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Research Article

Auction-Based Resource Allocation for Cooperative Video Transmission Protocols over Wireless Networks

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Cooperative transmission has been proposed as a novel transmission strategy that takes advantage of broadcast nature of wireless networks, forms virtual MIMO system, and provides diversity gains. In this paper, wireless video transmission protocols are proposed, in which the spectrum resources are first allocated for the source side to broadcast video packets to the relay and destination, and then for the relay side to transmit side information generated from the received packets. The proposed protocols are optimized to minimize the end-to-end expected distortion via choosing bandwidth/power allocation, configuration of side information, subject to bandwidth and power constraints. For multiuser cases, most of current resource allocation approaches cannot be naturally extended and applied to the networks with relay nodes for video transmission. This paper extends the share auction approach into the cooperative video communication scenarios and provides a near-optimal solution for resource allocation. Experimental results have demonstrated that the proposed approach has significant advantage of up to 4 dB gain in single user case and 1.3 dB gain in multiuser case over the reference systems in terms of peak-to-signal-noise ratio. In addition, it reduces the formidable computational complexity of the optimal solution to linear complexity with performance degradation of less than 0.3 dB.

1. Introduction

Over the past few decades, wireless communications and networking have experienced unprecedented growth. With the advancement in video coding technology, transmitting real-time encoded video programs over wireless networks has become a promising service for applications such as video-on-demand and interactive video telephony. Recently, Distributed Source Coding (DSC) and Wyner-Ziv (WZ) coding have been proposed for video transmission [1, 2]. In DSC, the relay transcodes video packets to form the multiple descriptions of the video contents [1, 2]. The reencoded video is coded by WZ coding, that is, instead of sending the original video, the relay sends side information to the destination to improve the decoded video quality. Combining the directed transmitted video and relay's side information, the destination can explore the source diversity to improve the reconstructed video quality.

On the other hand, cooperative communication [3–15] has recently attracted significant attention as an effective transmission strategy, which efficiently takes advantage of the broadcast nature of wireless networks. The basic idea is to let nodes in a wireless network share information and transmit data cooperatively as a virtual antenna array. This collaboration significantly improves the system performance. With the fast growth of the video streaming technology, the concept of cooperative video communication can enable the relay nodes to play more intelligent and active roles in processing, transcoding, or re-adapting the media information received before transmitting to the next node. As a consequence, the advantage of flexibility simultaneously increases the complexity of the network management and resource allocation. So far there is little work in studying the full-fledged cooperative video network due to the high complexity.

Due to the distributed nature of the relay nodes, it is nature to connect the idea of DSC to video cooperative communication. In this paper, we propose a wireless video transmission protocol that leverages the benefits of both cooperative transmission and the idea of DSC. There are two phases involved in the transmission. In the first phase, the source broadcasts the video to the relay and destination. The relay conducts transcoding for the received video content to coarse quality and transmits it as side information. In the second phase, the relay chooses one of two options, that is, either to transmit the coarse-quality video packets using the amplify-and-forward or decode-and-forward protocols, or to encode the coarse-quality video using forward error coding (FEC), and then transmit the parity data to the destination. We assume a control channel is available to let the destination know the processing settings chosen by the relay node. The destination decodes the video transmitted in the first phase and transcodes it using the same coding parameters deployed in the relay node. The coarse-quality video generated at destination will be combined with the side information sent from the relay to improve the reconstructed coarse-quality video. (To achieve real-time streaming, when the source collects one new group of pictures (GOPs), the encoded bitstream of previous GOP can be transmitted by the proposed scheme.) In this paper, an optimization problem is formulated to minimize the end-to-end expected distortion by dynamically choosing the protocol mode, bandwidth/power allocation, FEC coding parameter, subject to the bandwidth and power constraints. From the analysis and simulation results using 3D-Set Partitioning in Hierarchical Trees (3D-SPIHT) video coding [16], the proposed cooperative video transmission protocol has a significant PSNR gain over the traditional direct video transmission. Especially by employing the cooperative video transmission with side information, we have obtained up to 4 dB gain over the amplify-and-forward or decode-and-forward protocols.

For the multiuser case, we concentrate on the resource allocation method using auction theory, which is a subfield of the game theory which attempts to mathematically capture behavior in strategic situations, in which an individual's success in making choices depends on the choices of others. In the auction scenarios, there is a central spectrum moderator that masters the resources and there are autonomous users that request resources in the network. Very recently, researchers start to explore the auction-theory-based solutions for resource allocation for video communications [17, 18] based on a Vickrey-Clarke-Groves VCG auction. General cooperative data communications based on share auction is also studied in [7, 19].

For our proposed cooperative video transmission, we study the video communications over the full-fledged cooperative network, and we focus on how to use relay nodes to improve the overall system performance, and especially on how to conduct resource allocation for relays. Each relay helps to connect a group of transmitters with a number of receivers. During the resource allocation process, the spectrum resources are first allocated for the transmitters who broadcast video packets to the relay and destination, and then for the relay nodes that transmit side information generated from the received packets to the destination, clearly to balance the resource allocation among source and relay nodes, and the resources used by the relays for each source are very critical for the overall network performance. We propose a quasishare auction-based approach, which explores the concept of share auction into this new domain. (In general the share auction concept cannot be naturally extended to video communications, due to the complexity to express the cooperative video end-to-end distortion and to obtain the close form update function.) Experimental results have demonstrated that the proposed approach has significant advantage of up to 1.3 dB gain over the reference system. In addition, it reduces the formidable computational complexity of the optimal solution to linear complexity with performance degradation of less than 0.3 dB.

This paper is organized as follows. In Section 2, the basics of cooperative transmission are studied, and the channel model, modulation, and coding scheme are discussed. In Section 3, the cooperative video transmission protocol is proposed and analyzed. In Section 4, the proposed resource allocation using quasishare auction is demonstrated and analyzed for multiuser case. A performance upper bound is also proposed. Simulations' results are shown in Section 5, and conclusions are drawn in Section 6.

2. Traditional Cooperative Communication Protocols and Channel Model

For the cooperative transmission system, we first consider a single source-destination case, in which there are source node s, relay node r, and destination node d. A more general multiuser case will be discussed in Section 4. The cooperative transmission consists of two phases. In Phase 1, source s broadcasts its information to both destination node d and relay node r. The received signals $Y_{s,d}$ and $Y_{s,r}$ at destination d and relay r can be expressed as

$$Y_{s,d} = \sqrt{P_s G_{s,d}} X_{s,d} + n_d, \tag{1}$$

$$Y_{s,r} = \sqrt{P_s G_{s,r}} X_{s,d} + n_r, \tag{2}$$

respectively, where P_s represents the transmit power to the destination from the source, $X_{s,d}$ is the transmitted information symbol with unit energy at Phase 1 at the source, $G_{s,d}$ and $G_{s,r}$ are the channel gains from s to d and r, respectively, and n_d and n_r are the additive white Gaussian noises (AWGNs). Without loss of generality, we assume that the noise power is the same for all the links, denoted by σ^2. We also assume that the channels are stable over each transmission frame.

For *direct transmission*, without the relay node's help, the signal-to-noise ratio (SNR) that results from s to d can be expressed by

$$\Gamma^{DT} = \frac{P_s G_{s,d}}{\sigma^2}. \tag{3}$$

For the *amplify-and-forward (AF)* cooperation transmission, in Phase 2, the relay amplifies $Y_{s,r}$ and forwards it to the destination with transmitted power P_r. The received signal at the destination is

$$Y_{r,d} = \sqrt{P_r G_{r,d}} X_{r,d} + n'_d, \tag{4}$$

where

$$X_{r,d} = \frac{Y_{s,r}}{|Y_{s,r}|} \tag{5}$$

is the energy-normalized transmitted signal from the source to the destination at Phase 1, $G_{r,d}$ is the channel gain from the relay to the destination, and n'_d is the received noise at Phase 2. Substituting (2) into (5), we can rewrite (4) as

$$Y_{r,d} = \frac{\sqrt{P_r G_{r,d}}\left(\sqrt{P_s G_{s,r}} X_{s,d} + n_r\right)}{\sqrt{P_s G_{s,r} + \sigma^2}} + n'_d. \tag{6}$$

Using (6), the relayed SNR at the destination for the source can be obtained by

$$\Gamma^{\mathrm{AF}}_{s,r,d} = \frac{P_r P_s G_{r,d} G_{s,r}}{\sigma^2 \left(P_r G_{r,d} + P_s G_{s,r} + \sigma^2\right)}. \tag{7}$$

Therefore, by (3) and (7), we have the combined SNR at the output of maximal ratio combining (MRC) as

$$\Gamma^{\mathrm{AF}} = \Gamma^{\mathrm{DT}}_{s,d} + \Gamma^{\mathrm{AF}}_{s,r,d}. \tag{8}$$

Notice that even though the SNR is improved, the bandwidth efficiency is reduced to half due to the half duplex of source transmission and relay transmission.

In the *decode-and-forward* (DF) cooperation transmission protocol, the relay decodes the source information in Phase 1 and retransmits to the destination in Phase 2. The destination combines the direct transmission information and relayed information together. The achievable rate can be calculated as follows:

$$R^{\mathrm{DF}} = \max_{0\le\rho\le1} \min\{R_1, R_2\} = \log_2\left(1 + \Gamma^{\mathrm{DF}}\right), \tag{9}$$

where

$$R_1 = \log_2\left[1 + \left(1-\rho^2\right)\frac{P_s G_{s,r}}{\sigma^2}\right], \tag{10}$$

$$R_2 = \log_2\left(1 + \frac{P_s G_{s,d}}{\sigma^2} + \frac{P_r G_{r,d}}{\sigma^2} + \frac{2\rho\sqrt{P_s G_{s,d} P_r G_{r,d}}}{\sigma^2}\right). \tag{11}$$

In this paper, we assume Rayleigh fading scenario. The bit error rate for a packet can be written as [20]

$$P_r = \frac{1}{2} - \frac{1}{2}\sqrt{\frac{\Gamma}{1+\Gamma}}, \tag{12}$$

where Γ is either Γ^{DT} in (3), Γ^{AF} in (7), or Γ^{DF} in (9), depending on the transmission protocol. If each packet has the length of L bits, the packet dropping rate is $1 - (1 - P_r)^L$.

Reed-Solomon (RS) Code is an important subclass of the nonbinary BCH error-correcting codes in which the encoder operates on multiple bits rather than individual bits. An RS code is specified as $\mathrm{RS}(N, M)$. This means that the encoder takes M data symbols and adds parity symbols to make an N-symbol codeword. There are $N - M$ parity symbols. An RS decoder can correct up to t symbols that contain errors in a codeword, where $2t = N - M$. So by adapting t, we can have different level of channel protections. The coded BER can be closely bounded by [20]

$$P_r^{RS} \le \frac{1}{2}\left[1 - \sum_{i=0}^{t}\binom{N}{i}(P_r)^i(1-P_r)^{(N-i)}\right]. \tag{13}$$

(Notice that BER and SER for RS code have the relation BER / SER $= 2^{(m-1)}/(2^m - 1)$. (13) is the performance bound which is accurate when m is large.) Here we assume that the BER is equal to 0.5 if the number of errors is greater than t. RS codes can also be shortened to fit different coding length requirements.

3. Proposed Cooperative Video Transmission

In this section, we first propose our protocol in Section 3.1. Then an optimization problem is formulated to achieve the best performance in Section 3.2. We analyze the algorithm and discuss the implementation issues in Section 3.3 and Section 3.4, respectively.

3.1. Proposed Cooperative Video Transmission Protocols. Currently, most of researches on cooperative transmission focus on data transmissions. However, video has different characteristics from generic data, such as decoding dependency and delay constraint. We propose cooperative protocols for video transmission to better utilize system resources for performance improvement. Moreover, because of the broadcast nature of the phase 1 in cooperative transmission, the source information is distributed over the relays without any cost. We can further improve end-to-end video quality via exploring source diversity using the idea of DSC. In Figure 1, we propose a cooperative video transmission protocol that can leverage the benefits of both cooperative transmission and the idea of DSC. Specifically, in the first phase, the source broadcasts the video to the relay and destination. In the second phase, the relay has two choices as follows.

(1) The relay can use AF or DF to relay the packets of coarse contents of the video. The destination combines the direct transmission and relay transmission to improve the quality of the received video with error concealment.

(2) The relay can transcode the received video to a coarse-quality video and then encode the coarse-quality video using a systematic Reed-Solomon code. Only the parity is transmitted to the destination. The destination decodes the video transmitted in the first stage and transcodes it using the same coding parameters used by the relay node to construct the coarse-quality video. This coarse-quality video will be combined with the parity check bits sent from the

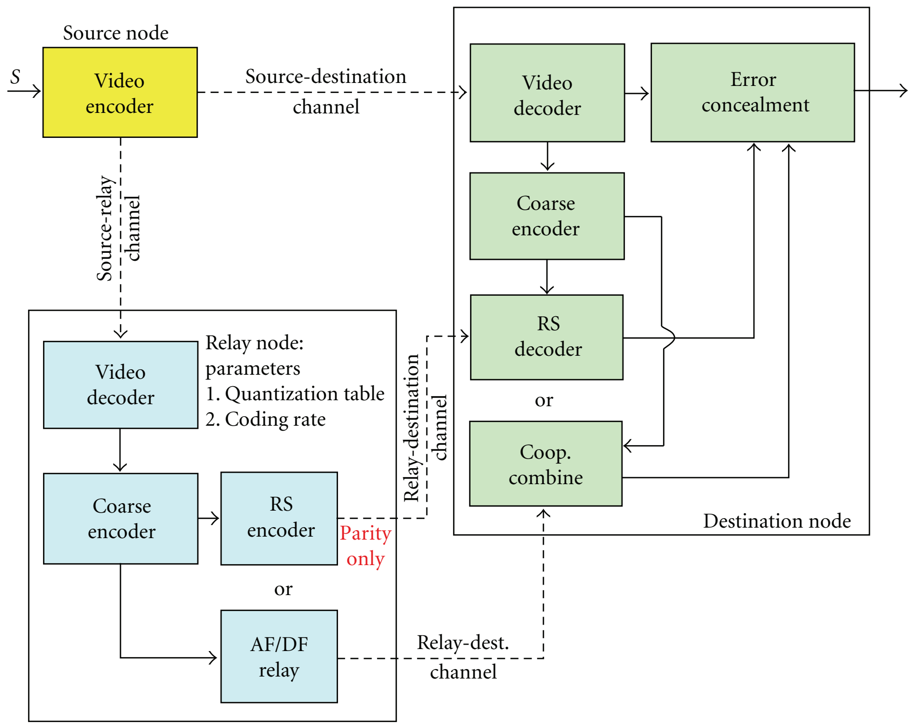

FIGURE 1: Proposed Video Cooperation Transmission.

relay to ensure the reconstructed coarse video quality which will be utilized for error concealment. (Notice that the relay might receive corrupted video packet. As a result, the relay might generate wrong parity bits and the performance at the destination can be impaired. To overcome this, source can use sufficient level of FEC to protect the video stream to transmit to relay and destination; so both relay and destination can have similar video quality. In other words, by carefully joint optimizing source coding and channel level along two paths, the final reconstructed video quality can be further improved.)

We can see that the proposed protocol explores not only the inherited spatial diversity and multipath diversity from cooperative transmission, but also the source diversity from the idea of DSC. Moreover, the proposed scheme is backward compatible, in the sense that the source-to-destination link is not modified. The current existing direct transmission scheme can coexist with the proposed scheme. This compatibility facilities the deployment of the proposed cooperative video transmission.

In the protocol, we assume that a control channel is available for the destination to know the processing procedures used in the relay node. However, the exchanging information, such as the RS coding rate, requires minimal of communication cost and update frequency.

3.2. Optimization of Proposed Protocols. In this paper, we use 3D-SPIHT [16] as the video encoder, due to its advantage that SPIHT produces an embedded bitstream. Notice that if embedded video codecs are employed, the head segment of successful received packets serves as the coarse-quality version of the original video. Other video encoders can be implemented in a similar way.

Let us define $D_{\max}$ as the distortion without receiving any packets, ΔD_k as the distortion reduction when receiving packet k after successfully receiving packet $1, 2, \ldots, k-1$, and $P_k^{(X)}$ as the probability that receiving all packets from packet 1 to k successfully using protocol X. The estimated distortion can be written as

$$ED^{(X)} = D_{\max} - \sum_{k=1}^{K} \Delta D_k P_k^{(X)}, \tag{14}$$

where K is the maximal number of packets constrained by the bandwidth. Notice that in order to decode the kth packet, packet 1 to packet $k-1$ must be correctly decoded.

The problem is to optimize the power and bandwidth usage at the relay node under the system bandwidth and overall power constraints. For the power constraint, we assume the total overall power is bounded by P_0. For the bandwidth constraint, we suppose the source and relays share the same channel, the total number of packets transmitted from source and relay is K, and the packet length is L. So the total bandwidth is W, which is the constraint for both the direct source-destination transmission and relay-destination transmission. For any cooperative protocol, we suppose the relay sends a total of $\overline{k} < K$ packets to the destination. Due to the bandwidth constraint, the direct transmission has only $K - \bar{k}$ packets for transmission instead. We define the bandwidth parameter as

$$\theta = \frac{\bar{k}}{K}. \tag{15}$$

Notice that the constraints are the sum of bandwidth and the sum of power, which are fair compared to the direct transmission without cooperation. If we consider individual constraints (such as $P_s \leq P_0$ and $P_r \leq P_0$), the performance of the proposed scheme would be better since the constraints are looser.

Moreover, if we also optimize the RS coding rate $\eta = M/N$, the problem can be formulated as

$$\min_{\theta, P_s, P_r, \eta} E[D], \tag{16}$$

$$\text{s.t.} \begin{cases} \text{bandwidth constraint:} & 0 \leq \theta < 1, \\ \text{power constraint:} & P_s + P_r \leq P_0. \end{cases} \tag{17}$$

The problem in (16) is a constrained optimization problem. The objective function $E[D]$ will be explained in the following subsection. The constraints are the bandwidth and power constraints which are linear. The objective functions for different protocols might not be linear. Some standard nonlinear approaches such as interior-point-method [21] can be employed to solve the problem.

3.3. Performance Analysis. In this subsection, we study the performance of different transmission protocols. We define $p_{s,r}$ as the packet loss rate for sending a packet from source node to relay node, $p_{r,d}$ as the packet loss rate for sending a packet from the relay node to destination node, $p_{s,d}$ as the packet loss rate for sending a packet from the source node to destination node, p_{comb} as the packet loss rate for sending a packet from source node to destination node using combined decoding, and p_{DSC} as the packet loss rate for sending parity check bits from the relay. For direct transmission, relay transmission without combined decoding and relay transmission with combined decoding using AF/DF, we suppose that all transmissions are protected by $\text{RS}(L, M_1)$, where L is the packet length and M_1 is the message length.

3.3.1. Direction Transmission. The power for the source is P_0. The successful transmission probability for receiving all correct packet 1 to packet k can be written as

$$P_k^{(\text{DT})} = \left(1 - p_{s,d}\right)^k, \tag{18}$$

where $p_{s,d}$ can be calculated from (3), (12), and (13). The distortion is

$$E\left[D^{(DT)}\right] = D_{\max} - \sum_{k=1}^{K} \Delta D_k P_k^{(\text{DT})}. \tag{19}$$

Notice that all bandwidth is used for direct transmission.

3.3.2. Relay Transmission without Combined Decoding. We use equal power for the source and relay in this scenario. Using this protocol, the packet is lost if both the direct transmission and relay transmission fail. Thus,

$$P_k^{(\text{RT})} = \begin{cases} 1 - p_{s,d}\left(1 - (1 - p_{s,r})(1 - p_{r,d})\right)^k, & k \leq \bar{k} = \dfrac{\theta W}{L}, \\ P_{\bar{k}}^{\text{RT}} \left(1 - p_{s,d}\right)^{k - \bar{k}}, & K - \bar{k} \geq k > \bar{k}, \end{cases} \tag{20}$$

where the first case represents the situation where the relay retransmits the packets, while the second case represents the direct transmission only. The total transmitted packets from the source is reduced to $K - \bar{k}$, due to the relay transmission.

Then, we need to solve the following problem to achieve the minimal expected distortion:

$$E\left[D^{(\text{RT})}\right] = \min_{(0 \leq \theta < 1)} E\left[D^{(\text{RT})}(\theta)\right] = D_{\max} - \sum_{k=1}^{K - \bar{k}} \Delta D_k P_k^{(\text{RT})}. \tag{21}$$

Clearly it can be solved by line-search over θ.

3.3.3. Relay Transmission with Combined Decoding Using AF/DF. For AF, p_{comb} can be calculated by (8), (12), and (13). For DF, p_{comb} can be calculated by (9), (12), and (13). It can be proved that the power constraint and bandwidth constraint in (16) can be decoupled without loss of optimality. Due to the page limitation, we omit the proof. We assume that the power is optimally allocated in this case. Similarly to the previous case, we can write

$$P_k^{(CD)} = \begin{cases} \left(1 - p_{\text{comb}}\right)^k, & k \leq \bar{k} = \dfrac{\theta W}{L}, \\ P_{\bar{k}}^{(CD)} \left(1 - p_{s,d}\right)^{k - \bar{k}}, & K - \bar{k} \geq k > \bar{k}. \end{cases} \tag{22}$$

The first case and second case have the similar physical meaning as (20). Similar to (21), we can also write

$$E\left[D^{(CD)}\right] = \min_{(0 \leq \theta < 1)} E\left[D^{(CD)}(\theta)\right] = D_{\max} - \sum_{k=1}^{K - \bar{k}} \Delta D_k P_k^{(CD)}. \tag{23}$$

3.3.4. Relay Transmission with Parity Check. In our proposed protocol, instead of sending the original packets from the source, the relay encodes using another RS code $\text{RS}(L, M_2)$, and sends the parity bits with length of $L - M_2$ only. The destination combines the direct transmission part of M_2 bits and the relay transmission bits to improve the link quality. In this case, $\theta = (L - M_2)/L$. Here we assume the equal power allocation for the source and relay. We can write

$$P_k^{(\text{DSC})} = \left(1 - p_{\text{DSC}}\right)^k, \tag{24}$$

where the packet error rate is the product of the successful packet transmission rate of source-to-relay path and the successful packet transmission rate after RS(L, M_2) decoding from the source to the destination, that is,

$$p_{\mathrm{DSC}} = 1 - (1 - p_{s,r})\left(1 - P^{\mathrm{RS}}_{s,r,d}\right)^L. \quad (25)$$

Define $t' = (L - M_2)/2$. We have the BER after the decoding of RS(L, M_2) code for both direct transmission and relay transmission as

$$P^{\mathrm{RS}}_{s,r,d} \leq \frac{1}{2}\left[1 - \sum_{j=0}^{t'}\sum_{i=0}^{t'-j}\binom{M_2}{j}(P_{s,d})^j(1-P_{s,d})^{(M_2-j)} \times \binom{L-M_2}{i}(P_{r,d})^i(1-P_{r,d})^{(L-M_2-i)}\right]. \quad (26)$$

Here $P_r^{s,d}$ is the BER of direct transmission calculated from (3) and (12), and $P_r^{r,d}$ is the BER of transmission from the relay to the destination calculated from

$$\Gamma_{r,d} = \frac{P_r G_{r,d}}{\sigma^2} \quad (27)$$

and (12). We use the fact that the RS code can decode up to t' errors in either direct transmission part or the relay transmission part in (26). Notice that in order to have the fair comparison with the other schemes, the direct transmission of this scheme is also protected by an RS code RS(M_2, M_1), where M_1 is the length of original source bits per packet.

3.4. Implementation Consideration. It is possible to incorporate other video transcoding/processing algorithms into the proposed system. For example, we can use a transcoder to convert the received video into a lower-resolution and lower-quality version after the following processing. (1) Use a down-sampling algorithm to change the resolution of the image, for example, the QCIF image (176×144) can be converted to a 96×80 resolution image using 6/11 horizontal scalar and 5/9 vertical scalar. The scaling ratio is adjustable. (2) Use a QP for quantizing the DCT coefficients; (3) use a truncation tool to adjust the SNR quality. The transcoded version is packed in a single packet and transmitted to the destination. A certain time of retransmission is allowed for this packet. Therefore, the scalar, QP, and truncation parameters in the transcoder side can be jointly optimized with the source coding parameters at the transmitter side to achieve the best performance. In the receiver side, the received packets from the main channel and the relay channel are used together to recover the original videos. The information sent by relay channel can help to recover the lost packets sent via the main channel. Of course, the uppersampling is needed for the lower-resolution image to get back to the original size.

The other issue is the complexity for coordination for resource allocation. The optimization in (16) is performed, and resource allocation parameters (such as bandwidth and power) are sent back to the source and relay. The size of the information (a few bytes in our case) is relatively trivial compared with the video packets.

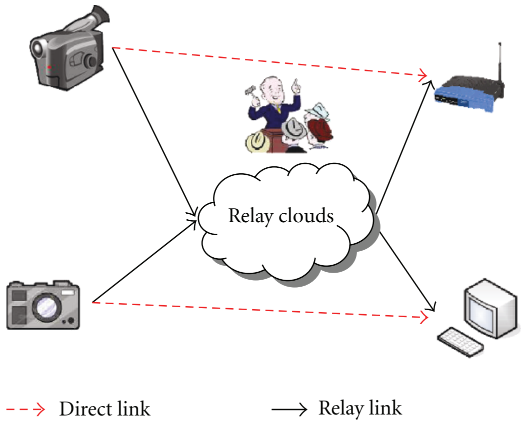

Figure 2: Multiple User Resource Allocation in Relay.

4. Proposed Quasishare Auction Schemes for MultiUser Case

In the previous section, we study the single source-relay-destination case in which one relay tries to help one source-destination pair for the received PSNR. In this section, based on the proposed video cooperative protocol, we investigate multiuser case in which one relay tries to help a group of source-destination pairs to achieve the social optimum, that is, the overall PSNR. We first formulate the multiuser resource allocation problem for the relay node in Section 4.1. Then, the quasishare auction is proposed and analyzed in Section 4.2. Finally, we employ one approach in the literature to our problem as the performance bound in Section 4.3.

4.1. Multiuser Resource Allocation for Relay Node. We consider the full-fledged cooperative network, in which each node can serve as transmitter, relay, or receiver. To make problem a bit simpler, we assume that the nodes that play relay functions have been predetermined (so the relay node determination problem is not in the scope of this paper), so that each relay helps to connect a group of transmitters with a number of receivers as shown in Figure 2. In this paper, we suppose the cooperative transmission system has source node s_i, one relay node r and destination node d_i.

Denote set $\mathcal{I}$ as I source-destination pairs accessing one particular relay node in the network. To achieve real-time transmission, the overall allocated transmission time slots for all nodes to transmit I GOPs is set to the required time to playback one GOP. We reserve t% of time slots for relay node. The rest of time slots are allocated to each source-destination pair equally. Due to the distributed location of the nodes, each source-destination pair experiences different channel condition in both direct and cooperative transmission path. Besides, since different sources transmit different video sequences and the contents are changing over time, the relay needs to dynamically adjust rate allocation to provide optimal video quality. The main issue is how to assign relay's time slots to each source-destination pair for delivering side information to achieve overall optimal video quality. Define

θ_i as the fraction of relay's time slots assigned to source-destination pair i and η_i as the channel coding rate selected by the source i. We can formulate the considered network within each GOP time scale as

$$\min_{\theta_i,\eta_i} \sum_{i\in\mathcal{I}} E[D_i(\theta_i,\eta_i)], \tag{28}$$

$$\text{s.t.} \quad \begin{cases} \sum_{i\in\mathcal{I}} \theta_i \leq 1, \\ 0 < \eta_i \leq 1, \quad \forall i \in \mathcal{I}. \end{cases} \tag{29}$$

By given one θ_i, the minimal achievable distortion for received video at destination i can be calculated as follows:

$$ED_{s_i,r,d_i}(\theta_i) = \min_{\eta_i} E[D_i(\theta_i,\eta_i)]. \tag{30}$$

The problem in (30) can be solved locally in each source.

For the relay, the resource allocation problem is to optimize the overall distortion by dividing the relay's resources, which are the time slots. The problem can be formulated as

$$\min_{\theta_i} \sum_{i\in\mathcal{I}} ED_{s_i,r,d_i}(\theta_i), \tag{31}$$

$$\text{s.t.} \sum_{i\in\mathcal{I}} \theta_i \leq 1. \tag{32}$$

In the next two subsections, we discuss two solutions to solve the problem in (31).

4.2. Proposed Quasishare Auction. In this subsection, we find a distributed solution to solve (28). Due to the distributed nature, different source-destination pairs try to optimize their own performances in a noncooperative way. Notice that this noncooperation is between the different source-destination pairs, and cooperative transmission is employed for the relay retransmission. Based on the idea from share auction, we propose a quasishare auction that takes advantage of setting for cooperative video transmission. The rules of the quasishare auctions are described below.

(i) *Information*. Public available information includes noise density σ^2 and bandwidth W. The relay also announces a positive *reserve bid* (or reserve price in some literature) $\beta > 0$ and a *price* $\pi > 0$ to all sources. Each source i also knows the channel gains along direct and cooperative transmission path, namely, G_{s_i,d_i}, $G_{s_i,r}$, and G_{r,d_i}.

(ii) *Bids.* Source i submits $b_i \geq 0$ to the relay.

(iii) *Allocation.* Relay allocates proportions of time slot for source-destination pair i according to

$$\theta_i = \frac{b_i}{\sum_{j\in\mathcal{I}} b_j + \beta}. \tag{33}$$

(iv) *Payments.* In our case, source i pays the relay $C_i = \pi\theta_i$.

A bidding profile is defined as the vector containing the sources' *bids*, $\mathbf{b} = (b_1,\ldots,b_I)$. The bidding profile of source i's opponents is defined as $b_{-i} = (b_1,\ldots,b_{i-1},b_{i+1},\ldots,b_I)$, so that $\mathbf{b} = (b_i; b_{-i})$. Each source i chooses bid b_i to maximize its payoff

$$S_i(b_i; b_{-i},\pi) = \Delta E[D_i(\theta_i(b_i; b_{-i}))] - C_i(b_i; b_{-i},\pi), \tag{34}$$

where

$$\Delta E[D_i(\theta_i(b_i; b_{-i}))] = E[D_{s_i,r,d_i}(0)] - E[D_{s_i,r,d_i}(\theta_i(b_i; b_{-i}))]. \tag{35}$$

Each source chooses its price to maximize its payoff function in (34). If the price is increased, then from (33), the relay allocates more time slots to this user. As a result, the distortion is reduced. However, the cost C_i also increases. Consequently, if the other users do not change their prices, there is an optimal point to set the price.

Although video's rate-distortion (RD) curve is often a *convex* decreasing function; however, (35) is generally not a *concave* increasing function owing to applying optimization over all possible channel coding rate for each θ_i in (30). Notice that above payoff function for the quasishare auction is similar to the soul of "Pricing Anarchy," in which the users pay the tax for their usage for the system resources.

Here, we omit the dependency on β. If the reserve bid $\beta = 0$, then the resource allocation in (33) only depends on the ratio of the bids. In other words, a bidding profile $k\mathbf{b}$ for any $k > 0$ leads to the same resource allocation, which is not desirable in practice. That is why we need a positive reserve bid. However, the value of β is not important as long as it is positive. For example, if we increase β to $k\beta$, then sources can just scale $\mathbf{b}$ to $k\mathbf{b}$, which results in the same resource allocation. For simplicity, we can simply choose $\beta = 1$ in the practice.

In (34), if the others' *bidsb*$_{-i}$ are fixed, source i can increase its time slot θ_i in (33) by increasing b_i. As a result, the distortion is reduced and $\Delta E[D_i]$ is improved. However, the payoff faction needs to pay the price for θ_i. Depending one different price per unit π announced by the relay, there are three different scenarios:.

(1) If π is too small, the payoff function S_i in (34) is still an increasing function. As a result, the source tries to maximize its own benefit by setting price high. Consequently, $b_i \to \infty$.

(2) If π is too large, the payoff function S_i is a decreasing function. As a result, the source would not participate in the bidding by setting $b_i = 0$.

(3) If π is set to the right value, the payoff function S_i is a quasi-concave shape function, that is, it increases first and then decreases within the feasible region. Consequently, there is an optimal b_i for the source to optimize its performance.

Based on the observation above, the quasishare auction algorithm is shown as follows. The relay conducts line search for π from the situation in which $b_i = 0, \forall i$ to the situation in which $b_i = \infty, \forall i$. For each π, different sources set bids to optimize their own performances and report the expected distortion to the relay. By doing so, the computation is distributed to each source node. Among all π s', the relay selects the solution with the best overall system performance and announces the final θ_i to each source i.

Compared with the share auction and the proposed quasishare auction, the final results are the same if the bid update for share auction can be obtained and $\Delta E[D_i]$ is a concave increasing function. For data communication, the bids can be updated in a close form. However, due to the complexity to express the cooperative video end-to-end distortion, the close form update function cannot be obtained. As a result, we can only apply the quasishare auction for the video cooperative transmission.

4.3. Performance Upper Bound. In this subsection, we investigate a performance upper bound similar to the VCG auction proposed in the literature and compared with our proposed approach. (Notice that the VCG auction [22–24] is not the contribution of this paper. Moreover, we do not claim any efficiency result in a repeated dynamic setting, where more sophisticated strategies can be adopted.) In the performance upper bound, the relay asks all sources to reveal their evaluations of the relay's time slots, upon which the relay calculates the optimal resource allocation and allocates accordingly. A source pays the " performance loss" of other sources induced by its own participation of the auction. In the context of cooperative video transmissions, the performance upper bound can be described as follows.

(i) *Information.* Public available information includes noise density σ^2 and bandwidth W. Source s_i knows channel gain G_{s_i,d_i}. The relay knows channel gains G_{r,d_i} for all i and can estimate the channel gains $G_{s_i,r}$ for all i when it receives bids from the sources.

(ii) *Bids.* Source s_i submits the function $Q_i(\theta_i, G_{s_i,r}, G_{r,d_i})$ to the relay, which represents the distortion decrease as a function of the relay parameter θ_i and channel gains $G_{s_i,r}$ and G_{r,d_i}:

(iii) *Allocation.* The relay determines the time slot allocation by solving the following problem (for notational simplicity we omit the dependence on $G_{s_i,r}$ and G_{r,d_i}),

$$\boldsymbol{\theta}^* = \arg\max_{\theta} \sum_{j\in\mathcal{I}} Q_j\left(\theta_j\right). \tag{36}$$

(iv) *Payments.*For each source i, the relay solves the following problem.

$$\theta^{*/i} = \arg\max_{\theta,\theta_i=0} \sum_{j} Q_j\left(\theta_j\right), \tag{37}$$

that is, the total distortion decreases without allocating resource to source i. The payment of source i is then

$$C_i = \sum_{j\neq i, j\in\mathcal{I}} Q_j\left(\theta_j^{*/i}\right) - \sum_{j\neq i, j\in\mathcal{I}} Q_j\left(\theta_j^{*}\right), \tag{38}$$

that is, the performance loss of all other sources because of including source i in the allocation.

Source i in the performance upper bound obtains the *payoff* function as

$$Y_i = \Delta D_i(\theta_i) - C_i. \tag{39}$$

Although a source can submit any function it wants, it has been shown [22] that it is a (weakly) dominant strategy to bid truthfully, that is, revealing the true function form of its distortion decrease

$$Q_i(\theta_i) = \max\{D_{s_i,r,d_i}(0) - D_{s_i,r,d_i}(\theta_i), 0\}. \tag{40}$$

As a result, the resource allocation of the performance upper bound as calculated in (36) achieves the *efficient* allocation [22]. Note that the sources do not need to know global network information, that is, no need of knowing the channel gains related to other sources in the network. The auction can achieve the efficient allocation in one shot, by allowing the relay to gather a lot of information and perform heavy but local computation.

Although the performance upper bound has the desirable social optimal, it is usually computationally expensive for the relay to solve $I + 1$ nonconvex optimization problems. To solve a nonconvex optimization, the common solution like interior point method needs a complexity of $O(I^2)$. As the result, the overall complexity for the performance upper bound is $O(I^3)$, while the proposed quasishare auction has linear complexity. Furthermore, there is a significant communication overhead to submit $Q_i(\theta_i)$ for each source i, which is proportional to the number of source nodes and reserved time slot for relay node. In the proposed scheme, the bids and the corresponding resource allocation are iteratively updated. This is similar to the distributed power control case, where the signal-to-interference-noise ratio and power update are iteratively obtained. As a result, the overall signalling can be reduced.

5. Simulation Results

In order to test the proposed scheme, we set up two sets of simulations. First, we study the single source-relay-destination case for our proposed cooperative video transmission. Then, we investigate the multiuser case for the proposed resource allocation using auction theory.

5.1. Single Source-Relay-Destination Case. The overall power is $P_0 = 0.2$ W, the noise power is -100 dbmw, and the propagation factor is 3. The source is located at the origin and the destination is located at (1000 m, 0 m). The relay is moved from the (100 m, 400 m) to (900 m, 400 m). The packet length is $L = 255$. Two tested video streams are *Foreman* and *News* in QCIF resolution (176×144) with refresh rate 30 frames per second.

In Figures 3 and 4, we show the PSNR as a function of the relay location for video *News* and video *Foreman*, respectively. Here we normalize the relay location in x-axis over the distance from the source to the destination. From the figures, we can see that the direct transmission has the worst performance and generates the unacceptable

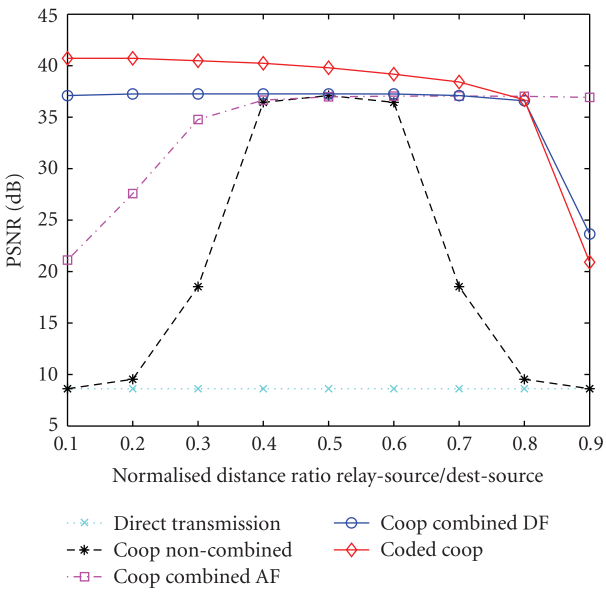

Figure 3: PSNR versus Relay Location (Video News).

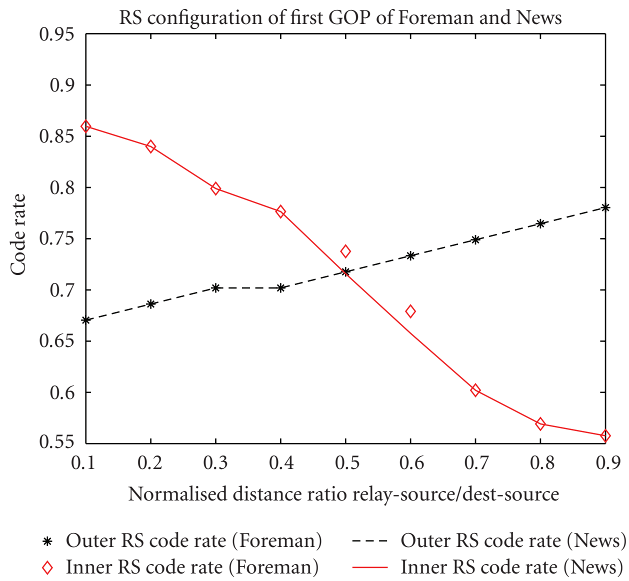

Figure 5: RS Code Rate for Cooperative Protocol with Parity Check.

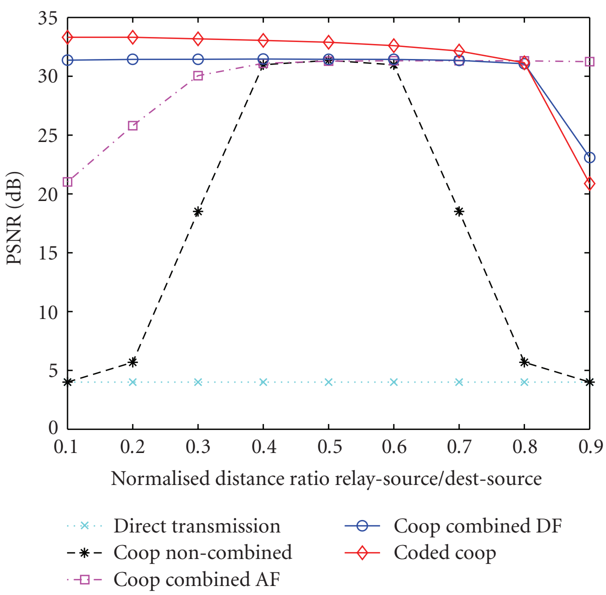

Figure 4: PSNR versus Relay Location (Video Foreman).

reconstructed video quality. The cooperative transmission without combining of SNR at the receiver has the best performance when the relay is located at the middle of the source and the destination. For the AF protocol, the best performance is achieved when the relay is relatively close to the destination; for the DF protocol, the optimal relay location is toward the source, and the DF protocol has better performance than the AF protocol when the relay is close to the source. These facts are very different from the data domain cooperative transmission. Finally, the relay transmission with parity check (shown as coded coop) has superior performance (about 4 dB gain) than the other protocols when the source and relay are close. When the relay is far away from the source, its performance degrades fast. This is because the performance is impaired by the source-relay link. On the whole, the proposed cooperative protocols achieve better performances than those of direct transmission, and the characteristics of the performance improvement are very different from the data domain cooperative protocols.

In Figure 5, we show the RS code rates for different videos of inner code (RS code for direct transmission) and outer code (RS code for relay transmission), respectively. We can see that the inner coding rate is reduced when the relay is far away from the source. This is because the source-relay channel needs more protection. On the other hand, when the relay is close to the source, the relay-destination link is protected more by the lower outer RS code rate. This two-level RS codes provide the cooperative video transmission scheme with additional 4 dB gain in video quality.

Notice that the proposed cooperative system will not always perform well in every relay location. The location of relay needs to be close to the source-destination link. Otherwise, the cooperative transmission will not work, in the sense that the optimization in (16) degrades to traditional direct transmission with $\theta = 0$.

The other concern is to study which protocol fits a certain situation best. For the AF/DF protocol, the received SNR can be significantly increased. This is especially true for low SNR case. However, the signal needs to be stored in the receiver for combining at the second state. This increases the implementation cost. For the relay transmission without combined decoding, the implementation cost is minor, but it has inferior performance when the SNR is low. The proposed scheme with parity check provides an improvement over the relay transmission without combined decoding in a cost effective manner. However, the relay needs to be close to the source to ensure a the good source-relay channel.

Table 1: Performance gap: low motion.

Bandwidth (kbps)	95.63	191.25	286.88	382.50	478.12
Optimal (dB)	30.36	34.29	36.83	38.82	40.44
Proposed (dB)	30.16	34.12	36.52	38.61	40.22
Gap (dB)	0.2	0.17	0.31	0.21	0.22

Table 2: Performance gap: high motion.

Bandwidth (kbps)	765	956.2	1530	1912.5	2677.5
Optimal (dB)	30.16	31.18	33.73	35.17	37.68
Proposed (dB)	30.01	31.02	33.59	34.92	37.37
Gap (dB)	0.15	0.16	0.14	0.15	0.31

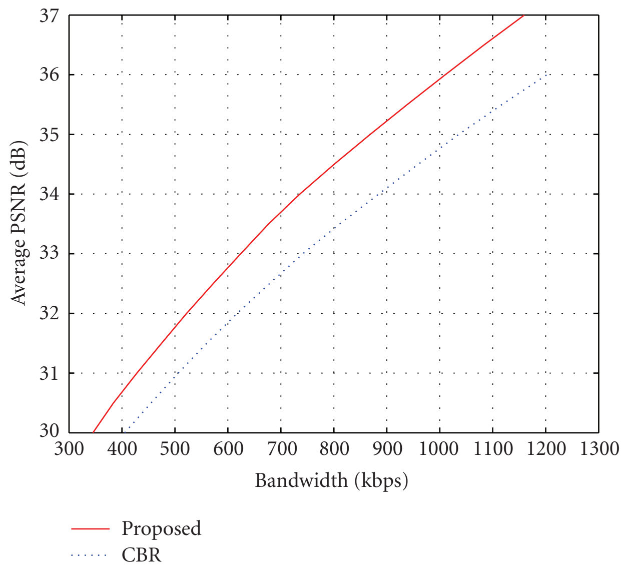

Figure 6: Average versus Bandwidth.

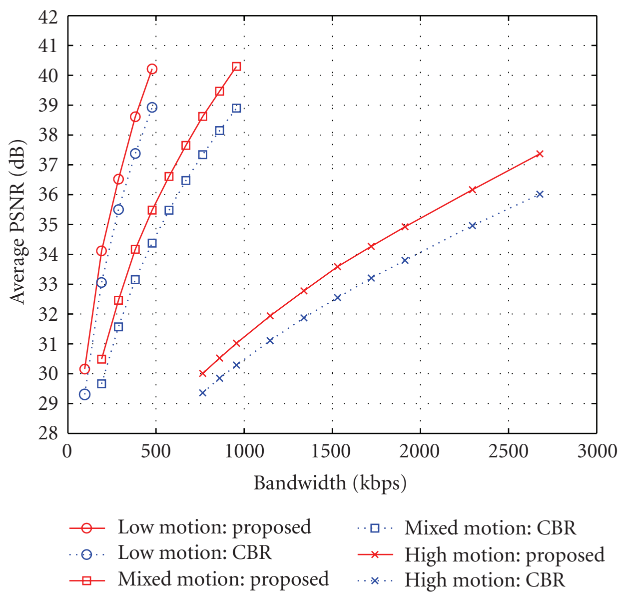

Figure 7: PSNR versus Bandwidth for Different Motion Activities.

5.2. Multiple User Case. For multiple user case, the simulations are setup as follows. The power for all source nodes and relay node is 0.1 W, the noise power is $5 * 10^{-10}$ W, and the propagation factor is 3. Source node 1 to node 3 are located at (−400 m, 0 m), (−300 m, 50 m), and −200 m, −20 m), respectively. The corresponding destination node 1 to 3 are located at (200 m, 0 m), (400 m, 100 m), and (300 m, 30 m), respectively. The relay is located at the origin. We reserve 30% of bandwidth for relay to transmit the parity check bits. The packet length is L = 255. We use a 3D-SPIHT [16] codec to compress video sequence in QCIF resolution (176 × 144) with refresh rate 30 frames per second. The GOP is set to 16, and each source node will transmit 10 GOPs to its corresponding destination node. To evaluate the performance under different video content and different level of motion activity in the video sequence, we compare three different sets of video sequences. The first set consists of low motion video sequences: *news*, *grandma*, and *akiyo*. The second set contains high motion video sequences *stefan*, *foreman*, and *coastguard*. The third set contains mixed level of motion video sequences, including *silent*, *foreman*, and *news*.

To demonstrate that the proposed scheme can utilize the relay's bandwidth effectively to achieve better perceptual quality, we compare the constant bit rate (CBR) scheme which allocates equal amount of time slots for relay to transmit parity bits for each video source. In Figure 6, we show the average PSNR gain when we compare the proposed scheme and the CBR scheme for all three video sets. As we can see, the proposed scheme can have PSNR gain between 0.8 dB and 1.3 dB when the received video quality is between 30 dB and 40 dB, which is a noticeable quality improvement. The performance gain achieved by the proposed scheme is mainly contributed by jointly leveraging the diversity of different video source RD characteristics and nodes' channel conditions, and dynamically allocating suitable amount of time slots to each video source. To further assess the impact of different level of motion activities, we show the PSNR performance for three different video sets in Figure 7. As revealed, the performance gain is consistent for all levels of motion activities owing to the dynamic resource allocation.

To evaluate how close the performance of the proposed scheme can approach to the optimal solution, we list the

Table 3: Performance gap: mixed motion.

Bandwidth (kbps)	191.25	478.12	573.75	765.00	956.25
Optimal (dB)	30.65	34.34	36.89	38.89	40.54
Proposed (dB)	30.49	34.17	36.61	38.62	40.30
Gap (dB)	0.16	0.17	0.28	0.27	0.24

PSNR difference between the proposed scheme and the optimal solution in Tables 1, 2, and 3. As shown in these three tables, the performance loss is only between 0.1 dB and 0.3 dB. Note that the computation complexity and the communication overhead to obtain the optimal solution are extremely high. The proposed distributed scheme can achieve similar video quality by requiring much lower computation and communication overhead.

6. Conclusions

In this paper, we propose the cooperative video transmission protocols using auction theory. The source broadcasts its information in the first stage. The relay can either retransmit the low quality video packets or transmit the coded parity bits instead. The destination uses this relay information as side information to improve the quality of video transmission. We formulate the problem as to minimize the estimated distortion under the power and bandwidth constraints. Four different cooperative schemes are compared for the performance improvement over different scenarios and for the implementation concerns. The proposed video cooperative scheme has the best performance among all schemes, if the source and relay are closely located together. For multiuser case, we further propose the resource allocation for the relay to improve the multiuser cooperative video transmission using quasishare auction. Specifically, based on the observation of available information, we propose a quasishare auction for the relay to allocate the transmission time slots with improved signaling and convergence. Compared to the performance upper bound which is complicated and unpractical, the proposed quasishare auction can reduce the complexity, while the performance gap is only 0.1 dB to 0.3 dB.

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