

ROUTING AND COOPERATIVE RELAY SELECTION IN MULTI-HOP NETWORKS FOR VIDEO TRANSMISSION

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Keywords: cooperative relay, video transmission, multi-hop, PSNR, delay, hop count

Abstract

Video streaming service in multihop wireless networks becomes more popular and practical with the advanced technology. This paper considers video transmission in multihop wireless networks with cooperative relay to increase the transmission rate at the bottleneck link. For each video source and destination (s-d) pair we are interested in determining the route and possible cooperative relay node to guarantee the required transmission rate, delay and high Peak Signal to Noise interference Ratio (PSNR). The problem is formulated as a mixed integer nonlinear programming (MINLP) problem which is NP-hard. An algorithm which is based on the maximum capacity path is developed to obtain the highest data rate path which satisfies delay bound and hop-count limitation. The performance of the algorithm is demonstrated with various conditions in the simulation.

1 Introduction

Cooperative communications have emerged as a promising approach to achieve spatial diversity and thereby reduce the negative effects of fading on wireless channels. Spatial diversity is generally in the form of employing multiple transmitter receiver antennas (e.g., multiple-input and multiple-output (MIMO)) [1]. However, equipping a wireless node with multiple antennas may not be practical. Recent studies address this limitation through the use of a new paradigm known as cooperative communications that draws from the idea of using the broadcast nature of the wireless channel to achieve spatial diversity. Under cooperative communications nodes equipped with a single transceiver (cooperative relay) capture a neighboring source's transmission and relay it to the designated destination. The destination combines multiple streams of the same information from both source and relay nodes to recover the original information with high probability. Therefore, by cooperatively relaying the information to the destination, nodes equipped with single antenna achieve the same advantages as those found in MIMO systems. Cooperative communications thus provides spatial and path diversity that improves system performance with a single antenna and increases the transmission rate and reliability [1, 2].

Video transmission requires high throughput (e.g., video: 0.5~4 Mbps, audio: 192kbps) and stringent delay. Espe-

cially, interactive video delay above 400ms and streaming video delay over 4-5s is unacceptable. Transmission data rate should be equal to or greater than video encoding rate. Video transmission sometimes requires heterogeneous rate demand, meaning each video session requires a different video quality (HD, FHD, etc.) according to the kind of devices, channel quality, etc.

However, the common objective of most research is to optimize physical layer performance measures (BER, link outage probability) or overall network throughput. They don't consider the impact of cooperation on video transmission. In this paper, we focus on the video transmission with cooperative relay. We consider multiple access strategies such as Time Division Multiple Access (TDMA) for multiuser systems and multiple sources.

The remainder of this paper is organized as follows. In Section 2, we discuss related work in detail. Section 3 provides reference model for cooperative communications and introduces the problem formulation. Proposed algorithm is explained in Section 4 with computation result in Section 5. Finally, we conclude this paper in Section 6.

2 Related work

Research of cooperative communications at the physical layer has been very active in recent years. In [3, 4], achievable rates and diversity gains are investigated. In [5], studies on physical transmission techniques such as amplify-and-forward (AF) and decode-and-forward (DF) are introduced. In [6], the study focused on node assignment problem in single-hop network. In [7, 8], the authors proposed heuristics to solve the routing problem with relay node assignment.

For multi-hop networks, Sharma et al. [9] studied a joint optimization problem of relay node assignment and flow routing, with the objective to maximize the minimum rate among a set of concurrent sessions. They developed a mathematical model and proposed a solution procedure based on the branch-and-bound framework augmented with cutting planes. Sharma focused on cooperative systems where one relay node receives data from only one node, and to transmit data to one other node. However, in multiuser systems, multiple sources may be accessing the cooperative channel simultaneously, and, thus, multiple access strategies must be devised to separate such as TDMA with single antenna.

For multi-hop video transmission, Kompella et al. [10] investigated the joint problem of optimal path selection and rate allocation for multiple video sessions, with the objective to minimize the video distortion. However, co-

operative communications was not considered for the multi-hop video transmission in the study. There are several excellent contributions in cooperative video transmission. In [11, 12], Guan et al. studied cross-layer design techniques for video streaming over single-hop cooperative networks. The problem of joint rate control, relay selection, and power allocation is formulated as a mixed-integer nonlinear problem, with the objective of maximizing the sum PSNR of a set of concurrent video sessions. We consider joint flow routing and cooperative relay node selection for video transmission in multi-hop wireless networks.

3 Problem statement

3.1 Cooperative communications in Multi-hop Networks

Cooperative communications refers to systems or techniques that allow users to help transmit each other's messages to the destination. The essence of cooperative communications is to exploit (1) the wireless broadcast advantage and (2) the relaying capability of neighboring nodes so as to achieve higher data rate and lower transmission error [2]. Most cooperative transmission schemes involve two phases of transmission: a coordination phase, where users exchange their own source data with each other and/or the destination, and a cooperation phase, where the users cooperatively retransmit their messages to the destination.

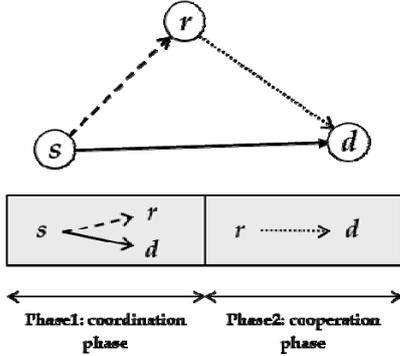


Figure 1. A simple protocol of a three-node model for cooperative communications

Figure 1 shows a simple protocol of a three-node model for cooperative communications, where node s is a source node, node d is a destination node, and node r is a relay node. In the coordination phase (i.e., Phase1), the source node broadcasts its data to both the relay and the destination and in the cooperation phase (i.e., Phase2), the relay forwards the source's data to enhance reception at the destination. There are two common cooperation strategies: amplify and forward (AF) and decode and forward (DF). In AF, the relay simply amplifies the received signal and forwards it to the destination. With DF, the relay first decodes the received signal, and then forwards it if it can be successfully decoded.

In this paper, we employ orthogonal channels to resolve contention in multi-hop wireless network. Under this

model, each node uses separate channels for transmission and reception and thus can transmit and receive data on different channels at the same time without self-interfering. In order to achieve the maximum rate under cooperative communications, we assume that the source and e relay node should transmit at their maximum power P . Thus, we set $P_s = P_r = P$. We also consider the amplify and forward strategy.

3.2 Network Setting

We consider a multi-hop video transmission network, where each source node compresses a video sequence at a given rate. We employ orthogonal channels in the network, which allow different nodes to transmit simultaneously without interference. The video content is queued at the each node buffer and then transmitted to the destination through multi-hop direct or cooperative links. It is assumed that a node can be parts of several links using TDMA technology in the network.

In [14], Zhao *et al.* showed that for a single hop, the diversity gain obtained by exploiting multiple relay nodes is only marginally higher than the diversity gain that can be obtained by selecting the best relay. As a result, we only consider at most one relay node for cooperative communications between each pair of sender and receiver.

3.3 Delay analysis

End-to-end delay indicates the time taken to send a packet from a source to a destination node. Contrary to bandwidth, delay is an additive metric. Thus, the delay along a path is equal to the sum of the delays on the one-hop links (each node) of this path. The packet delay on a specific one-hop link, denoted by D , can be divided into three parts [15]. The transmission delay ($D_{transmission}$) is the amount of time required to push all of the packet's bits into the wire. In other words, this is the delay caused by the data-rate of the link. The queuing delay (D_{queue}) which represents the interval between the time the packet enters in the queue of the link's emitter and the time that the packet becomes the head of line packet in this node's queue. The propagation delay ($D_{propagation}$) is the amount of time it takes for the head of the signal to travel from the sender to the receiver. The electric signals travel quite fast, so their propagation time is negligible.

$$D = D_{transmission} + D_{queue} (+D_{propagation})$$

We employ a simple M/M/1 tandem queue model as in [11]. The packet arrival follows a Poisson distribution of parameter video encoding rate, the service rate follows an exponential distribution of parameter link capacity. The output process of an M/M/1 queue in steady state is Poisson with the same parameter as the input process [15,16]. The average queuing delay D_s of video session s is additive and can then be expressed as

$$D_s = \sum_{link(i,j) \in Path_s} \frac{L_s}{C_{ij} - R_{ij}} \quad (1)$$

where C_{ij} and R_{ij} are the capacity and the aggregated video encoding rates traversing link (i, j) , respectively, and L_s is the average packet length. $Path_s$ is the set of the link for video session s transmission.

3.4 Multiple access

In [9], Sharma focused on cooperative systems where one relay node receive data from only one node, and to transmit it to one other node. However, in multiuser systems, multiple sources may be accessing the cooperative channel simultaneously, and, thus, multiple access strategies must be devised to separate such as TDMA with single antenna [1].

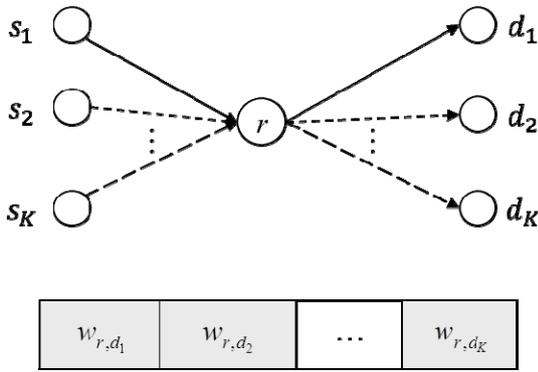


Figure 2. Shared relay

Specifically, we consider the case of designated relays, where each source is served exclusively by one or multiple relays, and the case of shared relays, where multiple sources are served by a common set of relays. In the case of designated relays, the resources of a given relay are allocated completely to a single source and, thus, the system is simple to implement. However, the diversity gain achievable in this case is often limited since the number of relays that can be designated to one particular source is usually small. In the case of shared relays, more than one source may be transmitting through a common set of relays and, thus, the resources at the relays must be properly allocated to maximize cooperative advantages received by the sources. Higher diversity gains can potentially be achieved compared to the designated relays.

Denote by $w_{ij,M}$ and $w_{ij,C}$ the resource proportion used on link (i, j) for multi-hop relay and cooperative relay, respectively. $w_{ij,M}$ and $w_{ij,C}$ are defined since a link can be used as a part of direct transmission and cooperative relay simultaneously in the network. The summation of $w_{ij,M}$ and $w_{ij,C}$ for node i should be equal or smaller than one.

3.5 Video Rate-Distortion Model

The video quality is measured in terms of PSNR, which is a monotonically decreasing function of the mean-square error (MSE) [17].

$$PSNR_s = 10 \log_{10} (Distortion_{\max} / Distortion_s) \quad (2)$$

$PSNR_s$ represents the PSNR of video session s . $Distortion_s$ is the corresponding video distortion and $Distortion_{\max}$ is a constant parameter representing the maximum of possible distortion.

PSNR is most commonly used to measure the quality of reconstruction of lossy compression codecs. The signal in this case is the original data, and the noise is the error introduced by compression. In [18], the rate-distortion model is analysed as

$$PSNR_s = \beta_0 + \beta_1 R_s + \beta_2 R_s^2 \quad (3)$$

where β_0, β_1 and β_2 are video-specific parameters. It provides estimated values for end-to-end PSNR using rate R_s of video session s .

3.6 Mathematical Model

In this section, we present a mathematical model of maximizing the sum of PSNRs of multiple video sessions by jointly controlling the video encoding rate, relay selection, flow routing, and weight problem. Denote \mathcal{S} as the set of video sessions and \mathcal{N} as the set of nodes in the networks. Set \mathcal{N} has three subsets of nodes, 1) the set of source nodes, $N_s = \{s_1, s_2, \dots, s_n\}$, 2) the set of destination nodes, $N_d = \{d_1, d_2, \dots, d_n\}$, and 3) the set of remaining nodes that are available for serving as relay nodes, $N_r = \{r_1, r_2, \dots, r_m\}$.

In [9], a sophisticated version of the model for node selection and flow routing in multi-hop networks is proposed. We modified the objective function, several constraints and variables to be suitable for the video transmission environment.

A binary variable is defined to indicate whether an available relay node is used as Cooperative Relay (CR) or not.

$$CR_{ij}^k = \begin{cases} 1 & \text{if node } k \text{ is used as a CR on link } (i, j) \\ 0 & \text{otherwise} \end{cases}$$

We also introduce another binary variable to specify whether or not the link from i to j is active in the routing solution.

$$MR_{ij} = \begin{cases} 1 & \text{if node } j \text{ is the next hop node of node } i \\ 0 & \text{otherwise} \end{cases}$$

The binary variable f_{ij}^s indicates whether the link (i, j) is used or not for the session s .

$$f_{ij}^s = \begin{cases} 1 & \text{if link } (i, j) \text{ is used by video session } s \\ 0 & \text{otherwise} \end{cases}$$

Equation (4) represents that a link (i, j) should be used as part of a path to assign a node k as a CR node.

$$MR_{ij} - \sum_{\substack{k \neq i, k \neq j \\ k \in \mathcal{N}}} CR_{ij}^k \geq 0 \quad (4)$$

The constraint (5) indicates that total sum of resource weights of link (i, j) for a certain node i and all the node j cannot exceed one.

$$\sum_{j \in N} w_{ij,M} + \sum_{j \in N} w_{ij,C} \leq 1 \quad \forall i \in N \quad (1)$$

Equation (6) shows the flow conservation of each node. A video flow is transmitted from the source node to the destination node. The source node only has the outflow and the destination node only has the inflow. For all the other nodes, except for the source and destination nodes, the outflow and the inflow should be the same.

$$\sum_{j \in N} R_s \cdot f_{ij}^s - \sum_{j \in N} R_s \cdot f_{ji}^s = \begin{cases} R_s, & i \in N_s \\ 0, & i \in N_r \\ -R_s, & i \in N_d \end{cases} \quad (2)$$

Constraint (7) indicates that a certain video session s can use at most one link at a certain node among several links starting from the node. In other words, a video session s cannot pass through several paths.

$$\sum_{j \in N} f_{ij}^s \leq 1 \quad \forall i \in N \quad (3)$$

Each video session requires a minimum encoding rate R_{\min}^s for video session s , i.e.,

$$R_s \geq R_{\min}^s \quad \forall s \in S \quad (4)$$

The aggregated video encoding rates traversing link (i, j) cannot exceed the available link capacity

$$R_{ij} \leq C_{ij} \quad \forall s \in S, \forall \text{link}(i, j) \quad (5)$$

The aggregated video encoding rates on link (i, j) can be calculated by

$$R_{ij} = \sum_{s \in S} R_s \cdot f_{ij}^s \quad (6)$$

The available link capacity can be determined utilizing the binary variables indicating whether direct transmission or cooperative relay is employed and the time weight variable. If direct transmission is employed, then the first term of the (11) is non-zero and the second term is zero; the converse is true when cooperative relay is employed.

$$C_{ij} = (MR_{ij} - \sum_{k \in N, k \neq j} CR_{ij}^k) w_{ij,D} C_D(i, j) + (\sum_{k \in N, k \neq j} CR_{ij}^k) (w_{ij,D} \cdot w_{kj,C}) C_{AF}(i, j, k) \quad (7)$$

The average queuing delay for each video session cannot exceed the play out deadline,

$$D_s \leq D^{deadline} \quad \forall s \in S \quad (8)$$

Considering that delay and error probability tend to increase as hop number of a session increases in multi-hop networks, the hop number of a session cannot exceed hop count limit α .

$$\sum_{\text{link}(i,j) \in \text{Path}_s} f_{ij}^s \leq \alpha \quad \forall s \in S \quad (9)$$

We have the following problem formulation:

Max $\sum PSNR_s$

s.t. (4),(5),(6),(7),(8),(9),(12),(13)

$CR_{ij}^k, MR_{ij}, f_{ij}^s \in \{0,1\}$ ($i \in N, j \in N, k \in N, i \neq j \neq k$)

$R_s \geq 0 \quad \forall s \in N_s$

$w_{ij,M}, w_{ij,C} \geq 0 \quad \forall \text{link}(i, j)$

4 Proposed solution procedure: Maximum capacity path algorithm

The problem formulated in previous section is a MINLP problem which is NP-hard [9,11]. No existing algorithms can solve the problem in polynomial time. Therefore, we propose an algorithm to maximize the total sum PSNRs of all the video sessions considering the flow routing, relay node selection, and video rate allocation.

In the proposed algorithm, the path selection and initial rate allocation is based on the maximum capacity path problem. The algorithm has the following three phase: i) path determination and minimal required rate allocation for each video session, ii) cooperative relays selection, and iii) video rate assignment.

Phase 1: Path Determination (f_{ij}^s determination)

In the phase 1, for each video session, the path with the maximum capacity is determined. Each video session requires a minimal video rate. The order of source-destination (s-d) pairs, namely video sessions, for path determination follows the decreasing order of R_{\min}^s . The video rate allocated to session s, R_s , should not be smaller than the minimal required video rate of session s and should not be greater than the link capacity, C_{ij} .

Note that the end-to-end capacity of a session in a multi-hop network is determined by the capacity of bottleneck link, a path with the maximal bottleneck capacity is selected for the session. Since PSNR and the allocated video rate have positive correlation as shown in $PSNR_s = \beta_0 + \beta_1 R_s + \beta_2 R_s^2$, a path with high capacity has a potential to get high R_s and high PSNR value. Also high link capacity provides low delay. Considering that delay and error probability tend to increase as the hop count of a session increases in multi-hop networks [21], the hop count of a session is limited in the proposed algorithm. The effect of hop count limitation is analysed based on the computation result. For the selected maximum capacity path for an s-d pair, assign R_{\min}^s to R_s temporarily and recalculate the remaining capacities of each link in the network. The process is repeated until R_{\min}^s is allocated to all the available s-d pairs.

Phase2. Cooperative Relay Selection (CR_{ij}^k, MR_{ij} determination)

After R_{\min}^s is allocated to all s-d pairs in phase 1, video rate of each session is increased by increasing bottleneck link capacity by adopting the CR.

Step1. Phase 1 may not satisfy the minimal required video rate and delay limitation for some s-d pairs. In this step,

the CR is employed for such a video session to increase the bottleneck link capacity.

If the CR-assisted link is not the bottleneck of the path anymore, a new bottleneck is searched and the procedure is repeated until the minimal required video rate is satisfied. When there is no possible path for a session even after CR allocation, it is concluded that the session has no available path.

Phase 3: Video Rate Assignment (determination of $R_s, w_{ij,M}, w_{ij,C}$)

After Phase 2 the increased capacity of each bottleneck link is reallocated to the video sessions such that the PSNR increment is the biggest among the available sessions at each CR-assisted link.

5 Simulation results

Performance of the proposed algorithm is evaluated with $N=30$, and 50 nodes randomly placed in an area of $800m \times 500m$. $n=4, 6, 8,$ and 10 s-d pairs are randomly distributed in the communication area. The path-loss coefficient between node s and d is given by $|h_{sd}|^2 = \|s-d\|^{-4}$, where $\|s-d\|$ is the distance (in meters) AWGN noise power variance is set to 10^{-10} W at all nodes. We set $W = 0.2$ MHz bandwidth for each channel. The maximum transmission power at each node is set to 1W. We consider Akiyo video sequences as shown in Table 1 and use the mathematical model in Section 3.5 to calculate the PSNR with given video parameters and link capacities. In Table 1, the units of $D^{deadline}$ and L_s are *ms* and bits, respectively. Video rate demands for video sessions are set to 0.2Mbps or 0.5Mbps at the rate of 1:1. For high confidence level, we simulate 500 times for all cases and evaluate average values.

Table 1. Video Parameters

| Video | β_0 | β_1 | β_2 | $D^{deadline}$ | L_s |
|-------|-----------|-----------|-----------|----------------|-------|
| Akiyo | 26.32 | 17.056 | -3.848 | 350 | 3040 |

From figures 3-6, we see that sum_PSNR values are low when the hop-count limitation is low. It is because low hop-count limitation makes the problem difficult to find an available path. In Figure 4, the value of sum_PSNR is the biggest as 205.9dB when the hop-count limitation is six. The value gets smaller as the hop count limitation increases over six and converges to 204.9dB. When the number of nodes is 50, the effect of hop count limitation gets bigger. This is because the number of hops of a path tends to increase to find the maximum capacity compared to the case of 30 nodes. The overall trend in 50 nodes is similar with the 30 node case as shown in Figures 7-10. We see from the figures that the sum_PSNR decreases as the hop count increases. This is because the delay increases with the increased hop count for some sessions, which results in degraded video quality with reduced PSNR.

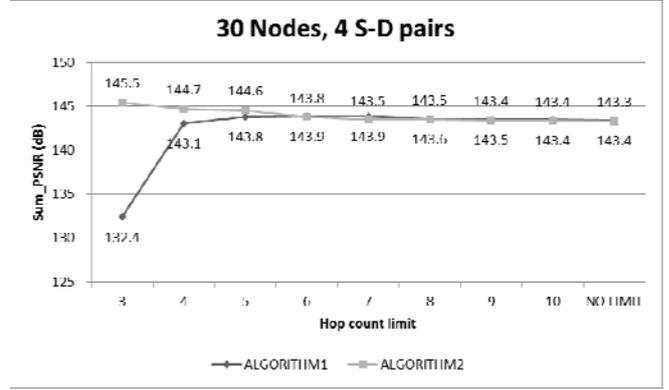


Figure 3 sum_PSNR in 30 nodes, 4 s-d pairs

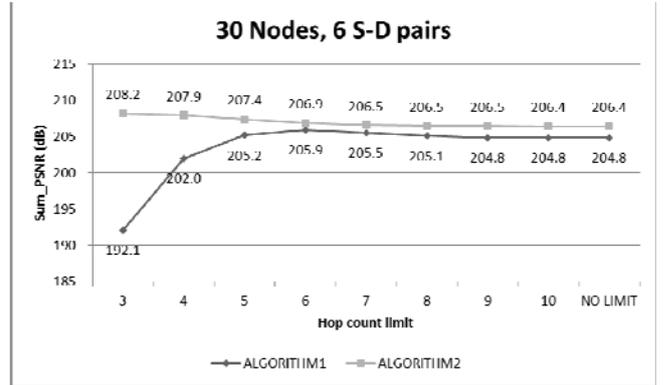


Figure 4 sum_PSNR in 30 nodes, 6 s-d pairs

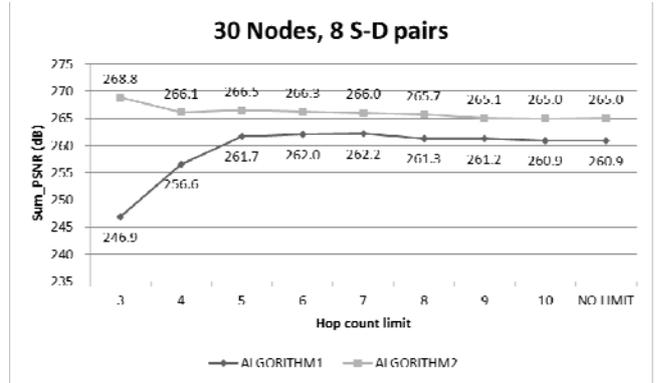


Figure 5 sum_PSNR in 30 nodes, 8 s-d pairs

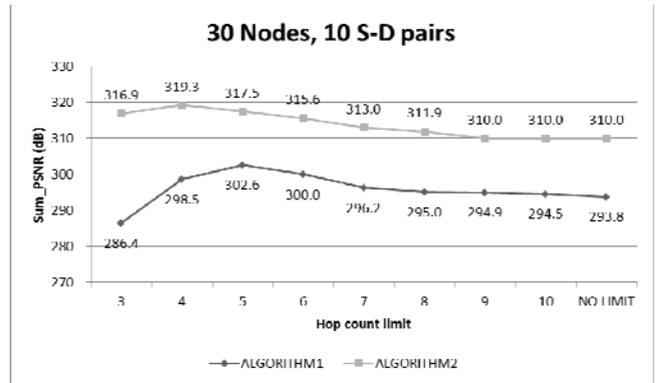


Figure 6 sum_PSNR in 30 nodes, 10 s-d pairs

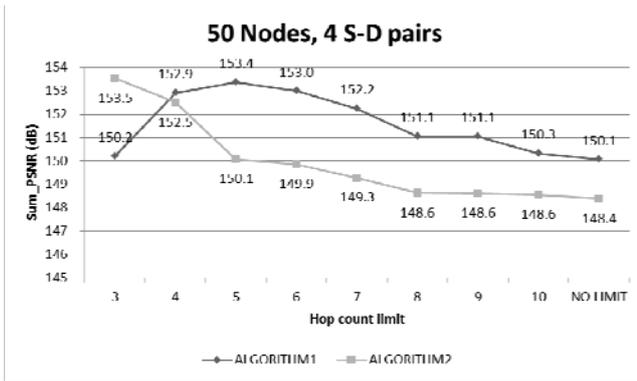


Figure 7 sum_PSNR in 50 nodes, 4 s-d pairs

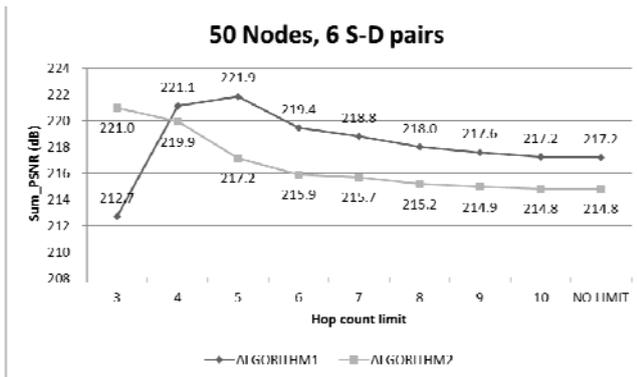


Figure 8 sum_PSNR in 50 nodes, 6 s-d pairs

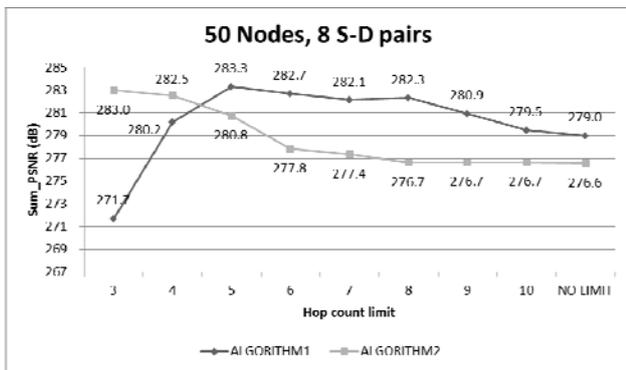


Figure 9 sum_PSNR in 50 nodes, 8 s-d pairs

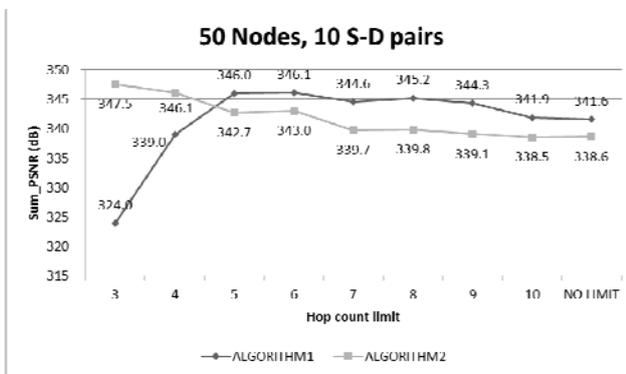


Figure 10 sum_PSNR in 50 nodes, 10 s-d pairs

6 Conclusion

We examined efficient video transmission in the cooperative multi-hop wireless networks. The problem is to maximize the sum_PSNR of video sessions by jointly controlling the video encoding rate, link capacity allocation, routing, and relay selection. The problem is formulated as a MINLP problem, which is difficult to handle. An algorithm based on the maximum capacity path is developed to obtain the highest data rate path which satisfies delay bound and hop-count limitation. Simulation is performed in various conditions. First, the effect of various hop-count limitations is examined. The sum_PSNR value increases as the hop-count limit value increases, but turns to decrease as the value keeps increasing. We also see that the sum_PSNR value is also dependent on the number of nodes in the network. Outstanding performance is demonstrated with the proposed algorithm when the average link capacity is high in a dense network. To conclude, the proposed algorithm guarantees good performance when the channel quality is high compared to the user requirement level.

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