iLte}T_o}^{E_i} \Big(\mathbb{I}_{\{e_i>\theta_i E_{iFull}\}}\alpha_{i0} \quad (12) \\ & + (1-\mathbb{I}_{\{e_i>\theta_i E_{iFull}\}})\alpha_{i1} + k_i e_i\Big) de_i \\ & = \mathbb{I}_{\{e_i>\theta_i E_{iFull}\}}\alpha_{i0} T_o Pt_{iLte} + k_i E_i T_o Pt_{iLte} \\ & + (1-\mathbb{I}_{\{e_i>\theta_i E_{iFull}\}})\alpha_{i1} T_o Pt_{iLte} - \frac{k_i T_o^2 Pt_{iLte}^2}{2} \end{aligned}$$

$$\begin{aligned} Cost_o = & \int_{e_o=E_o-(Pt_{oWifi}+Pt_{oLte})T_o}^{E_o} \Big(\mathbb{I}_{\{e_o>\theta_o E_{oFull}\}}\alpha_{o0} \\ & + (1-\mathbb{I}_{\{e_o>\theta_o E_{oFull}\}})\alpha_{o1} + k_o e_o\Big) de_o \\ & = \mathbb{I}_{\{e_o>\theta_o E_{oFull}\}}\alpha_{o0} T_o (Pt_{oWifi} + Pt_{oLte}) \\ & + (1-\mathbb{I}_{\{e_o>\theta_o E_{oFull}\}})\alpha_{o1} T_o (Pt_{oWifi} + Pt_{oLte}) \\ & + k_o E_o T_o Pt_{oWifi} + k_o E_o T_o Pt_{oLte} \\ & - \frac{k_o T_o^2 (Pt_{oWifi} + Pt_{oLte})^2}{2} \quad (13) \end{aligned}$$

where T_o is the transmission time. $Pt_{iLte}T_o$ is the energy consumption of bidder i and $(Pt_{oWifi} + Pt_{oLte})T_o$ is the energy consumption of auctioneer o. Let $cnst_{i1} = (\mathbb{I}_{\{e_i>\theta_i E_{iFull}\}}\alpha_{i0} + (1-\mathbb{I}_{\{e_i>\theta_i E_{iFull}\}})\alpha_{i1})T_o + k_i E_i T_o$, $cnst_{i2} = -\frac{k_i T_o^2}{2}$, $cnst_{o1} = (\mathbb{I}_{\{e_o>\theta_o E_{oFull}\}}\alpha_{o0} + (1-\mathbb{I}_{\{e_o>\theta_o E_{oFull}\}})\alpha_{o1})T_o + k_o E_o T_o$ and $cnst_{o2} = -\frac{k_o T_o^2}{2}$, $Cost_i$ and $Cost_o$ become:

$$Cost_i = cnst_{i1} Pt_{iLte} + cnst_{i2} Pt_{iLte}^2 \quad (14)$$

$$\begin{aligned} Cost_o = & \; cnst_{o1}(Pt_{oWifi} + Pt_{oLte}) \\ & + cnst_{o2}(Pt_{oWifi} + Pt_{oLte})^2 \quad (15) \end{aligned}$$

When using EAC approach, The expressions for $Cost_o$ and $Cost_i$ are as follows:

$$Cost_i = Pt_{iLte}T_o \tag{16}$$

$$Cost_o = (Pt_{oWifi} + Pt_{oLte})T_o \tag{17}$$

IV. Problem Analysis and Discussion

The optimization variable in problem (5)-(11) is β. With LCF approach, equation 5 is not convex. With EAC approach, it is convex. In rest of this section, we analyze the optimization problem and illustrate how to solve it.

Consider following five pivot values of β: $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4$.

$$(1-\beta_0)B_o = R_{omaxLte} \rightarrow \beta_0 = 1 - \frac{R_{omaxLte}}{B_o} \tag{18}$$

$$\begin{aligned}\beta_1 B_o &= W_{wifi}\log_2(1+\frac{Pr_{minWifi}}{N_0 W_{wifi}+I_{wifi}})\\ \rightarrow \beta_1 &= \frac{W_{wifi}}{B_o}\log_2(1+\frac{Pr_{minWifi}}{N_0 W_{wifi}+I_{wifi}})\end{aligned} \tag{19}$$

$$\begin{aligned}\beta_2 B_o &= W_{iLte}\log_2(1+\frac{Pr_{minLte}}{N_0 W_{iLte}})\\ \rightarrow \beta_2 &= \frac{W_{iLte}}{B_o}\log_2(1+\frac{Pr_{minLte}}{N_0 W_{iLte}})\end{aligned} \tag{20}$$

$$\begin{aligned}(1-\beta_3)B_o &= W_{oLte}\log_2(1+\frac{Pr_{minLte}}{N_0 W_{oLte}})\\ \rightarrow \beta_3 &= 1-\frac{W_{oLte}}{B_o}\log_2(1+\frac{Pr_{minLte}}{N_0 W_{oLte}})\end{aligned} \tag{21}$$

$$\begin{aligned}\beta_4 B_o &= \min\{R_{oimaxWifi}, R_{imaxLte}\}\\ \rightarrow \beta_4 &= \frac{\min\{R_{oimaxWifi}, R_{imaxLte}\}}{B_o}\end{aligned} \tag{22}$$

Where $Pr_{minWifi}$,Pr_{minLte} are the sensitivity power level of the Wi-Fi receiver and cellular receiver, respectively. $\beta_1 B_o$, $\beta_2 B_o$ and $(1-\beta_3)B_o$ give the channel capacity with the maximum available bandwidth of bidder i's cellular link, the Wi-Fi link between bidder i and auctioneer o and auctioneer o's cellular link, respectively.

β is constrained between β_0 and β_4. If $\beta_0 > \beta_4$, the problem has no feasible solution. The functions to compute the three transmit powers Pt_{iLte}, Pt_{oWifi} and Pt_{oLte} depend on the relation between β and β_1, β_2 and β_3:

When $\beta \leq \beta_1$:

$$Pt_{oWifi} = \frac{Pr_{minWifi}}{H_{wifi}(d_{io})} = C_{oWifi} \tag{23}$$

When $\beta \leq \beta_2$:

$$Pt_{iLte} = \frac{Pr_{minLte}}{H_{lte}(d_i)} = C_{iLte} \tag{24}$$

When $\beta \geq \beta_3$:

$$Pt_{oLte} = \frac{Pr_{minLte}}{H_{lte}(d_o)} = C_{oLte} \tag{25}$$

When $\beta \geq \beta_1$:

$$\begin{aligned}Pt_{oWifi} &= \frac{(2^{\frac{\beta B_o}{W_{wifi}}}-1)(N_0 W_{wifi}+I_{wifi})}{H_{wifi}(d_{io})}\\ &= 2^{\frac{B_o\beta}{W_{wifi}}}D_{oWifi} - D_{oWifi}\end{aligned} \tag{26}$$

When $\beta \geq \beta_2$

$$\begin{aligned}Pt_{iLte} &= \frac{(2^{\frac{\beta B_o}{W_{iLte}}}-1)N_0 W_{iLte}}{H_{lte}(d_i)}\\ &= 2^{\frac{B_o\beta}{W_{iLte}}}D_{iLte} - D_{iLte}\end{aligned} \tag{27}$$

When $\beta \leq \beta_3$

$$\begin{aligned}Pt_{oLte} &= \frac{(2^{\frac{(1-\beta)B_o}{W_{oLte}}}-1)N_0 W_{oLte}}{H_{lte}(d_o)}\\ &= 2^{\frac{-B_o\beta}{W_{oLte}}}F_{oLte} - D_{oLte}\end{aligned} \tag{28}$$

C_{oWifi},C_{iLte}, C_{oLte}, D_{oWifi}, D_{iLte}, F_{oLte} and D_{oLte} are the constant parts of the equations. The equations above suggest that when the service data rate is smaller than the channel capacity provided with the maximum bandwidth, the transmission power is constant, otherwise, the transmission power increases as the data rate increases.

From permutation theory we know that there are 6 different relations of β_1, β_2 and β_3. For each relation, the optimization problem can be divided into four problems, each of which optimizes on a different feasible range of β. For example, when $\beta_1 \leq \beta_2 \leq \beta_3$, the four ranges of β are $[\max\{\beta_0,0\}, \min\{\beta_1,\beta_4,1\}]$, $[\max\{\beta_1,\beta_0,0\}, \min\{\beta_2,\beta_4,1\}]$, $[\max\{\beta_2,\beta_0,0\}, \min\{\beta_3,\beta_4,1\}]$, $[\max\{\beta_3, \beta_0,0\}, \min\{\beta_4,1\}]$. The optimization problem for $\max\{\beta_0,0,\beta_1\} \leq \beta \leq \min\{\beta_2,1,\beta_4\}$ becomes:

$$\begin{aligned}\underset{\beta}{\text{Minimize}}\quad & cnst_{o1}(2^{\frac{B_o\beta}{W_{wifi}}}D_{oWifi} + 2^{\frac{-B_o\beta}{W_{oLte}}}F_{oLte})\\ & + cnst_{o2}\cdot(2^{\frac{B_o\beta}{W_{wifi}}}D_{oWifi} - D_{oWifi}\\ & + 2^{\frac{-B_o\beta}{W_{oLte}}}F_{oLte} - D_{oLte})^2\end{aligned} \tag{29}$$

$$\text{s.t.}\quad \max\{\beta_0,0,\beta_1\} \leq \beta \leq \min\{\beta_2,1,\beta_4\} \tag{30}$$

Let $X = 2^{\frac{B_o\beta}{W_{wifi}}}$, $Y = 2^{\frac{-B_o\beta}{W_{oLte}}}$, the optimization function becomes:

$$\begin{aligned}\underset{X,Y}{\text{Minimize}}\quad & cnst_{o1}(D_{oWifi}X + F_{oLte}Y)\\ & + cnst_{o2}\cdot(D_{oWifi}X - D_{oWifi}\\ & + F_{oLte}Y - D_{oLte})^2\end{aligned} \tag{31}$$

s.t.

$$2^{\max\{\beta_0,0,\beta_1\}\cdot B_o/W_{wifi}} \leq X \leq 2^{\min\{\beta_2,1,\beta_4\}\cdot B_o/W_{wifi}} \tag{32}$$

$$YX^{\frac{W_{wifi}}{W_{oLte}}} = 1 \tag{33}$$

Now the objective function is in convex form, but constraint (33) is non-convex, we relax (33) to the two constraints below:

$$Y \geq X^{\frac{-W_{wifi}}{W_{oLte}}} \tag{34}$$

$$Y \leq (2^{\min\{\beta_2, 1, \beta_4\} B_o / W_{wifi}})^{\frac{-W_{wifi}}{W_{oLte}}} \quad (35)$$

This relaxed optimization problem (31)-(32),(34)-(35) gives a lower bound for the objective function of the optimization problem (31)-(33). Use the optimal β computed from this relax optimization problem, we calculate the actual energy cost $Cost_o + Cost_i$. In the simulation study, we calculate the gap between the actual energy cost computed using β computed from the relaxed optimization problem and the optimal objective value computed from the relaxed optimization problem (lower bound of the optimal solution to problem 31)-(33), the ratio of gap over the actual energy cost is 0.0191 with standard deviation of 0.0353. This number indicates that our relaxation problem gives a solution that is very close to the optimal solution.

With 6 different relations between β_1, β_2 and β_3, and four different settings for Pt_{iLte}, Pt_{oWifi} and Pt_{oLte} in each relation, there are total of 24 representation of the optimization problems (only 8 distinct representations). Some of the optimization problem are convex, some are not. The non-convex optimization problem will use similar relaxation approach proposed above to solve. We use CVX to solve the optimization problem.

V. Auction Mechanism Design

With multiple bidders participating in the auction, the auctioneer needs to select the right bidder and make the appropriate payment to the selected bidder. In this section, we introduce the auction mechanism in the auction game. The following selection rule and payment rule are modified version of the selection rule and payment rule from the classic Vickrey auction mechanism [11].

Selection Rule: Auctioneer selects the bidder i_o that provides the minimal bid:

$$i_o = \arg\min_i b_i \quad (36)$$

where b_i is the bid offered by bidder i, which is also the $Cost_i + Cost_o$ optimized in Section IV.

If the energy cost of the cooperative transmission with the selected bidder is higher than the energy cost when auctioneer self serves itself (transmits streaming traffic without cooperation) or the optimal β value is 0 when computing the optimal bid offered by the selected bidder, the auctioneer will self serve itself.

Payment Rule: the auctioneer pays the winning bidder i the second lowest bid minus the auctioneer's energy cost $Cost_{oi}$ and it pays 0 to the bidders that lose in the auction, namely:

$$P_i = \begin{cases} b_i - Cost_{oi} & \text{if i wins} \\ 0 & \text{if i loses} \end{cases}$$

The payment is paid in credit. The auctioneer reduces the same amount of the payment from its credit balance, and the winning bidder adds the same amount of payment to its credit balance. Finally, the utility of bidder i is

$$U_i = P_i - Cost_i \quad (37)$$

If bidder does not cheat, then its utility will always be non-negative. In the case where bidder i wins, $P_i = (second\ lowest\ bid - Cost_{oi})$, then $U_i = (second\ lowest\ bid - Cost_{oi} - Cost_i) = (second\ lowest\ bid - lowest\ bid) \geq 0$. In the case where bidder i loses, $P_i = 0$, $U_i = (0-0) = 0$.

In the simulation study, we assume UEs are honest and report information truthfully. What's more, more than one UE is allowed to start the auctions simultaneously. So it is possible that a bidder participates into multiple auctions, and is selected as the winner in multiple auctions. To resolve this confliction, we set up the following negotiation rules:

- The auctioneers confirm with each bidder for serving in an increasing bid order. If the bidder accepts the offer, the auctioneer stops and selects the bidder for relay transmission, and sends 'end auction' signals to other bidders. If the bidder temporarily rejects the offer, the auctioneer continue confirming with the next lowest bidder until it reaches an agreement with one bidder or ends up self serves itself when all bidders end the participation.
- When the bidder is contacted by a auctioneer for confirming the cooperation offer, it first checks whether the auctioneer offers the highest utility among the available auctioneers in the auctions it participates in. If it is, then the bidder accepts the offer, and sends end participation signals to other auctioneers. If it is not, the bidder temporarily rejects the offer, waiting for other auctioneers to contact, until all auctioneers end the auction.

VI. Numerical Results

In this section, we study the performance of our proposed user cooperation scheme. We assume all bidders are honest and the informations sent to auctioneers are truthful. In the MATLAB simulation platform, we set up one MBS, two hotspots and 100 UEs. The hotspot centers are uniformly distributed within 400 meters from the MBS, and 50 UEs are uniformly deployed within 100 meters from each hotspot center, respectively.

The cellular carrier center frequency used in the simulation is 2 GHz, and the total cellular spectrum bandwidth is 20 MHz. The bandwidth of cellular channel are evenly distributed among 100 UEs. Wifi channel has 40 MHz bandwidth. UE's maximum transmission power of cellular channel and Wi-Fi channel are 23 dBm and 10 dBm, respectively. The sensitivity power level for Wifi interface and cellular interface are -40 dBm and -101.5 dBm, respectively. We use a noise power spectrum density of -174 dBm/Hz. The path loss model for cellular channel is $PL(dB) = 15.3 + 37.6 \log_{10} R$, where R is in meters [12]. The Wi-Fi signal path loss model is $PL(dB) = 32.2 \log_{10}(d)$, where d is in meters [13].

We only consider data transmission energy, which is a small portion of smartphone's energy usage. The initial energy balance for all UEs are 2150 J. α_{i0} and k_i used in the LCF energy cost approach are 2150 and -10, respectively for all UEs.

The streaming traffic model is set up as following: the simulation lasts for 60 time slots, and each time slot lasts for 30 seconds. In each time slot, a UE starts streaming event with

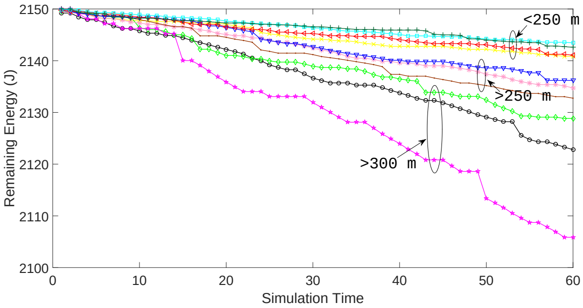

Fig. 2: Selected UEs' available energy vs simulation time with LCF user cooperation scheme.

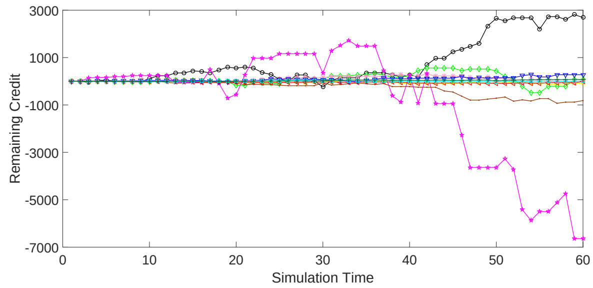

Fig. 3: Selected UEs' available credit vs simulation time with LCF user cooperation scheme.

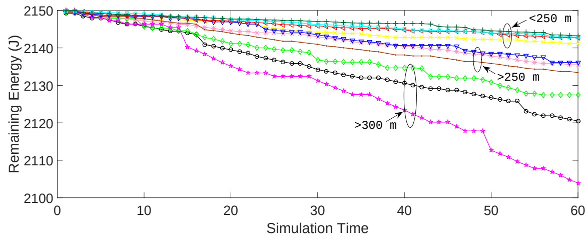

Fig. 4: Selected UEs' available energy vs simulation time with EAC user cooperation scheme.

certain probability. Each streaming event lasts for 30 seconds. For each UE i, the number of streaming events generated during the simulation time is poisson distribution with mean λ_i. $\lambda_i = 20$ for all UEs in the simulation setup. At the beginning of simulation, UE i poisson randomizes the number of events x_i that will appear throughout the simulation round. At the beginning of each time slot, UE i has probability of $\frac{x_i}{S}$ to start the streaming event. S is the number of remaining time slots. if UE i starts the event in current time slot, then for next time slot, $x_i = x_i - 1, S = S - 1$. Otherwise, $x_i = x_i, S = S - 1$. UEs that do not start streaming event in current time slot remain idle.

In rest of the section, we study the performance of three operation schemes, self serving scheme (UE transmits its streaming traffic without cooperation), user cooperation scheme with LCF energy cost approach (LCF scheme), and user cooperation scheme with EAC energy cost approach (EAC scheme).

Fig.2 to Fig.5 give the energy balance and credit balance of 10 selected UEs throughout a selected simulation round using LCF scheme and EAC scheme, respectively. The energy balance for all UEs are decreasing as simulation goes under both schemes. The UEs further way from the MBS consume more energy than UEs closer to MBS. Under different user cooperation schemes, UEs' credit balances have very different values. The LCF scheme gives very large credit value due to its representation of the cost function, we can control the credit values by tuning the parameters in the cost function. The credit balance in EAC scheme is much smaller with consumed energy as the energy cost. Both figures show that the credit balance is fluctuated as time goes, because UE sometimes acts as the auctioneer and sometimes acts as the bidder. UEs further away from MBS has more dramatic fluctuation in credit balance. Since their neighbor UEs are also very far way from the MBS, the energy cost will also be much higher. The balance figures do not show a direct relation of higher energy cost results in higher credit balance. The credit balance fluctuation is jointly determined by UE's streaming frequency, UE's locations from the MBS and neighbor UEs' streaming frequency.

Fig.6 shows the ratio of UEs' energy consumption applying LCF scheme over the energy consumption applying self serving scheme. Fig.7 shows the ratio of UEs' energy consumption applying EAC scheme over the energy consumption applying self serving scheme. For both LCF and EAC scheme, the consumed energy is averaged around 50% of the consumed energy when use self serving scheme. The results suggest that LCF and EAC scheme can greatly reduce energy consumption. The rational behind the improvement is following: When apply user cooperation scheme, the UEs that rely on neighbor UEs for transmission will share a portion β of total streaming bit rate to neighbor UEs, and β is around $30\% - 50\%$ in our simulation results. UE has a transmission power $Pt_{oLte} = (2^{\frac{(1-\beta)B_o}{W_{oLte}}} - 1)D_{oLte})$. When $\beta = 0$ (self serving), $B_o = 3 \times 10^6$ bps and $W_{oLte} = 0.2 \times 10^6$Hz, then $Pt_{oLte}(\beta = 0) = (2^{15} - 1)D_{oLte}$. When $\beta = 0.5$ (user cooperation), $Pt_{oLte}(\beta = 0.5) = (2^{7.5} - 1)D_{oLte}$. The difference between $Pt_{oLte}(\beta = 0)$ and $Pt_{oLte}(\beta = 0.5)$ is more than a factor of 2. We can now see the advantage of

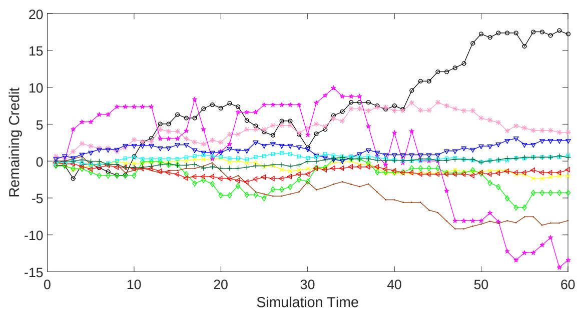

Fig. 5: Selected UEs' available credit vs simulation time with EAC user cooperation scheme.

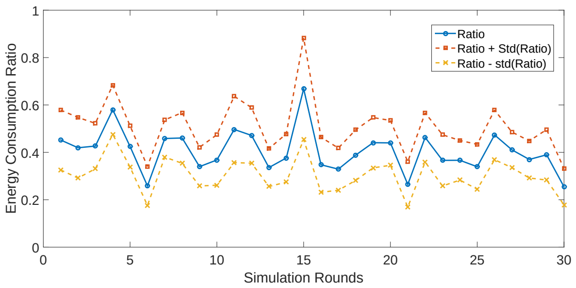

Fig. 6: Ratio of UEs' energy consumption with LCF Scheme over energy consumption with self serving scheme

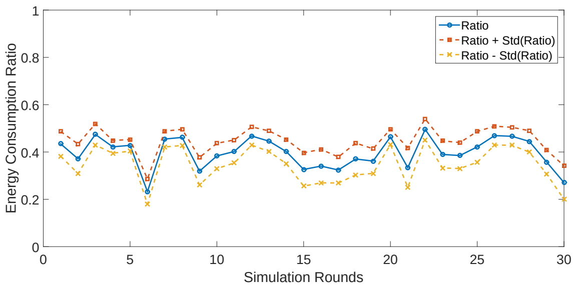

Fig. 7: Ratio of UEs' energy consumption with EAC Scheme over energy consumption with self serving scheme

applying user cooperation in saving more energy than self serving scheme.

Fig.8 shows the performance comparison between two user cooperation schemes LCF and EAC. The upper circled line shows the ratio of total UEs' energy consumption applying LCF scheme over total UEs' energy consumption applying EAC scheme. The ratio is close to 1, and LCF scheme outperforms EAC scheme by about 2-3%. The lower line is the ratio of standard deviation of UEs' remaining energy with LCF scheme over the standard deviation of UEs' ramaining energy with EAC scheme. The standard deviation of UEs' remaining energy indicates how balanced are the energy consumption among all UEs in the system. The ratio shows that LCF scheme outperforms EAC scheme in balancing UE's energy consumption. In LCF scheme, UEs with lower energy will have higher energy cost as indicated by the cost function introduced in Section II. As a result, the auctioneer will be more liking to choose the bidder with higher remaining energy to serve. EAC scheme does not take UEs' remaining energy into consideration, auctioneer applying EAC scheme selects bidder which can provides with minimal energy consumption, even the UEs that have very low remaining energy already.

VII. Conclusions

In this paper, we proposed user cooperation solution with auction theory to schedule multipath traffic of streaming application. We designed the selection rule and payment rule in the auction mechanism. With the assumption that UEs are all honest players, our proposed solution showed great

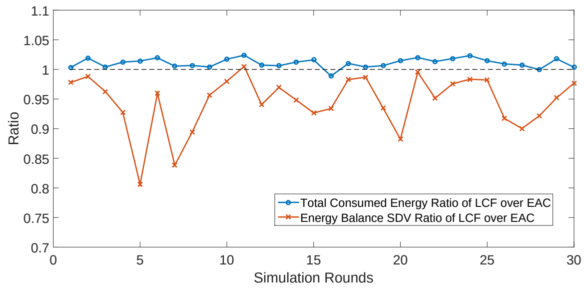

Fig. 8: Total UEs' energy consumption and UEs' remaining energy standard deviation comparison between LCF scheme and EAC scheme

advantage in reducing energy consumption compared to non-cooperation solution. The improvement is up to $50-60\%$. Our proposed solution also motivates UEs to participate in the user cooperation auction game with non-negative utilities. What's more, LCF scheme shows potential in balancing the UE's remaining energy in the system.

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