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Cooperative Multi-Path Routing Solution With Real-Time Optimization for Streaming Application Using Auction Theory

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ABSTRACT Cooperation among network devices is a promising approach 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 a cooperative multi-path routing solution for wireless Users Equipment (UEs)' streaming applications. We assume that UEs use multi-path transport layer service, and establish two paths for streaming, one path goes through its cellular link, and the other path is established using a Wi-Fi connection with a neighbor UE. We study a user coordinated multi-path routing solution with two different energy cost functions, a Linear Cost Function (LCF) and Energy As the Cost (EAC) and design user cooperative real-time optimization and failure protection operations for the streaming application. To stimulate UEs to participate in the user cooperation operation, we design a credit system enabled by an auction mechanism. We compare the performance of user cooperation schemes to the non-cooperative scheme, and using simulation results show that applying the proposed user cooperation scheme and establishing multi-path connections for streaming has an advantage in improving the service rate and streaming success rate, and reduces energy consumption compared to non-cooperation solutions. User cooperation scheme with LCF energy cost function can also help balance the energy consumption among UEs in the system compared to user cooperation scheme with EAC energy cost function.

INDEX TERMS User cooperation, multi-path communication, auction theory, streaming applications.

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. However, wireless networks are constrained by the limited network resources (spectrum, transmitting power, etc.). Cooperation schemes can help improve network coverage, transmission throughput, spectral efficiency and power efficiency by using network resources more efficiently.

Network cooperation and user cooperation are two promising cooperation schemes to use current network resources to increase bit rate, improve service reliability, and meet the users quality of service (QoS) requirements. Fig.1 shows an example of network cooperation and user cooperation. Network cooperation solution [2], [3] 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 rates. A number of studies that applied the network cooperation approach to improve network performance [4]–[11]. The disadvantage of the network cooperation approach is that not all wireless networks have coverage over the mobile devices. For example, Wi-Fi 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. The user cooperation approach allows mobile devices in the vicinity to relay for each other in order to provide mobile users with stable quality of service. Its advantages over network cooperation approach is that:

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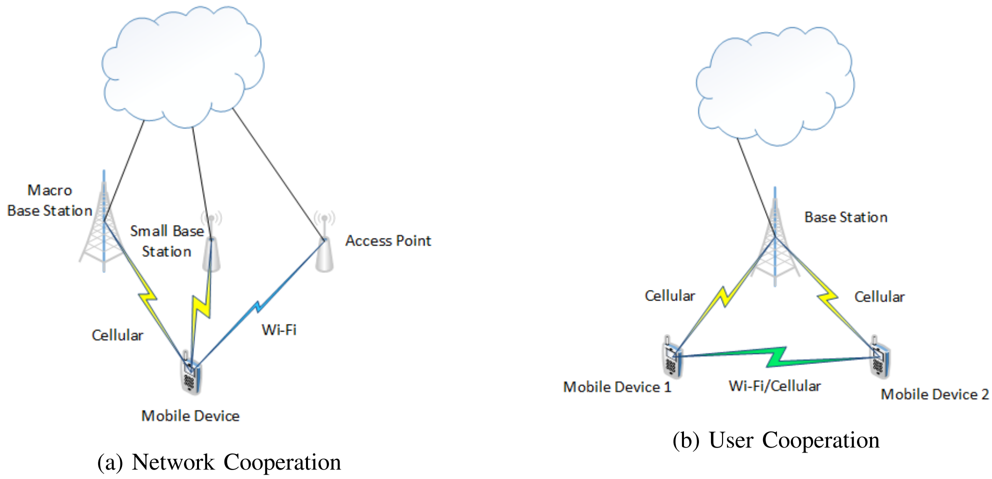


FIGURE 1. **Cooperation schemes in wireless networks. (a) Network Cooperation. (b) User Cooperation.**

1) power consumption of a UE is balanced by nearby UEs that relay packets for it; 2) if a UE can only connect to a cellular network or a Wi-Fi network, it can still enhance its bandwidth by connecting to relay UEs using its other available wireless interfaces [12].

In this paper, we study user cooperation solutions of streaming applications. There are three types of applications (app) on mobile devices (real time streaming and interactive multimedia communication app, web browsing app, app download app). The reason we focus on streaming applications is that the real time streaming and interactive multimedia communication apps have the highest priority in case of service failure, since they require minimizing packet delivery delay to give good QoS. It is important to study operational schemes that can improve performance of streaming applications. There are a number of device to device (D2D) communication technologies that can be used for user cooperation purposes [13]–[15]:

- Bluetooth: most energy efficient, and only supports point-to-point connections. It is difficult to create large groups of devices using Bluetooth and it has relatively low speeds.
- Wi-Fi 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 significantly more energy than the other devices.
- Wi-Fi Direct [16]: allows true peer-to-peer operation and high speeds.
- LTE Direct [17]: It is an emerging and promising technology that uses the LTE band for energy-efficient device-to-device communication and discovery.

The key issues in cooperative mobile user relay system are as follows:

- Willingness of nearby mobile devices to forward other UEs' packets. This is because users can not see immediate benefit and reward for their cooperation, and their operations are limited by their battery and radio resource.
- Information security of the data relayed by nearby mobile devices.
- Preventing misbehaving users (selfish, malicious, or hackers) from taking advantage of the user relay system.

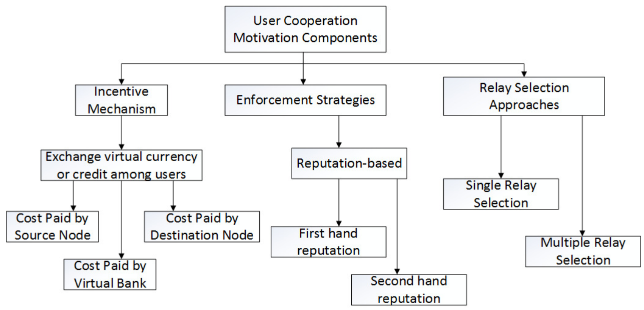


FIGURE 2. **User cooperation components with motivation.**

A. LITERATURE REVIEW

There is a large body of literature on relay selection with and without user cooperation in wirelss networks. Study [18] provides a summary of different research components for user cooperation schemes with different motivations, and it is shown in Fig. 2. Good incentive mechanisms improve users' willingness to provide relaying functionalities for other users. Enforcement strategies prevent misbehaving users from taking advantage of the system. Good relay selection approaches let users choose other users as relays in order to benefit themselves the most.

Several papers have focused mostly on relay selection with resource allocation, route selection and interference cancelation in cooperative communication as main objectives, while making the assumption that the UEs are willing to provide relay service without any incentives. These include references [19]–[22].

Other work in the literature has studied both incentive mechanisms for user cooperation and relay selection approaches jointly to improve the performance of D2D communications. In the rest of this subsection, we provide a brief review of some of the relevant literature.

Game theory and auctioning were some of the approaches used for relay selection. In [23] a bidding game is used for selecting a most suitable partner in a cooperative wireless communication system. The source acts as the auctioneer while the relays or partners act as the bidders in the game. The resource being auctioned here is power, and the relay which offers the highest bid in terms of price is selected and allocated power by the source node. Reference [24] proposed a user relay cooperation stimulating strategy among users which is based on cooperative game theory. Using a pricing-based mechanism, each node can decide whether to cooperate and how to cooperate. Cooperative game theory assists in providing an optimal system utility and provides fairness among users. Another game theoretic approach for routing in mobile ad hoc networks was introduced in [25]. Nodes act as greedy and selfish agents who accept payments for forwarding data for other agents if the payments cover their individual costs incurred by forwarding data. A reactive routing protocol, Ad hoc-VCG, is introduced to achieve design objectives of truthfulness in revealing their true cost for data forwarding as well as routing cost efficiency in a game-theoretic sense by paying to the intermediate nodes a premium over their actual costs for forwarding data packets. The developed routing protocol implements a variation of the Vickrey, Clarke, and Groves (VCG) mechansim in a mobile network setting. Reference [26] also studied routing and packet forwarding in wireless ad hoc networks. It introduced a game-theoretic approach, also integrating the VCG algorithm to stimulate cooperation. The authors in an earlier version of this paper, [27], considered multi-path routing with cooperation using two interfaces, one using a cellular link, and the second uses a Wi-Fi interface through a neighbor UE. A user cooperation strategy based on auctioning theory was introduced.

Contract-based approaches were also used for cooperation. For example, reference [28] which used incentives between the relay nodes' cooperative service and the source's relay selection assuming dual symmetric information scenarios. Cooperative communication as a labor market, and a contract-theoretic model for relay incentive is proposed to achieve the dual objectives of ability-discrimination and effort-incentive. To incentivize potential relay nodes to participate in cooperative communication, optimization problems are formulated to maximize the source's utility under the multiple information scenarios. In [29] the same authors extended the work to the case of asymmetric channels. Another contract based approach is introduced in reference [30] which proposes a contract-based cooperative spectrum sharing mechanism to exploit transmission opportunities for D2D links and also achieve the maximum profit of the cellular links. A cooperative relaying scheme that employs superposition coding at both the cellular transmitters and D2D transmitters is developed. A contract-theoretic framework is used to model the spectrum trading process based on the cooperative relaying scheme. Optimal power-payment contracts for the cellular links are derived using control theoretic approaches.

Cooperation and incentives have also been used in energy harvesting. Reference [31] considers user cooperation and a pricing mechanism in a wireless-powered communication network where two users harvest energy from an access point in the downlink. Users also independently transmit their information to a hybrid access point in the uplink using the individually harvested energy. The paper proposes a cooperative scheme among users. Compared with the source user (SU), the channel conditions for a helping user (HU), which is closer to the hybrid access point is usually better for downlink energy harvesting and for transmitting uplink information. The helping user uses its harvested energy to forward the SU's information to the hybrid access point. A pricing strategy is introduced to incentivize the helping user to help the source user. Reference [32] considers a D2D transmitter cooperating with a cellular network by acting as a relay to serve one of the cellular users, and considers the case in which the D2D transmitter is equipped with an energy harvesting capability. The trade-off between the amount of energy used for relaying and the energy used for decoding the cellular user data at the relaying node is investigated. An optimization problem to maximize the cellular user rate subject to a minimum rate requirement constraint for the D2D link is formulated, the case when receiving nodes are equipped with successive interference cancellation (SIC) capability and investigate the effect of using SIC on our proposed system performance is considered.

Incentivized relay operation has also been introduced in cognitive radio networks. For example, reference [33] considers a heterogeneous cognitive wireless networks (HeCoNets)) consisting of macrocells that are overlaid by small cells (e.g, femtocells, picocells). These small cells operate over the cognitive radio paradigm. Picocells and famtocells use unlicensed channels. Cognitive picocell users' equipments (CPUEs) and cognitive femtocell users (CFUEs) receive incentives from cooperating with each other to improve the unlicensed channels usage and mitigate inter-tier and intra-tier interference while maximizing sum-rate of users in the HetCoNet. Coalitional game theory is applied in which CPUEs and CFUEs are considered as players of the game. Also, reference [34] uses underlay links for relaying, hence improve spectrum efficiency via spectrum sharing. Multiple QoS metrics are considered jointly to enhance the performance of underlay device-to-device relaying links. A heuristic for relay selection is introduced, and a game theoritic approach for designing a power adjustment scheme for improving both energy efficiency and convergence time is developed. In addition, in reference [35] D2D transmitters act as relays to assist cellular users in exchange for using licensed spectrum. The authors formulated the pairing problem between cellular users and D2D pairs as a one-to-one matching game. Incomplete channel information is considered, and a learning algorithm is proposed. Reference [36] considers the use of full duplex D2D underlay communications. Two modes are developed: 1) the MU-MIMO based mode, in which users work as a network MIMO to forward the data, and 2) the sequential forwarding mode in which the spatial distribution of nodes is explored with the objective of improving the transmission rate. Optimal power allocation is performed. In [37] full duplex D2D communications is also studied. It considers centralized and distributed power control, and formulates optimization problems to maximize the D2D link sum-rates.

The social connections between devices have been considered by reference [38]. This paper proposes a social-aware energy-efficient relay selection mechanism that considers hidden social ties among mobile users to ensure that more users are willing to participate in the cooperative communications. It also takes into consideration the physical constraints, and develops an optimization problem based on game theory in ordre to reduce energy consumption and interference.

Other ad hoc schemes were presented in the literature. These include [39], in which a cheat-proof credit-based system, called Sprite, is proposed for stimulating cooperation among selfish nodes in mobile ad hoc networks. The system provides incentives for mobile nodes to cooperate and report actions honestly. The authors in [40] also addressed cooperation in mobile ad hoc networks, and introduced a scheme that is based on assessing users reputation. The scheme can stimulate and also enforce nodes to cooperate in a selfish ad hoc environment, and another mechanism was introduced to detect and exclude potential threats of selfish mobile nodes.

B. PAPER CONTRIBUTIONS

Different from the above related work, in this paper, we study a single relay multi-path transmission scenario. We assume UEs are supported by a multi-path transmitting protocol, such as the Multipath TPC (MPTCP) [41] or the Multipath RTP (MPRTP) [42]. We study user cooperation schemes for UEs' streaming application in a large heterogenous networks, and we study user's behavior using auction theory. 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 traffic UEs to relay traffic. 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. In this work, we only study UEs' uplink cellular transmission. The simulation study shows that our proposed user cooperation schemes improve system performance by improving service rate and streaming event success rate and reducing the energy consumption compared to non-cooperation schemes. 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.

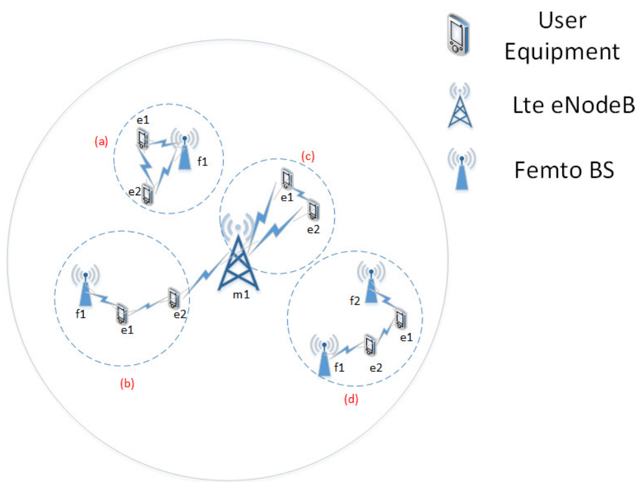


FIGURE 3. Network model.

C. PAPER ORGANIZATION

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 III-C explains the proposed solution of the streaming traffic allocation problem. The participation rules of the auction game are provided in Section IV. The failure recovery operations are introduced in Section V. The numerical results are discussed in Section VI. Finally, the paper is concluded in Section VII.

II. SYSTEM MODEL

The system models a heterogeneous wireless network environment as shown in Fig.3. A Macro Base Station (MBS) is located in the center of the cell, and a number of Femto Base Stations (FBS) overlaid within MBS's transmission range. We assume that the FBSs operate in open group access mode, which means that a UE can be served by any BS in the system that provide it with the maximum received signal strength. What's more, the common cellular spectrum is evenly distributed to UEs that are associated with BSs (whether it is associated with FBS or MBS). Therefore, there is no interference to UEs' cellular link. A number of Users Equipment (UEs) are deployed within the transmission range of the MBS. For each FBS, there is a number of UEs deployed within its transmission range as well. In this paper, we assume UEs are enabled with device to device (D2D) communication technology and UEs' streaming applications supported by multi-path transport layer protocol. Therefore, when a UE i starts a streaming event, it first initiates an auction process, in which the idle neighbor UEs within i's transmission range participate to bid for relaying traffic for UE i. The winning neighbor UE helps in relaying traffic for UE i, and UE i pays a certain amount of credits to the wining neighbor UE for the service.

Fig.3 illustrates four different multipath streaming scenarios using device-to-device relay transmission.

- **Scenario (a)**: UE e1 establishes two paths for streaming traffic. One path is e1's cellular link connected to FBS f1, and the other path is its Wi-Fi link connected to UE e2. Both e1 and e2 are served by FBS f1.
- **Scenario (b)**: Similar to scenario (a), e2 relays traffic for e1 through the Wi-Fi link, however, e1 connects to FBS f1, and e2 connects to MBS m1.
- **Scenario (c)**: UE e2 relays traffic for e1 through the Wi-Fi link; however, both e1 and e2 connect to MBS m1.
- **Scenario (d)**: e1 and e2 connects to different FBSs, and e2 relays traffic for e1 through the Wi-Fi link.

In this paper, we assume UEs belong to different selfish users, therefore, UEs have no obligation to forward other UEs' traffic unless they enjoy positive utility with the payment made to them. We denote UEs with the streaming event as auctioneers, and their neighbor idle UEs that are 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 encoded and not known to other UEs (sealed bid). Auctioneers then run the auction following the rules proposed in Section IV. Our objectives of this work are as follows: 1) propose an operational scheme for auctioneers such that their service rate is maximized and the total operation power consumption can be minimized; 2) propose real-time optimization and failure protection operation for auctioneers that further improves UEs' performance. The first objective is discussed in Section III and IV, and the second objective is described in Section V.

To simplify this work, we assume the system operates in a timeline with a constant time step and all active UEs are connected to the BS whichever provides the strongest received signal power. At the beginning of each time slot, auctioneers broadcast a message to neighbor UEs. The bidders that receive the request and are capable of relaying data report information back to the auctioneers. The auctioneers then decide the operation solutions based on the received information from bidders.

We assume each bidder i reports $Info_i$ to the auctioneer o, where $Info_i$ is given by:

$$\{H_{iLte}(d_i), H_{oiWifi}(d_{io}), P_{imaxLte}, k_i, \alpha_{i0}, \alpha_{i1}, E_{iFull}, \theta_i, E_i\}$$

Each element in $Info_i$ is explained below:

- $H_{iLte}(d_i), H_{oiWifi}(d_{io}), P_{imaxLte}$: $H_{iLte}(d_i)$ is the channel gain in dB between bidder i and the BS it is associated with. $H_{oiWifi}(d_{io})$ is the channel gain in dB between bidder i and auctioneer o. $P_{imaxLte}$ is the maximum transmission power of bidder i.
- $k_i, \alpha_{i0}, \alpha_{i1}, \theta_i, E_{iFull}$: in reality, UEs with lower energy balance are less likely to provide service. Therefore, we assume the energy price of every UE is a linear function of its current energy balance. Let $\mathcal{A}_i = \{e_k : e_k > \theta_i E_{iFull}\}$ be the set of energy balances larger than a threshold. Then, bidder i's energy unit price

$$\alpha_i = \mathbb{I}_{\mathcal{A}_i}(e_i)\alpha_{i0} + (1 - \mathbb{I}_{\mathcal{A}_i}(e_i))\alpha_{i1} + k_i e_i,$$

where $k_i < 0$, and

$$\mathbb{I}_{\mathcal{A}_i}(e_i) = \begin{cases} 1 & e_i \in \mathcal{A}_i \\ 0 & e_i \notin \mathcal{A}_i \end{cases}$$

e_i is UE i's current energy balance, E_{iFull} is the energy balance when UE i's is fully charged, θ_i is a threshold $\in (0, 1)$ and α_{i1} is a very large number close to infinity. k_i is the slope of the linear function. α_{i0} is a parameter that controls the energy unit price when $e_i \in \mathcal{A}_i$. The cost function indicates that when UE i's current energy balance is below θE_{iFull}, it can not participate in the auction as a bidder. This is to prevent UE from draining out its battery by acting as relay. The total energy cost when e_i of UE i drops from energy balance E_1 to energy balance E_2 is calculated as follows:

$$\int_{e_i=E_2}^{E_1} \Big(\mathbb{I}_{\mathcal{A}_i}(e_i)\alpha_{i0} + (1 - \mathbb{I}_{\mathcal{A}_i}(e_i))\alpha_{i1} + k_i e_i\Big) de_i$$

- E_i: bidder i's remaining energy at the beginning of the time slot.

With $Info_i$, the auctioneer calculates the achievable rate through the cooperation communication with bidder i. When the achievable rate satisfies the lowest rate requirement, the auctioneer optimizes the streaming traffic allocation between itself and bidder i to minimize the total energy cost of the cooperation transmission. The formulation of this optimization problem is described in the next section.

III. COOPERATIVE MULTI-PATH ROUTING DESIGN

In this section, we introduce the auctioneer's operations after receiving information reported from bidders. We assume that the streaming application on the auctioneer supports three different constant bit rates $\{B_{low}, B_{med}, B_{high}\}$. If the application can not stream with a rate of at least B_{low}, the streaming application can not stream data at all and suffers from failure. Based on the feedback from bidders, auctioneers can encounter one of the following two scenarios:

- Coop-selfServe: no bidder is able to provide relaying service that satisfies the lowest rate requirement.
- CooP: some bidders are able to provide relaying service that satisfies at least the lowest rate requirement.

In scenario CooP-selfServe, auctioneers suffer from failure if they can not stream with the lowest required rate by themselves, otherwise, they initiate a single path streaming traffic towards the BSs they are associated with, and transmit at the highest streaming rate they can support. In scenario CooP, auctioneers compute the bid provided by each bidder by optimizing streaming traffic allocation between itself and the bidder. With each bidder, the streaming rate adopted by the streaming application at the auctioneer is the highest streaming rate supported by the cooperative transmission of the auctioneer and the bidder. With the known streaming rate, the auctioneer formulates an optimization problem to minimize total energy cost of cooperative communication with the bidder. The optimization variable is the portion $\beta \in [0, 1]$ of the total streaming traffic to be relayed by the bidder. The bid is calculated based on the optimized total energy cost, and is explained in more detail in Section IV.

In the rest of this section, we formulate the optimization problem to be solved by the auctioneer in scenario CooP. First, we decide the streaming rate, then we formulate the optimization problem.

A. SUPPORTED STREAMING RATE

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

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

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

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

Here W_{iLte}, W_{wifi} and W_{oLte} are the spectrum bandwidth allocated to bidder i's cellular connection, Wi-Fi connection between bidder i and auctioneer o and auctioneer o's cellular connection, respectively. Since we assume that cellular spectrum is evenly distributed among UEs no matter which BS they are associated with, therefore, $W_{iLte} = W_{oLte} = \frac{W_{total}}{N_{ue}}$, where W_{total} is the total bandwidth of the cellular spectrum and N_{ue} is the total number of UEs that are associated with BSs in the system at the current time slot. H_{iLte} and H_{oLte} are the channel gain of bidder i's cellular connection and auctioneer o's cellular connection, respectively. H_{oiWifi} is the channel gain of the Wi-Fi connection between bidder i and auctioneer o. $Pt_{imaxLte}$, $Pt_{maxWifi}$ and $Pt_{omaxLte}$ are the maximum transmission power of cellular interface of bidder i, Wi-Fi interface of auctioneer o and cellular interface of auctioneer o, respectively. N_0 is noise power spectrum density. d_o is the distance in meters between auctioneer o and its associated BS. I_{iWifi} is the interference towards the Wi-Fi receiver in bidder i.

With the computed maximum transmission rate TP_i, auctioneer o always selects the highest streaming rate restricted by TP_i:

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

where B_o is the selected streaming rate for the cooperative transmission among bidder i and auctioneer o.

B. OPTIMIZATION PROBLEM FORMULATION

The optimization problem to minimize the total energy cost of the cooperative transmission among bidder i and auctioneer o is formulated as follows:

$$\underset{\beta}{\text{Minimize}}\ Cost_o + Cost_i \tag{1}$$

$$\text{s.t. } \beta B_o \leq \min\{R_{oimaxWifi}, R_{imaxLte}\} \tag{2}$$

$$(1-\beta)B_o \leq R_{omaxLte} \tag{3}$$

$$0 \leq \beta \leq 1 \tag{4}$$

$Cost_o$ is the energy cost of auctioneer o, and $Cost_i$ is the energy cost of bidder i. Constraint (2) and (3) state that the streaming rate relayed by bidder i and auctioneer o should not exceed their corresponding transmission capacity.

In this paper, we study two different energy cost functions. The first one is the Linear Cost Function (LCF) introduced 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:

$$Cost_i = \int_{e_i=E_i-Pt_{iLte}T_o}^{E_i} \Big(\mathbb{I}_{\mathcal{A}_i}(e_i)\alpha_{i0} + (1-\mathbb{I}_{\mathcal{A}_i}(e_i))\alpha_{i1} + k_i e_i\Big) de_i \tag{5}$$

$$= cnst_{i1} Pt_{iLte} + cnst_{i2} Pt_{iLte}^2 \tag{6}$$

$$Cost_o = \int_{e_o=E_o-(Pt_{oWifi}+Pt_{oLte})T_o}^{E_o} \Big(\mathbb{I}_{\mathcal{A}_o}(e_o)\alpha_{o0} + (1-\mathbb{I}_{\mathcal{A}_o}(e_o))\alpha_{o1} + k_o e_o\Big) de_o$$

$$= cnst_{o1}(Pt_{oWifi} + Pt_{oLte}) + cnst_{o2}(Pt_{oWifi} + Pt_{oLte})^2 \tag{7}$$

where $cnst_{i1}$, $cnst_{i2}$, $cnst_{o1}$, $cnst_{o2}$ are:

$$cnst_{i1} = (\mathbb{I}_{\mathcal{A}_i}(e_i)\alpha_{i0} + (1-\mathbb{I}_{\mathcal{A}_i}(e_i))\alpha_{i1})T_o + k_i E_i T_o$$

$$cnst_{i2} = -\frac{k_i T_o^2}{2}$$

$$cnst_{o1} = (\mathbb{I}_{\mathcal{A}_o}(e_o)\alpha_{o0} + (1-\mathbb{I}_{\mathcal{A}_o}(e_o))\alpha_{o1})T_o + k_o E_o T_o$$

$$cnst_{o2} = -\frac{k_o T_o^2}{2}$$

T_o is the duration of one time slot. $Pt_{iLte}T_o$ is the energy consumption of bidder i during the time slot and $(Pt_{oWifi} + Pt_{oLte})T_o$ is the energy consumption of auctioneer o in the same time slot. In this paper, we only consider the transmission energy of the wireless interface.

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

$$Cost_i = Pt_{iLte} T_o \tag{8}$$

$$Cost_o = (Pt_{oWifi} + Pt_{oLte})T_o \tag{9}$$

C. PROBLEM ANALYSIS AND DISCUSSION

The optimization variable in problem (1)-(4) is β. The constraints of the problem are convex. Therefore, the convexity of the optimization problem depends on the convexity of the objective function. To analyze the convexity of the objective function, we first compute the transmission power Pt_{iLte}, Pt_{oWifi} and Pt_{oLte}.

Consider the following five pivot values of β: β_0, β_1, β_2, β_3, β_4:

$$(1-\beta_0)B_o = R_{omaxLte} \rightarrow \beta_0 = 1 - \frac{R_{omaxLte}}{B_o} \tag{10}$$

$$\beta_1 B_o = W_{wifi}\log_2\left(1 + \frac{Pr_{minWifi}}{N_0 W_{wifi} + I_{iWifi}}\right) \rightarrow \beta_1 = \frac{W_{wifi}}{B_o}\log_2\left(1 + \frac{Pr_{minWifi}}{N_0 W_{wifi} + I_{iWifi}}\right) \tag{11}$$

$$\beta_2 B_o = W_{iLte}\log_2\left(1 + \frac{Pr_{minLte}}{N_0 W_{iLte}}\right) \rightarrow \beta_2 = \frac{W_{iLte}}{B_o}\log_2\left(1 + \frac{Pr_{minLte}}{N_0 W_{iLte}}\right) \tag{12}$$

$$(1-\beta_3)B_o = W_{oLte}\log_2\left(1 + \frac{Pr_{minLte}}{N_0 W_{oLte}}\right) \rightarrow \beta_3 = 1 - \frac{W_{oLte}}{B_o}\log_2\left(1 + \frac{Pr_{minLte}}{N_0 W_{oLte}}\right) \tag{13}$$

$$\beta_4 B_o = \min\{R_{oimaxWifi}, R_{imaxLte}\} \rightarrow \beta_4 = \frac{\min\{R_{oimaxWifi}, R_{imaxLte}\}}{B_o} \tag{14}$$

where $Pr_{minWifi}$, Pr_{minLte} are the sensitivity power levels of the Wi-Fi receiver and cellular receiver, respectively. $\beta_1 B_o$ is the channel capacity of the Wi-Fi link between auctioneer o and bidder i with the lowest transmission power of auctioneer o's Wi-Fi interface. Similarly, $\beta_2 B_o$ is bidder i's cellular link channel capacity with the lowest transmission power. $(1-\beta_3)B_o$ is auctioneer o's cellular link channel capacity with the lowest transmission power.

β is constrained between β_0 and β_4. If $\beta_0 > \beta_4$, the problem has no feasible solution. The computation of Pt_{iLte}, Pt_{oWifi} and Pt_{oLte} depend on the relation betweenβ on the one hand, and β_1, β_2 and β_3 on the other hand:

$$\text{If } \beta \le \beta_1 : Pt_{oWifi} = \frac{Pr_{minWifi}}{H_{oiWifi}(d_{io})} = C_{oWifi} \tag{15}$$

$$\text{If } \beta \le \beta_2 : Pt_{iLte} = \frac{Pr_{minLte}}{H_{iLte}(d_i)} = C_{iLte} \tag{16}$$

$$\text{If } \beta \ge \beta_3 : Pt_{oLte} = \frac{Pr_{minLte}}{H_{oLte}(d_o)} = C_{oLte} \tag{17}$$

$$\text{If } \beta \ge \beta_1 : Pt_{oWifi} = \frac{(2^{\frac{\beta B_o}{W_{wifi}}} - 1)(N_0 W_{wifi} + I_{iWifi})}{H_{oiWifi}(d_{io})} = 2^{\frac{B_o\beta}{W_{wifi}}} D_{oWifi} - D_{oWifi} \tag{18}$$

$$\text{If } \beta \ge \beta_2 : Pt_{iLte} = \frac{(2^{\frac{\beta B_o}{W_{iLte}}} - 1)(N_0 W_{iLte})}{H_{iLte}(d_i)} = 2^{\frac{B_o\beta}{W_{iLte}}} D_{iLte} - D_{iLte} \tag{19}$$

$$\text{If } \beta \le \beta_3 : Pt_{oLte} = \frac{(2^{\frac{(1-\beta)B_o}{W_{oLte}}} - 1)(N_0 W_{oLte})}{H_{oLte}(d_o)} = 2^{\frac{-B_o\beta}{W_{oLte}}} F_{oLte} - D_{oLte} \tag{20}$$

The only unknown variable in the above equations is β, hence we use C_{oWifi}, C_{iLte}, C_{oLte}, D_{oWifi}, D_{iLte}, F_{oLte} and D_{oLte} to denote the constant parts of the equations above. Equations (15) to (20) indicate that when the streaming rate is smaller than the channel capacity with the minimal transmission power, the transmission power is constant and is the minimal transmission power that guarantees the signal being received at the receiver side is at its sensitivity level. Otherwise, the transmission power is a function of the streaming rate.

Since the transmission powers Pt_{iLte}, Pt_{oWifi} and Pt_{oLte} depend on β's relation with β_1, β_2 and β_3, the optimization problem is different with different feasible ranges of β. 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.

As an example, in the case of $\beta_1 \le \beta_2 \le \beta_3$, the four feasible ranges of β are $[\max\{\beta_0, 0\}, \min\{\beta_1, \beta_4, 1\}]$, $[\max\{\beta_1, \beta_0, 0\}, \min\{\beta_2, \beta_4, 1\}]$, $[\max\{\beta_2, \beta_0, 0\}, \min\{\beta_3, \beta_4, 1\}]$, $[\max\{\beta_3, \beta_0, 0\}, \min\{\beta_4, 1\}]$. If we apply the LCF energy cost function, the objective function when $\max\{\beta_1, \beta_0, 0\} \le \beta \le \min\{\beta_2, \beta_4, 1\}$ becomes:

$$\begin{aligned}
&Cost_i + Cost_o \\
&\quad = cnst_{i1}Pt_{iLte} + cnst_{i2}Pt_{iLte}^2 + cnst_{o1}Pt_{oWifi} \\
&\qquad + cnst_{o1}Pt_{oLte} + cnst_{o2}(Pt_{oWifi} + Pt_{oLte})^2 \\
&\quad = cnst_{i1}C_{iLte} + cnst_{i2}C_{iLte}^2 + cnst_{o1}2^{\frac{B_o\beta}{W_{wifi}}} D_{oWifi} \\
&\qquad + cnst_{o1}2^{\frac{-B_o\beta}{W_{oLte}}} F_{oLte} - cnst_{o1}(D_{oWifi} + D_{oLte}) \\
&\qquad + cnst_{o2} \cdot (2^{\frac{B_o\beta}{W_{wifi}}} D_{oWifi} - D_{oWifi} \\
&\qquad + 2^{\frac{-B_o\beta}{W_{oLte}}} F_{oLte} - D_{oLte})^2
\end{aligned} \tag{21}$$

The optimization problem therefore becomes:

$$\underset{\beta}{\text{Minimize}}\ Cost_i + Cost_o \tag{22}$$

$$\text{s.t. } \max\{\beta_1, \beta_0, 0\} \le \beta \le \min\{\beta_2, \beta_4, 1\} \tag{23}$$

The objective function in this case is not convex. Let $X = 2^{\frac{B_o\beta}{W_{wifi}}}$, $Y = 2^{\frac{-B_o\beta}{W_{oLte}}}$. Then, (22)-(23) become:

$$\begin{aligned}
\underset{X,Y}{\text{Minimize}}\ & cnst_{o1}(D_{oWifi}X + F_{oLte}Y) \\
& + cnst_{o2} \cdot (D_{oWifi}X - D_{oWifi} \\
& + F_{oLte}Y - D_{oLte})^2 + cnst_{i1}C_{iLte} \\
& + cnst_{i2}C_{iLte}^2 - cnst_{o1}(D_{oWifi} + D_{oLte})
\end{aligned} \tag{24}$$

$$\text{s.t. } YX^{\frac{W_{wifi}}{W_{oLte}}} = 1 \tag{25}$$

$$2^{\max\{\beta_1,\beta_0,0\}\cdot B_o/W_{wifi}} \le X \le 2^{\min\{\beta_2,\beta_4,1\}\cdot B_o/W_{wifi}} \tag{26}$$

Now the objective function is convex, but constraint (25) is non-convex. We therefore relax (25) to the two constraints below:

$$Y \geq X^{\frac{-W_{wifi}}{W_{oLte}}} \tag{27}$$

$$Y \leq (2^{\max\{\beta_1,\beta_0,0\}\cdot B_o/W_{wifi}})^{\frac{-W_{wifi}}{W_{oLte}}} \tag{28}$$

This relaxed optimization problem (24),(26),(27)-(28) gives a lower bound for the optimization problem (24)-(26). Using 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 ratio of actual energy cost computed over the optimal energy cost computed from the relaxed optimization problem, and the average ratio is 1.0211 with standard deviation of 0.1371. In addition, among all the relaxed optimization problems solved in the simulation, around 51% of them give the actual optimal result. This number indicates that our relaxation yields a solution that is very close to the optimal solution's lower bound, hence is close to the optimal solution.

When we apply LCF as the energy cost function, there are 6 different relations among β_1, β_2 and β_3, and four different settings for Pt_{iLte}, Pt_{oWifi} and Pt_{oLte} in each relation, there is a total of 24 possible representations of the optimization problems (only 8 distinct representations). Some of the optimization problems are convex, some are not. We use a relaxation approach similar to that used above to solve the non-convex optimization problems. If we apply EAC as the energy cost function, the objective function is convex in β's entire feasible range. So the optimization problem using EAC approach is solvable using convex solver without any relaxation. The convex solver we used in this paper is CVX [43].

IV. AUCTION MECHANISM DESIGN

With multiple bidders participating in the auction, the auctioneer needs to select the right bidder and to make the appropriate payment to the selected bidder. In this section, we introduce the auction mechanism designed for our user cooperative communication auction. The following selection rule and payment rule are a modified version of the selection rule and payment rule of the classic Vickrey auction mechanism [44].

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

$$i_o = \arg\min_i b_i \tag{29}$$

where b_i is the bid offered by bidder i, which is the $Cost_i + Cost_o$ optimized in Section III-C.

If the energy cost of the cooperative transmission with the selected bidder is higher than the energy cost when auctioneer self serves only (transmits streaming traffic without cooperation) with the same streaming rate or the optimized β value is 0, the auctioneer will self serve itself.

Payment Rule: the auctioneer pays the winning bidder i_o the lowest bid that is higher than b_{i_o} minus the auctioneer's energy cost $Cost_o$ when cooperating with bidder i_o. It pays 0 to bidders who lose in the auction:

$$P_i = \begin{cases} min\{b_j : b_j > b_i\} - Cost_o & \text{if i} = i_o \\ 0 & \text{if i} \neq i_o \end{cases}$$

In the case where there is only one bidder i or there is no bid higher than b_i, and auctioneer chooses to cooperate with the bidder, and the auctioneer then pays bidder $P_i = b_{max} - Cost_o$, where $b_{max} = Cost_o^{max} + Cost_i^{max}$, $Cost_o^{max}$ and $Cost_i^{max}$ are calculated with maximum transmission power on auctioneer o's cellular interface, Wi-Fi interface and bidder i's cellular interface.

The payment is made 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. The credit is used by bidders in this work to decide which auctioneer to serve in order to enjoy higher utility. There are other usages of the credit system, such as 1) preventing mobile users without any credits from requesting other mobile users for relay; 2) preventing UEs from falsely reporting information to gain extra credits, etc. In this work, we do not study enforcement strategies that can use the credit to prevent mobile users from cheating or taking advantage of the credit system.

Instead, we focus on studying honest users' behaviors when participating in auctions in the user cooperative system and how different energy cost functions affect users' energy usage differently. Therefore, the initial credit level for all UEs in the system is set as zero, and UEs are not forbidden from participating into the auction even when they have negative credits levels.

The utility of bidder i is

$$U_i = P_i - Cost_i \tag{30}$$

If bidder does not cheat by providing false information $Info_i$, its utility will always be non-negative. In the case where bidder i wins, $P_i = (second\ lowest\ bid - Cost_o)$, then $U_i = (second\ lowest\ bid - Cost_o - Cost_i) = (second\ lowest\ bid - lowest\ bid) \geq 0$. In the case where bidder i loses, $P_i = 0$, $U_i = (0 - 0) = 0$.

In this paper, we assume UEs are honest and report information truthfully. Also, 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 iterative matching process:

- Auctioneer:
  - Sorts bidders in an increasing order of submitted bids.
  - Iteratively confirms with bidders in the increasing order. If the bidder accepts the offer, the auctioneer stops and selects the bidder for relay transmission. If the bidder temporarily rejects the offer, the auctioneer continues to confirm with the next lowest bidder on the ordered list.

  - When the auctioneer finishes confirming with all bidders in the list without any offer, it refreshes its' bidder list (remove bidders that reject its offer permanently from the list), and continues to confirm with bidders in an increasing order of the refreshed list.
  - It ends the auction when it reaches an agreement with one bidder or all of its bidders reject its offer permanently. When it ends the auction, it broadcasts 'end auction' signal to all other remaining bidders.
- Bidder:
  - Sorts auctioneers (if the bidder participates in multiple auctions) in a decreasing order of utilities that the bidder can enjoy.
  - When contacted by one auctioneer, it checks if the auctioneer is the one that can provide it with the highest utility. If it is, bidder accepts the offer, and broadcasts 'reject permanently' signal to other auctioneers. If it is not, bidder temperately rejects the auctioneer.
  - Bidder removes the auctioneer from its' auctioneers list whenever it receives 'end auction' signals from the auctioneer.

V. REAL-TIME OPTIMIZATION AND FAILURE PROTECTION

In reality, UEs' locations as well as the channel conditions are changing over time, which can result in UEs' streaming services suffering from rate loss or total service failure. Therefore, the failure protection functionality is needed for better quality of service. What's more, the changing may improve the channel condition as well, in which case the streaming application should be able to adjust the streaming rate to improve quality of service accordingly.

In this paper, UEs are assumed to operate with constant time step, and UEs' new movement and channel condition are updated at the beginning of each time slot. During each time slot, UEs' movement and channel condition remain static. UEs' streaming service lasts for more than one time slot. When UEs stream traffic, they perform real-time optimization and failure protection in slots other than the first slot.

A. OPERATIONS WHEN UEs SELF SERVE IN STREAMING

In this case, UEs self serve themselves with rate B^k when stream traffic at time slot k. At the beginning of time slot $k+1$, UEs first update the channel capacity TP^{k+1}. If $TP^{k+1} \geq B^{low}$, UEs continue streaming with the highest streaming rate that TP^{k+1} supports. If $TP^{k+1} < B^{low}$, UEs start an auction to retry the streaming service. When no bidder in the auction can help with the streaming, UEs end the streaming service and announce streaming service disconnection failure.

B. OPERATIONS WHEN UEs COOPERATE TO TRANSMIT WITH OTHER UEs IN STREAMING

In this case, UEs cooperate to with other UEs at time slot k. For example, auctioneer o establishes two-path streaming connections. One path goes through auctioneer's cellular connection with base station BS_o, and another path goes through auctioneer's Wi-Fi connection with bidder i. Below are the possible failures during streaming.

- **AucLinkFailure**: Cellular link between auctioneer o and base station BS_o suffers from quality drop or disconnection.
- **BidLinkFailure**: Cellular link between bidder i and base station BS_i suffers from quality drop or disconnection.
- **WiFiLinkFailure**: Wi-Fi link between auctioneer o and bidder i suffers from quality drop or disconnection.

In time slot k, auctioneer o streams with rate B^k, and β^k portion of the rate is relayed by bidder i. At the beginning of time slot $k+1$, the updated channel capacity is TP^{k+1}. Different values of TP^{k+1} result in different operations for auctioneer o:

- $TP^{k+1} < B_{low}$: auctioneer o ends the cooperation with bidder i, and retries the streaming service by starting another auction process. If there is no bidder available during the new auction, auctioneer o ends the streaming service and announces streaming service disconnection failure.
- $TP^{k+1} \geq B_{low}$: auctioneer o updates B^{k+1} to be the highest streaming rate that TP^{k+1} supports, meanwhile re-optimizes β^{k+1} to minimize the total energy cost.
  - $B^{k+1} \leq R^{k+1}_{omaxLte}$: auctioneer o self serves itself if self-serving consumes lower energy cost. Otherwise, the auctioneer cooperates with bidder i with the optimized β^{k+1}. At the end of time slot $k+1$, the credits paid to bidder i are updated accordingly.
  - $B^{k+1} > R^{k+1}_{omaxLte}$: auctioneer cooperates with bidder i, where $\beta^{k+1}B^{k+1}$ is relayed by the bidder, i.

To summarize, when UEs perform real-time optimization and failure protection, they will try to continue the cooperation with the neighbor UEs that relayed the traffic in previous time slot until the streaming service fails and needs retrial. This is to make sure that UEs' streaming service goes smoothly throughout the entire streaming event, since starting a new auction is time costly.

VI. SIMULATION RESULTS

In this section, we study the performance of our proposed user cooperative multi-path routing scheme. We first introduce the wireless network environment set up and UEs' battery model and streaming model in Section VI-A and Section VI-B, respectively. The detailed simulation results are shown in Section VI-C.

A. WIRELESS NETWORK ENVIRONMENT

In the MATLAB simulation platform, we set up one MBS, 5 FBSs and 100 UEs. The FBSs are uniformly distributed within 200 meters from the MBS, and for each FBS, there are 10 UEs uniformly deployed within 50 meters from the FBS. In addition, there are another 50 UEs uniformly deployed within 250 meters from the MBS. This simulation setup simulates a two-layer heterogeneous wireless network environment.

The cellular carrier center frequency used is 2 GHz, and the total cellular spectrum bandwidth is 20 MHz. A UE associates with the BS that provides it with the strongest signal strength. The cellular channel spectrum is evenly distributed among UEs that are associated with BSs. A Wi-Fi channel has a 40 MHz bandwidth [45]. UE's maximum transmission power of cellular interface and Wi-Fi interface are 23 dBm and 10 dBm, respectively. The sensitivity power level for Wi-Fi interface and cellular interface are -40 dBm and -101.5 dBm, respectively. The noise power spectrum density is -174 dBm/Hz. The path loss model for cellular channel is $PL(dB) = 15.3+37.6 \log_{10} R+X_c$, where R is in meters [46], and X_c is Gaussian random variable with zero mean and standard deviation $\delta_c = 15$. X_c reflects the attenuation caused by flat fading. The Wi-Fi signal path loss model is $PL(dB) = 32.2 \log_{10}(d)+X_w$, where d is in meters [47], and X_w is Gaussian random variable with zero mean and standard deviation $\delta_w = 8$. Because each UE uses different portion of the cellular spectrum, there is no interference to BS's cellular interface. We assume that each UE's Wi-Fi interface suffers interference from half of signal power received from all the other UEs transmitting at maximum transmission power. In the simulation, the number of UEs that are transmitting using Wi-Fi interface is less than half of the total UEs in the system, therefore, the interference to Wi-Fi interface considered here is a reasonable approximate.

To simulate the dynamics of the channel conditions, at the beginning of each time slot, we re-randomize the flat fading variable X_c and X_w, and each UE walks randomly within 1 meter from its position in previous time slot. At the beginning of each time slot, FBS suffers from cell outage with probability Pr_f. We study network performance with Pr_f selected from a number of different values [0, 0.015, 0.03, 0.045, 0.06, 0.075, 0.09, 0.105, 1].

B. UE'S BATTERY MODEL AND STREAMING MODEL

In practise, only a portion of UE's battery is used for wireless transmission. Therefore, we set the initial energy balance for all UEs as 2150 J (10% of Iphone 5s battery capacity [1570 mAh, 3.8 V].). α_{i0} and k_i used in the LCF energy cost approach are 2150 and -1, respectively.

The three constant bit rates that streaming application supports are $B_{low} = 1Mbps$, $B_{med} = 2Mbps$ and $B_{high} = 3Mbps$.

The simulation lasts for 90 time slots, and each time slot lasts for 30 seconds. In each time slot, each UE starts streaming event with certain probability. Each streaming event lasts for 3 time slots. For each UE i, the number of streaming events x_i generates during the entire simulation (90 time slots) is poisson distributed with mean $\lambda_i = 10$. At the beginning of time slot k, each UE streams as in following different cases:

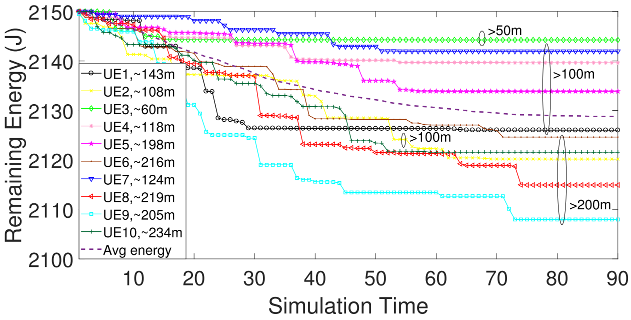
- UE i is idle, it starts a streaming event with probability $\frac{x_i}{S/3}$, where $S = 90 - k + 1$ is the number of remaining time slots. When S is smaller than 3, the probability of starting streaming event is 0.
  - If UE i starts the streaming event in time slot k, then it continues the streaming event in the following 2 time slots, and at the end of time slot $k+2$, the streaming event is finished, UE i updates $x_i = x_i - 1$, $S = S - 3$, and becomes idle in the beginning of time slot $k+2$;
  - If UE i does not generate streaming event in time slot k, it updates $x_i = x_i$, $S = S - 1$ at the end of time slot k, and remains idle.
- UE i continues streaming the event generated in previous time slot.
- UE i announces the streaming event disconnection failure. It updates $x_i = x_i - 1$, $S = S - 1$ at the end of time slot k.

C. PERFORMANCE ANALYSIS

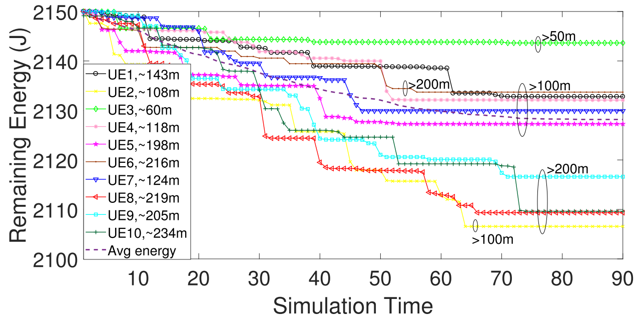
In the simulation, we assume all bidders are honest and report information truthfully to auctioneers. In the rest of the section, we compare the performance of three operation schemes: self serving scheme where UE transmits its streaming traffic without cooperation during the entire simulation (non-cooperation scheme); user cooperative multi-path routing scheme with LCF energy cost approach (LCF scheme), and user cooperative multi-path routing scheme with EAC energy cost approach (EAC scheme).

Fig.4a and Fig.5a give the energy balance and credit balance of 10 selected UEs throughout a selected simulation round using EAC scheme. Fig.4b and Fig.5b give the energy balance and credit balance of the same 10 selected UEs throughout the same selected simulation round using LCF scheme. The failure probability of FBS in the selected simulation round is 1, which means all FBSs are failed from the beginning of the simulation and UEs are served by MBS throughout the simulation. Fig.4a and Fig.4b show that the energy balance for all UEs are decreasing as simulation goes under both LCF and EAC schemes. What's more, some of the UEs have higher remaining energy balance than average remaining energy balance of all UEs in the system, and other UEs have lower remaining energy balance. The UEs further away from the MBS consume more energy than UEs closer to MBS. The energy level is also affected by UEs' total number of generated streaming events throughout the simulation, and how the generated streaming traffic is transmitted (cooperative or self-served). UE 2 in Fig.4a and UE 2, UE 6 in Fig.4b are such examples.

In both credit balance figures of LCF scheme and EAC scheme, the credit balance is fluctuated as time goes. This is due to the fact that throughout the simulation, UE sometimes

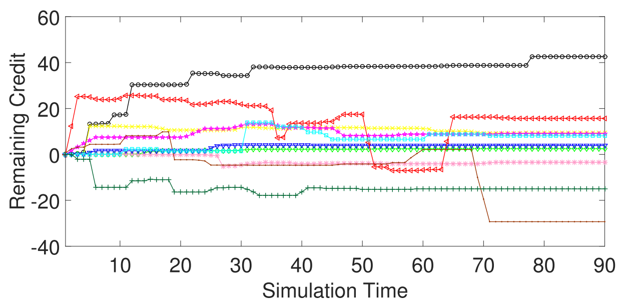


(a) With EAC energy cost function.

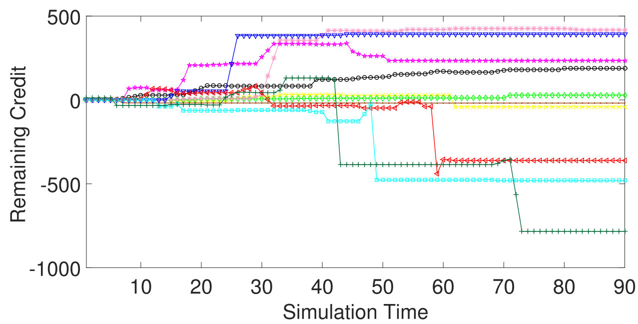


(b) With LCF energy cost function.

FIGURE 4. Selected UEs' available energy vs simulation time with cooperation scheme.

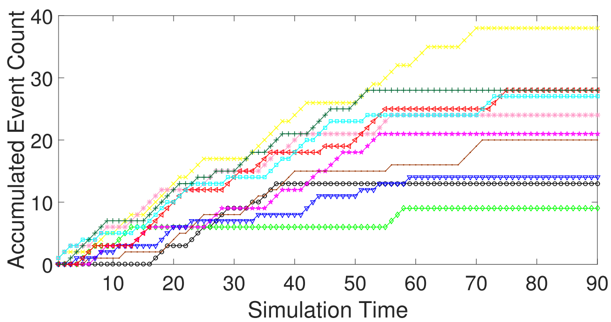


(a) With EAC energy cost function.

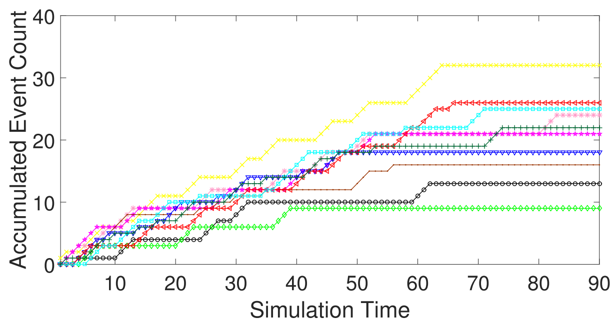


(b) With LCF energy cost function.

FIGURE 5. Selected UEs' available credit vs simulation time with cooperation scheme.



(a) With EAC energy cost function.

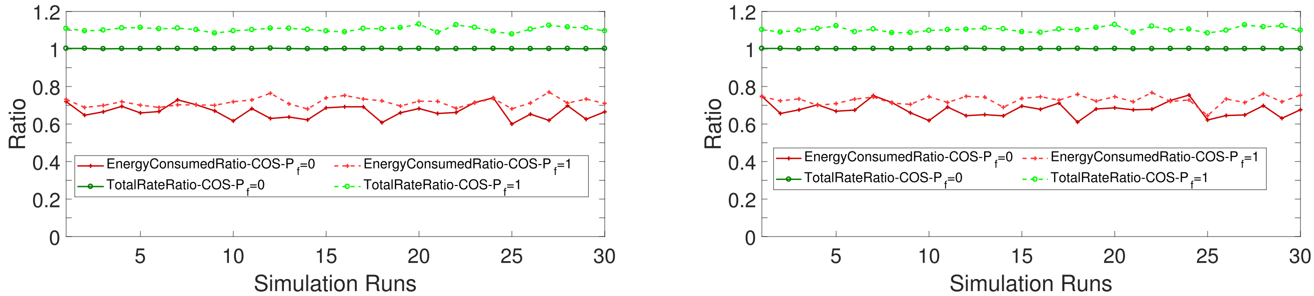


(b) With LCF energy cost function.

FIGURE 6. Selected UEs' accumulated event count vs simulation time with cooperation scheme.

acts as the auctioneer and sometimes acts as the bidder. UEs further away from MBS have more dramatic fluctuation in credit balance. This is because their neighbor UEs are also very far way from the MBS, and the energy costs are much higher as well. Fig.4 and Fig.5 do not show a direct relation of higher energy cost results in higher credit balance. In fact, the credit balance fluctuation is jointly determined by UE's streaming frequency, UE's locations from BSs and neighbor UEs' streaming frequency. In Fig.5b, the LCF scheme results in very large credit value due to its used cost function, and we can control the credit value by tuning the parameters in the cost function.

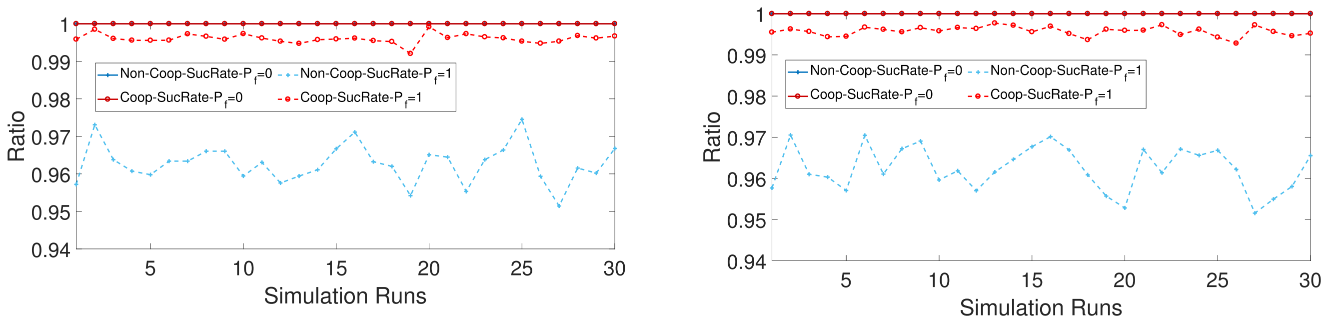
Fig.6 shows the accumulated streaming event count at each time slot of the same 10 selected UEs as in Fig.5. In the figure, UEs that streaming event successfully increase the accumulated event count in a continuous 3 time slots, otherwise, UEs fail the streaming event. Comparing Fig.4, Fig.5 and Fig.6, UEs with lower streaming event are more likely to have higher energy balance. UEs with higher streaming events, higher energy balance are more likely to have lower credit balance. UEs with lower streaming events, lower energy balance are more likely to have higher credit balance. As a summary, both UEs' energy level fluctuation and credit balance fluctuation are affected jointly



(a) With EAC energy cost function.

(b) With LCF energy cost function.

FIGURE 7. Ratio of UEs' rate consumption with cooperation schemes over rate consumption of non-cooperation scheme and energy consumption with cooperation schemes over energy consumption with non-cooperation scheme.



(a) With EAC energy cost function.

(b) With LCF energy cost function.

FIGURE 8. UEs' streaming event success rate with cooperation schemes over success rate with non-cooperation scheme.

by UE's streaming frequency, UE's locations from BSs, neighbor UEs' streaming frequency and UEs' approach for transmission.

Fig.7 shows the performance comparison between cooperation schemes and non-cooperation scheme (Self Serving) with two different FBS failure probabilities. The green circled line shows a rate ratio of cooperation scheme over non-cooperation scheme over different simulation runs. The rate is a summation of all UEs' streaming rate over 90 simulation slots with FBS failure probability being 0. It shows that cooperation schemes and non-cooperation scheme provide the same throughput when FBS failure probability is 0. In fact, given the three different streaming rate levels (B_{low}, B_{med}, B_{high}), cooperation schemes and non-cooperation scheme can support most of UEs with B_{high} when there is no FBS failure. When FBS failure probability becomes 1, cooperation schemes can provide UEs with higher rate compared to non-cooperation scheme, and this is shown by the light green circled dash line.

Fig.7 also shows UEs' total energy consumption ratio of both cooperation schemes over non-cooperation scheme. UEs with cooperation schemes consume less energy compared to UEs with non-cooperation scheme. When FBS failure probability is 0, UEs with cooperation schemes and non-cooperation scheme enjoy the same sum rate, however, in cooperation schemes, UEs consume about 35% less energy compared to that in non-cooperation scheme.

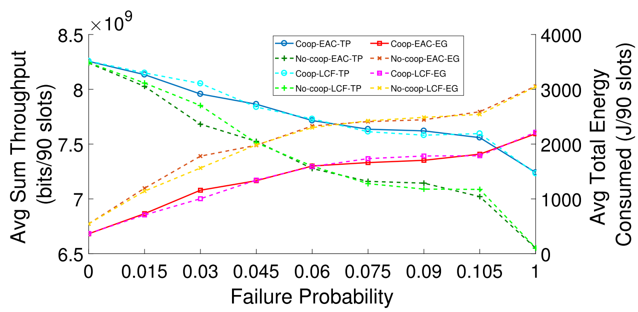


FIGURE 9. UE's sum throughput (TP) and total energy consumed (EG) averaged over 30 simulation runs vs different FBS failure probabilities.

With FBS failure probability being 1, the energy efficiency improvement of cooperation schemes over non-cooperation scheme is around 30%. But cooperation schemes provide UEs with higher rate compared to non-cooperation scheme.

Fig.8 shows UEs' streaming event success rate of cooperation schemes and non-cooperation scheme. When FBS failure probability is 0, UEs' streaming event success rate is 1 for both cooperation scheme and non-cooperation scheme. With FBS failure probability being 1, the success rate for both cooperation scheme and non-cooperation scheme is lower than 1, and cooperation schemes provide higher success rate.

Fig. 9 shows the sum rate of all UEs over 90 simulation slots averaged over 30 simulation runs under different FBS failure probabilities. The averaged sum rate decreases as FBS

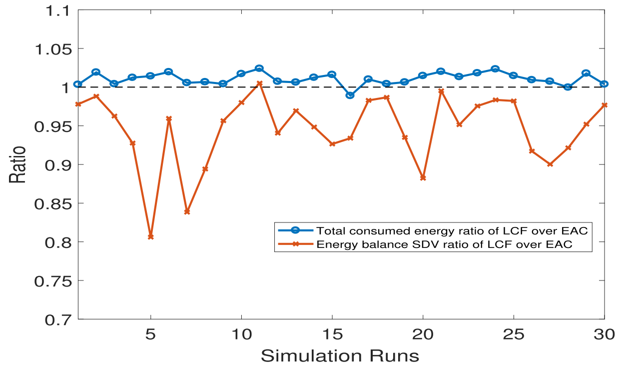


FIGURE 10. Total UEs' energy consumption and UEs' remaining energy standard deviation comparison between LCF scheme and EAC scheme.

failure probability increases. UEs with cooperation schemes have better throughput compared to non-cooperation scheme when FBSs are suffering from failure, and the improvement increases as FBS failure probability increases.

Fig.9 also shows the total energy consumption of all UEs over 90 simulation slots averaged over 30 simulation runs. The energy consumption increases as FBS failure probability increases. FBSs are located closer to UEs, therefore, UEs consume lower energy when transmitting to FBSs. When FBSs fail, UEs need to transmit to MBS, and consume more energy. The figure also shows that UEs with cooperation schemes consume less energy compared to UEs with non-cooperation scheme, and the energy consumed is around 30% less compared to non-cooperation scheme under different FBS failure probabilities.

To compare the performance between EAC energy cost function and LCF energy cost function in user cooperation scheme, we run simulation with a different simulation set up [27]. In the new simulation set up, there is no FBS in the system, and all UEs are served by MBS. What's more, UEs' streaming event lasts for one time slot. The network environment are static throughout the simulation (UEs do not move and channel condition does not change). This new simulation set up makes sure the simulations run with EAC and LCF scheme are only different in the energy cost function. Comparing the performance between EAC scheme and LCF scheme under this new simulation set up is much fair when we compare EAC scheme and LCF scheme under previous simulation set up. Because in previous simulation set up, streaming event lasts for 3 time slots. Longer streaming event results in different streaming behaviour throughout the simulation for the same UE under different cooperation schemes. This difference can be seen in Fig.6a and Fig.6b.

Fig.10 shows the performance comparison between two user cooperation schemes LCF and EAC under the new simulation environment. 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 consumes more energy than 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 is more likely to select the bidder with higher remaining energy. However, in EAC scheme, auctioneer selects bidder which can provide it with minimal energy consumption.

VII. CONCLUSION

In this paper, we proposed a user cooperative multi-path routing solution for streaming applications. We designed an auction mechanism which incentivizes UEs to provide relay service for other UEs. We also designed UEs' real-time optimization and failure protection operations to provide better quality of service. With the assumption that all UEs are honest players, our proposed solution showed great advantage in terms of improving service rate, improving streaming event success rate and reducing energy consumption compared to non-cooperative solutions. The proposed auction mechanism motivates UEs into participating in the user cooperation auction game with non-negative utilities. The comparison study also shows that LCF energy cost function has more potential in balancing the UE's remaining energy across all UEs in the system.

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