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Cooperative routing with video complexity for heterogeneous motion-level streaming

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ABSTRACT

Cooperative relay is a promising technique that can improve network capacity in multi-hop wireless networks. However, conventional video streaming schemes on cooperative relay networks do not consider the video complexity of each video sequence. In this paper, we develop and experimentally evaluate a video streaming scheme that considers video complexity over a cooperative multi-hop relay network. We first develop a video distortion model taking into account the video complexity of the video sequences. Then, we propose a flow-routing algorithm for heterogeneous motion-level video streams in multi-hop cooperative networks. To evaluate the video routing performance for heterogeneous motion-level video sequences, we conduct experimental simulations with the proposed routing algorithm and a video distortion model. Numerical results show that network performance improves when video sequences are routed while considering heterogeneous motion levels to maximize the minimum peak signal-to-noise ratio (PSNR) value for the video sessions. The simulation results also show that the adoption of cooperative relays and a hop-count limitation can also improve the routing performance of video streams.

1. Introduction

The amount of video traffic over wireless channels has remarkably increased over the past decade as increasingly more applications pushing media traffic traverse wireless networks. However, reliable video streaming on wireless networks is very challenging because wireless channel conditions and mobile rate demands have significant time-varying characteristics. Substantial effort has been dedicated to developing wireless video streaming schemes for the improvement of video streaming performance over wireless networks. In particular, cooperative relay communication is being focused on as a promising technique to improve network capacity in multi-hop wireless networks. Cooperative relay communications has advantages in that it is possible to acquire spatial diversity without requiring multiple antennas equipped within a node.

Many researchers have proposed resource allocation strategies or routing frameworks to obtain increment or optimality in data transmission performance over cooperative wireless networks [1–6]. Ng and Yu [1] proposed a utility maximization framework for relay strategy and resource allocation taking user traffic demand into consideration in wireless cooperative cellular data networks. Liu et al. [2] dealt with cooperative communication techniques assuming that relaying nodes can forward information fully or in part. Awad and Shen [3] studied resource allocation for OFDMA-based two-hop relay networks and proposed a sub-optimal algorithm for an NP-complete problem. Other researchers [4–6] have also investigated relay and resource allocation strategies to improve network performance. However, recent studies have devoted more attention to video streaming and multi-hop relays in cooperative wireless networks [7–10]. Guan et al. [7] proposed a global optimization algorithm based on a branch and bound framework, and on convex relaxation of non-convex constraints to solve the cross-layer design problem for video streaming over cooperative networks. Sharma et al. [8] developed a mathematical model and proposed a solution procedure based on the branch and bound with cutting planes (BB-CP) to explore the behavior of cooperative communication in multi-hop wireless networks. Mastronarde et al. [9] proposed a solution based on cooperative coding that warrants a uniformly better experience to video users, and requires relatively modest changes to the multiple access cross-layer optimization framework. In other studies, Mastronarde et al. [10] investigated the impact of cooperative relaying on uplink multi-user wireless video transmissions. Although these studies show outstanding achievement in video streaming schemes over wireless relay networks, a significant portion of the attention is paid to resource allocation strategies and data transmission schemes, and the characteristics of video sequences are not considered.

In this paper, we develop a video distortion model that takes into account the temporal complexity of video sequences. The model

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focuses on the relationship between distortion and video complexity, which is an important factor constituting the distortion function. Temporal video complexity can be defined as the average difference between a frame and the successive frames for a video sequence; thus, highly complex video sequences require higher data rates than those with low complexity. The complexity of each video sequence is assumed to be already calculated at the source node or another place. Video distortion is typically a representative factor that has a significant effect on the quality of video streaming services over wireless networks. There are two different types of distortion: loss distortion and source distortion. Loss distortion can be introduced by packet or frame losses caused by transmission packet errors. Source distortion arises from lossy video encoding at the transmission source node. Video sequences are typically highly compressed for volume reduction at the source node using lossy encoding methods, which necessarily causes video distortion. Those relations can be summarized as video complexity may have an effect on video distortion, and finally on the video streaming experience of the user. A number of researchers have investigated video complexity and distortion during video coding and transmission. Feng et al. [11] showed that the trade-off between distortion and delay can be dependent on the complexity of the video. Video distortion and motion complexity have also received attention in various other studies [12–14]. Although video complexity is a noticeable characteristic of video sequences and is highly relevant to video distortion, to the best of our knowledge, there is no study on video streaming schemes over wireless networks for heterogeneous motion-level video streams.

We also provide a flow-routing algorithm for heterogeneous motion-level video streams in multi-hop cooperative networks. The algorithm, which aims to maximize the minimum peak signal-to-noise ratio (PSNR) among multiple concurrent video sessions, consists of three phases: path determination between the source and destination nodes, relay selection, and rate assignment. The proposed algorithm is more appropriate for application to video on demand (VoD) than real-time video streams because the video complexity of video sequences needs to be calculated prior to transmission.

The main contributions of this paper are as follows. We develop a video distortion model that takes into account temporal video complexity, one of the main characteristics of video sequences. We also propose a flow-routing algorithm for heterogeneous motion-level video sequences over multi-hop cooperative networks applying the proposed video distortion model, which considers video complexity. In the proposed algorithm, each video sequence has a different priority in determining the routing path according to the video complexity, pursuing higher user fairness. Finally, we provide experimental results indicating that the video streaming quality, in terms of the minimum PSNR, can be improved by taking into account video complexity. Additional analysis demonstrates the effect of cooperative relay and hop-count limitation.

2. Video distortion model

PSNR is commonly used to measure the video reconstruction performance of lossy compression codecs, and is computed using the ratio between the maximum possible video distortion and the current distortion, as described in (1) [15]:

$$PSNR = 10 \cdot \log\left(\frac{D_{max}}{D}\right) \quad (1)$$

where D_{max} is the maximum distortion possible.

In the following subsections, equations for loss distortion and source distortion are introduced to compute the PSNR value for each video session.

2.1. Loss distortion

Video frames are decodable at the destination node when more than a minimum number of required packets arrive successfully. When a frame is not decodable owing to a high rate of packet errors during transmission, a frame recovery method can be applied to recover the information contained in the non-decodable frame. An error concealment method is used in this paper for frame recovery, in which the recent correctly decoded frame is copied and duplicated into the first lost frame and all its successors in a group of pictures (GOP). Because the recently decoded frames are copied to the subsequent frames, the expected distortion of a GOP depends on the location of the first frame loss. The expected loss distortion of video stream s when the ith frame is the first lost frame in a GOP is computed using (2) [14].

$$D_{i,S} = (G - i)\frac{G \cdot i \cdot D_{min,s} + (G - i - 1) \cdot D_{max,s}}{(G - 1) \cdot G} \quad (2)$$

The values of D_{min} and D_{max} depend on each video sequence and can be obtained through experimental measurements. A GOP is assumed to be composed of a total of G frames, i.e., one I-frame and $(G - 1)$ P-frames. As described above, some of the packets composing a frame can be lost during a video transmission from one node to the next. The transmission success rate of a packet for session s, denoted as $r_{pt,s}$, which indicates the probability that a packet of video sequence s is delivered from the source to destination successfully, can be calculated as

$$r_{pt,s} = (1 - PEP)^{h_s} \quad (3)$$

where variable h_s is the number of hops on the streaming path of corresponding session s, and the packet error probability (PEP) is the probability that a packet error occurs during a one-hop transmission. In this paper, for performance calculation simplicity, the PEP is assumed to be constant for all links.

A frame can be decoded successfully at the destination node when more than a minimum number of required packets, including the first packet, successfully arrive at the destination without error. The first packet is necessarily required for decoding because it has the required information to decode the video stream and also information on its successors. The minimum number of packets, s_s, required to decode a frame shows how sensitive the decoder is to packet errors. When the error sensitivity values of the I-frame and P-frame of session s are $s_{I,s}$ and $s_{P,s}$, the probability that an I-frame or a P-frame of a GOP is successfully decoded at the destination can be computed as

$$p_{I,s} = r_{pt,s} \cdot \sum_{i=s_{I,s}}^{n_{I,s}-1} \binom{n_{I,s} - 1}{i} r_{pt,s}^{i} \, (1 - r_{pt,s})^{n_{I,s}-1-i} \quad (4)$$

$$p_{P,s} = r_{pt,s} \cdot \sum_{i=s_{P,s}}^{n_{P,s}-1} \binom{n_{P,s} - 1}{i} r_{pt,s}^{i} \, (1 - r_{pt,s})^{n_{P,s}-1-i} \quad (5)$$

where variables $n_{I,s}$ and $n_{P,s}$ are the number of packets composing an I-frame and a P-frame for session s, respectively. The size of an I-frame is typically much larger than that of a P-frame because an I-frame contains all the information required to describe a frame, whereas a P-frame contains only information on the difference between the corresponding and previous frames. The ratio of the number of packets of the I- and P-frames in a GOP in session s, i.e., $n_{I,s}$ divided by $n_{P,s}$, is set as 10. The fraction of P-frames for various video sequences can be found in [16]. The values of $s_{I,s}$ and $s_{P,s}$ vary according to the video complexity [12]. More specifically, the values need to be high with a fast-motion video sequence because the loss of one frame of a fast-motion video causes high distortion compared to a slow-motion video sequence. The $s_{I,s}$ and $s_{P,s}$ are set proportional to the number of packets of each frame with a constant β and variable α, which reflects the video complexity.

$$s_{I,s} = \alpha_s \times \beta \times n_{I,s} \quad (6)$$

$$s_{P,s} = \alpha_s \times \beta \times n_{P,s} \quad (7)$$

Using (3) through (7), $P_{i,s}$, the probability that the first lost frame in a GOP is the i-th frame can be calculated. Because the loss probability of an I-frame differs from that of a P-frame, $P_{i,s}$ is calculated according to variable i as in (8):

$$P_{i,s} = \begin{cases} 1 - p_{I,s}, & i = 1 \\ p_{I,s} \cdot p_{P,s}^{i-2}(1 - p_{P,s}), & i \geq 2,\ 3,\ \ldots,\ G \end{cases} \quad (8)$$

where $p_{I,s}$ and $p_{P,s}$ are the transmission success probability of the I- and P-frames calculated in (4) and (5). The expected loss distortion of session s is calculated using (2) and (8).

$$D_{LO,s} = \sum_{i=1}^{G} D_{i,s} \cdot P_{i,s} \quad (9)$$

2.2. Source distortion

The relationship between encoding rate and video distortion in wireless networks has been modeled in many studies [16–19]. A rate-distortion function (10) is adopted for the source distortion assuming that the PSNR value is greater than zero without loss of generality [14].

$$PSNR_{SO,s}(R_s) = a + b\sqrt{\frac{R_s}{c}\left(1 - \frac{c}{R_s}\right)} \quad (10)$$

The expected source distortion of session s, $D_{SO,s}$, can be back-calculated from the $PSNR_{SO,s}$ in (10) using (1), where the coefficients a, b, and c can be calculated from three sets of R_s and the corresponding PSNR values that can be obtained through experimental measurement.

2.3. PSNR

The total distortion of session s, D_s, can be calculated as the sum of the source distortion and loss distortion, assuming that source distortion and loss distortion are uncorrelated [20].

$$D_s = D_{SO,s} + D_{LO,s} \quad (11)$$

From the total distortion for session s in (11), PSNR values can be calculated using (1), where D_{max} is set to 65025 considering that the video sequences are 8-bit quantized.

3. Mathematical modeling

3.1. Network setting

Several concurrent video sessions are considered to be in a multi-hop relay network, which have two kinds of relay nodes: multi-hop relay (MR) and cooperative relay (CR). MR nodes compose a unique path from the source node to the destination node. A CR node is assigned to a link of two MRs to increase the link capacity. The orthogonal channels are employed in a network; therefore, different nodes can transmit simultaneously without interference. Each video session is transmitted from a source node to a destination node directly or through one or more MR(s), while a CR may be assigned to a link on the path. Note that CRs are operated at the physical layer, whereas MRs are operated at the network layer. The physical limitations of a wireless node may prohibit it from transmitting (or receiving) different data on multiple channels at the same time. As a result, it is assumed that a relay node may serve either as a CR or as an MR, but not both at the same time. This also limits an MR to receiving data from only one node and to transmitting data only to one other node at any given time. Similarly, a CR node can support at most one link, and a source node (or a destination node) cannot serve as a CR. In addition, the assignment of a link is limited to at most one CR node.

3.2. Problem formulation

In this subsection, a mathematical model is presented that maximizes the minimum PSNR of concurrent video sessions by jointly controlling the flow routing, relay selection, and rate allocation. Denote S as the set of concurrent video sessions and N as the set of nodes in a wireless network. There are three kinds of node subsets in N: the set of source nodes, $N_s = \{sn_1,\ sn_2, \ldots,\ sn_n\}$; the set of destination nodes, $N_d = \{dn_1,\ dn_2,\ \ldots,\ dn_n\}$; and the set of the remaining nodes that are available to serve as relay nodes, $N_r = \{rn_1,\ rn_2, \ldots,\ rn_m\}$. The number of source nodes and the number of destination nodes are the same since one source and one destination are paired. Three binary variables, CR_{ij}^k, MR_{ij}, and MR_{ij}^s, are defined to indicate whether an available relay node is used as a CR, an MR, or neither.

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

$$MR_{ij} = \begin{cases} 1, & \text{if link } (i,\ j) \text{ is used as part of a path} \\ 0, & \text{otherwise} \end{cases}$$

$$MR_{ij}^s = \begin{cases} 1, & \text{if link } (i,\ j) \text{ is used as part of } path_s \\ 0, & \text{otherwise} \end{cases}$$

The routing path of session s is denoted as $path_s$. The binary variable MR_{ij}^s indicates whether link $(i,\ j)$ is used as part of $path_s$. Eq. (12) indicates that relay node k can be used as a CR for link $(i,\ j)$ when only link $(i,\ j)$ is part of a routing path for a video session.

$$MR_{ij} - \sum_{k \in N}^{k \neq i,\ k \neq j} CR_{ij}^k \geq 0 \quad (12)$$

Eq. (13) shows the flow conservation of each node. A source node has only an out-flow, whereas a destination node has an in-flow. The flow sum of other nodes apart from the source and destination nodes should be zero. Variable R_s indicates the allocated transmission rate for video session s.

$$\sum_{j \in N}^{i \neq j} R_s \cdot MR_{ij}^s - \sum_{ij}^{i \neq j} R_s \cdot MR_{ji}^s = \begin{cases} R_s, & i \in N_s \\ 0, & i \in N_r \\ -R_s, & i \in N_d \end{cases} \quad (13)$$

Constraint (14) states 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, video session s cannot pass through several paths.

$$\sum_{j \in N}^{i \neq j} MR_{ij}^s \leq 1 \quad \forall i \in N \quad (14)$$

Constraint (15) states that a link is allocated to at most one video session; that is, a link is not shared by several sessions.

$$\sum_{s}^{i \neq j} MR_{ij}^s \leq 1\ \forall i,\quad j \in N \quad (15)$$

When transmitting a video session over a cooperative wireless network, the allocated transmission rate R_s for video session s should not be smaller than the minimum encoding rate R_{min}. When the allocated transmission rate is R_s, all links composing the routing path, $path_s$, are allocated rate R_s. The value of R_s cannot exceed the link capacity for all links composing $path_s$. These constraints are expressed in (16).

$$R_{min} \leq R_s \leq C_{ij} \quad \forall s \in S,\ \forall \text{ link } (i,\ j) \in path_s \quad (16)$$

The available capacity of link $(i,\ j)$ can be calculated as in (17):

$$C(i,j) = W \cdot \log_2\left(1 + SNR_{ij}\right) \quad (17)$$

where W is the available bandwidth for each channel, and the signal-to-noise ratio (SNR) between nodes i and j, SNR_{ij}, can be computed as $SNR_{ij} = \frac{P_i}{\sigma_j^2}|h_{ij}|^2$. The variable σ_j^2 is Additive White Gaussian Noise (AWGN) power variance. The transmission power is assumed to be the same for all nodes. The path-loss coefficient between nodes i and j is $|h_{ij}|^2 = i - j^{-4}$ where $i - j$ is the distance between the two nodes in meters.

Considering that the transmission delay and PEP are positively dependent on the number of hops composing the corresponding path in multi-hop networks, it is assumed that the number of hops of $path_s$ cannot exceed limit α.

$$\sum_{\text{link } (i,j) \in Path_s} MR_{ij}^s \leq \alpha \quad \forall s \in S \quad (18)$$

From the equations described above, the following problem formulation is provided:

$$\text{Max} \quad \min_{s \in S} PSNR_s$$

$$\text{s.t.} \quad (12),\ (13),\ (14),\ (15),\ (16),\ (18)$$
$$CR_{ij}^k, MR_{ij}, MR_{ij}^s \in \{0,1\}\ (\{i,j,k\} \in N,\ i \neq j \neq k)$$
$$R_s \geq 0\ \forall s \in N_s$$

4. Flow routing algorithm

The problem formulation defined in the previous section is a nonlinear, non-convex problem. In general, mixed-integer nonlinear problems (MINLP) are NP-hard [8,21], meaning that the MINLP cannot be solved in polynomial time with any existing algorithms. Therefore, a heuristic algorithm to maximize the minimum PSNRs of all video sessions is proposed jointly considering video flow routing, relay node selection, and video rate allocation. Our proposed algorithm consists of three phases: *path determination, CR assignment, and rate assignment*.

4.1. Phase 1: path determination

In the first phase, a routing path is determined for each session, and an available rate is initially assigned when the path satisfies the minimum required rate. The following subsections summarize the path determination procedure.

4.1.1. Step 1: ordering video sessions

In step 1, all video sessions to be streamed are sorted in order of decreasing or increasing value of video complexity to obtain different levels of priority in selection of an available routing path. The proposed algorithm, comprising phases 1 through 3, is called a CRVC, meaning a cooperative routing algorithm that considers video complexity. The CRVC algorithm is subdivided into two similar algorithms according to the video ordering strategies, CRVC-D and CRVC-I, in which video sessions are sorted in order of decreasing and increasing value of video complexity, respectively. When there are ties while ordering video sessions, the corresponding videos can be ordered randomly.

The proposed two algorithms are applicable to different transmission conditions: good and bad video transmission environments. CRVC-D is appropriate for application to transmission conditions that are good enough to provide available transmission routes to all video sequences. Allocating the bandwidth to fast-motion video sequences with higher priority appears to be efficient for increasing the minimum PSNR because the frame loss caused by lack of bandwidth is more influential than slow-motion video sequences. Therefore, assigning high priority to the fast-motion video sequence, potentially with low PSNR, helps to increase the min PSNR while all video sessions find available paths to be routed. In contrast, it is proper to use CRVC-I when part of the video sessions may not find any available routes to be transmitted because of bad transmission conditions, because finding as many available transmission paths as possible to improve the minimum PSNR is important.

The video transmission condition is characterized by the following three factors in the simulation: PEP of a one-hop transmission, number of relay nodes in a fixed area, and the hop-count limit of a streaming path. The transmission environment improves with low PEP, sufficient number of relay nodes, and appropriate hop-count limit. It has been confirmed in experimental simulations that ordering of video sessions according to the video complexity in CRVC-D and CRVC-I is effective. We also define another similar routing algorithm, non-CRVC, which does not take into account video complexity, for comparison with CRVC-D and CRVC-I. The video sessions are ordered randomly in phase 1, step 1 in the non-CRVC.

4.1.2. Step 2: path selection

In step 2, the initial transmission path and rate assignment are determined for the ordered videos in step 1. Initial routing paths are determined by iteratively applying the Floyd algorithm to all video sessions. The Floyd algorithm is typically used to find the shortest path, similar to the Dijkstra algorithm. The computation complexity of the Floyd algorithm and the Dijkstra algorithm are $O(n^3)$ and $O(n^2)$, respectively. Although the Floyd algorithm is generally more time-complex than the Dijkstra algorithm, it may obtain the computation result faster under certain conditions because its computation process in a calculation loop is much simpler than the Dijkstra algorithm. Therefore, the Floyd algorithm is used for routing path determination in this paper. When an initial path is determined for a video session, the capacity of the path is set as the minimum capacity among the links composing the path, where each link capacity is calculated using (17).

After an initial path is selected, it is modified to comply with the hop-count limit to reduce excessive delay and packet error rate. The proposed flow routing algorithm seeks to find a path with higher capacity; thus, the path may have unnecessarily many links, eventually causing high delay and PEP. Therefore, an appropriate hop-count limit can overcome the weakness of the proposed path selection algorithm by limiting the number of links to a suitable level.

A hop reduction procedure is applied to the initial paths of which the number of transmission hops is higher than the hop-count limit *HL*. When an initial path has n hops, the link capacities are calculated for all virtual links $(i,\ i+2)$ where i is a node number that is greater than zero but less than $(n-1)$. Then, the virtual link of the largest capacity, link $(i,\ i+2)$, is exchanged with the two existing links, link $(i,\ i+1)$ and link $(i+1,\ i+2)$, resulting in the number of hops of the path decreasing to $(n-1)$. Exchanging the virtual link of the largest capacity with two existing links is carried out with the intention of retaining the capacity of the bottleneck link. The procedure is repeated until the routing path satisfies the hop-count limit.

4.1.3. Step 3: initial rate assignment

The capacity of the selected path in step 2 is determined as the capacity of the bottleneck link(s) composing the path. We set a minimum rate R_{min}, the minimally required data rate for video streaming, since a video may get significantly high distortion and delay when only low transmission rate is utilized. If the calculated path capacity is greater than R_{min}, the initial rate of the path is set as the calculated capacity. When the capacity is lower than R_{min}, Phase 2 is applied to the path to improve the available transmission rate above R_{min} using cooperative relays. Steps 1 through 3 are iterated for all video sessions.

Table 1
Simulation parameter set.

Parameter	Value
MAC protocol	IEEE 802.11
Physical layer	PHY 802.11b
Path loss model	Two-ray ground
Fading model	Rayleigh
Antenna model	Omnidirectional
Space dimension	800 m × 400 m
Number of nodes	30, 40, 50, 60

4.2. Phase 2: cooperative relay assignment

In *Phase 2*, CRs are assigned to the links that compose the path selected in *Phase 1, step 3* and do not satisfy R_{min}. After those links with capacity below R_{min} are selected, from the nearest link to the farthest link from the source node, the CR that improves the link capacity most is selected. The link capacity after a CR assignment is recalculated using (19), where i and j are MR nodes and r is a relay node.

$$C(i, r, j) = W \cdot \log_2\left(1 + SNR_{ij} + \frac{SNR_{ir} \cdot SNR_{rj}}{SNR_{ir} + SNR_{rj} + 1}\right) \quad (19)$$

If the updated link capacity is still lower than R_{min}, the corresponding video session is regarded as unable to find any feasible path and is abandoned. In such cases, the source and destination nodes of the path can operate as MRs or CRs for other video sessions. If the updated link capacity is equal to or greater than R_{min}, this procedure is repeated for all links whose capacity is below R_{min}. If all corresponding links are assigned CRs to be over R_{min}, the path capacity is also updated into the capacity of the bottleneck link. Subsequently, the bottleneck link of the path is checked to determine whether a CR is assigned to the link. If the bottleneck link has already been assigned a CR, the current routing path and assigned data rate are fixed and the video session is no longer considered for additional relay and rate assignment. Otherwise, the path takes an additional procedure in *Phase 3*.

4.3. Phase 3: rate assignment

In *Phase 3*, an additional rate is allocated to the video sessions by assigning CRs. First, the *PSNR* is calculated for the video sessions using (1), (9), and (10), where D_{max} is the maximum possible distortion and D_s is the distortion of the session. Next, the video session of the lowest PSNR is selected, and then the bottleneck link of the session is determined. Among CR candidates within the given area, the CR that improves the link capacity most is selected and assigned to the bottleneck link. The capacity of the link and the path are then recalculated and the new bottleneck link determined. If a CR is assigned to the new bottleneck link, the current rate of the path is fixed as is and the video session is no longer considered for CR assignment. Otherwise, the best CR is also assigned to the new bottleneck link and this procedure is repeated until the rate of the path is finally determined. *Phase 3* is repeated until data rates and CR allocations of all video sessions are determined.

5. Evaluation

In this section, the simulation results for the proposed flow routing algorithm are presented. We simulated the proposed algorithm in QualNet 5.01 [22]. The key parameters for the network configuration are summarized in Table 1.

We assumed an 800 m × 400 m rectangular area in which many nodes are randomly distributed. The simulation condition is similar to a real-world communication environment in which many mobile devices including laptops, tablets, and smartphones are in an open space such as a university campus or a large hall. Some devices tend to transmit video sequences of various video complexities simultaneously to designated targets in the same area utilizing the other devices as potential relay nodes.

Table 2
Maximum and minimum distortion for video sessions.

	FO	MO	MD	TA
D_{max}	1175	1822	123	631
D_{min}	15	11	0.87	13

We considered two different types of transmission environments, Conditions 1 and 2, where the transmission environment of Condition 1 was relatively better than that of Condition 2. Several factors, such as the number of nodes, the hop-count limit, and the PEP in this paper, can affect the network performance for video communications over wireless relay networks. The high numbers of nodes and the low PEP have a positive effect on the communication environment. However, the value of the hop-count limit that maximizes the communication performance is dependent on the case.

The simulation was repeated for various network settings to quantify the effect of considering video complexity on the video streaming quality. The number of nodes, N, was set to 40, 50, and 60 for Condition 1, and 30 and 40 for Condition 2. The nodes in the area could be source node, destination node, relay node, or idle node. There were eight sessions whose source and destination were randomly fixed among the given nodes. The link capacity was calculated in Mbps, where W was 0.2 MHz, and the AWGN power variance, σ_j^2, was 10^{-10} W. The transmission power, W, was set as 1 W. The hop-count limit, HL, was set as two through nine, which was determined so as to obtain a high network performance based on iterative simulations. The minimum rate R_{min} was set as 0.2 Mbps. A potential solution is presented in Fig. 1 with an 800 m × 400 m area, 20 nodes, and six video sessions. The relay nodes connected solely via dotted lines act as cooperative relays, whereas the other relays act as multi-hop relays.

Four kinds of well-known video sequences were used in the simulation, namely, Mother and Daughter (MD), Foreman (FO), Table (TA), and Mobile (MO), and each sequence was mapped to two sessions [23]. These sequences were in the 4:2:0 YUV format and were encoded/decoded using the H.264/AVC (advanced video coding) codec. The number of frames in a GOP, G, was set to 15. The number of packets for the I- and P-frames was 100 and 10, respectively, when R_s was 0.2 Mbps. The value of *PEP* was set to 0.0001 and 0.0005 in Conditions 1 and 2, respectively. The values of D_{max} and D_{min} of the four video sequences are given in Table 2 [8]. Decoder sensitivities $s_{I,s}$ and $s_{P,s}$ were set as one-tenth the number of packets of the I- and P-frames, respectively.

For a comparative experiment conducted to evaluate the effect of video complexity in the flow routing, another set of variable settings was used. Regarding this, all variables that were dependent on the video complexity had the values of the FO sequence. Each experiment was repeated 200 times, and the average values were used for performance evaluation.

5.1. Effect of video complexity

The flow routing simulation results for eight sessions in Condition 1 using CRVC-D are shown in Fig. 2. In this simulation, N was 40, 50, and 60, and HL and PEP were set to five and 0.0001, respectively. The algorithms CRVC-D w/o relay and non-CRVC were slightly modified from CRVC-D, and are different from CRVC-D in that CRs are not used in CRVC-D w/o relay and video complexity is not considered in non-CRVC. The simulation result indicates that the streaming

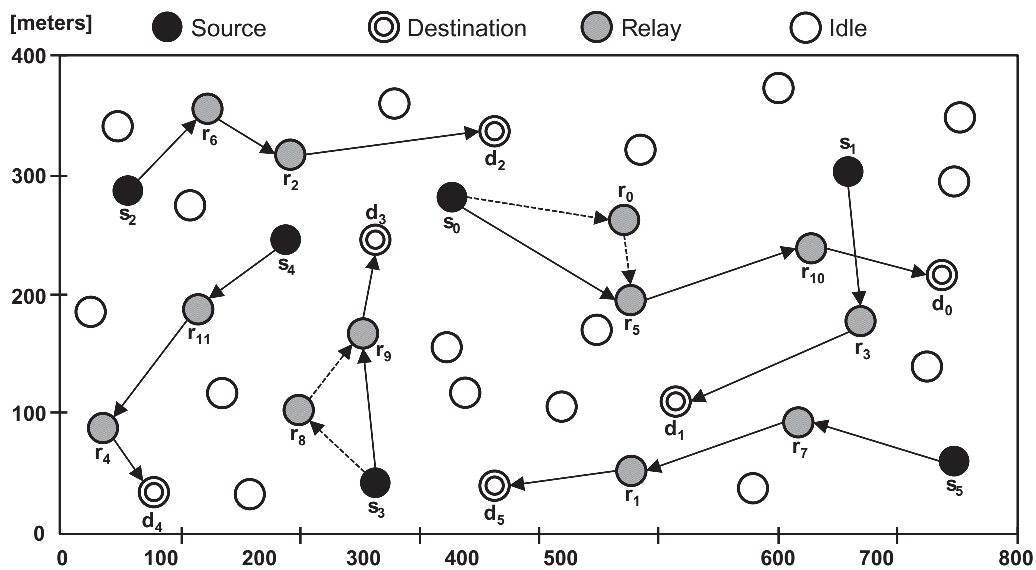

Fig. 1. A potential solution for relay assignment with 40 nodes and six source-destination pairs.

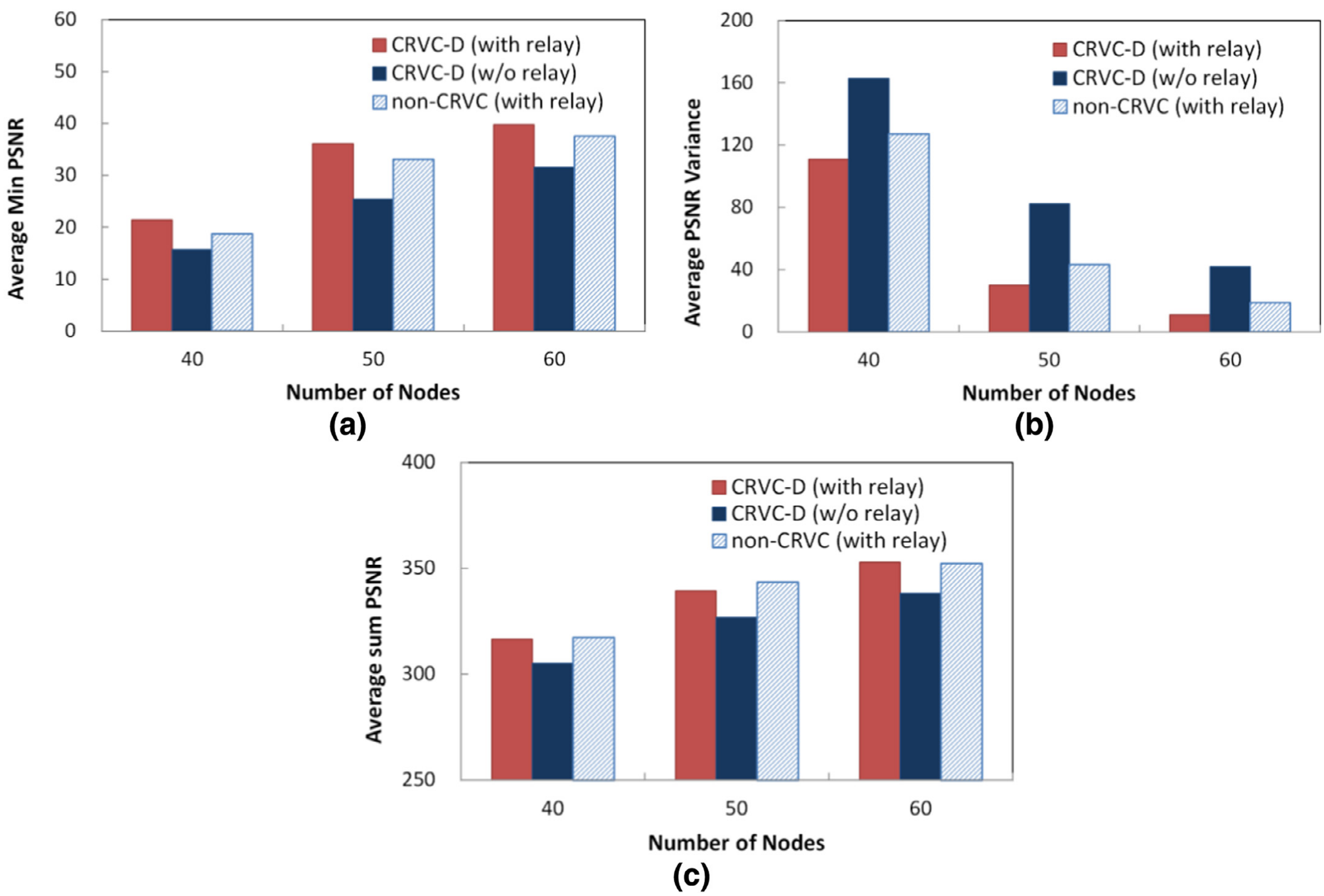

Fig. 2. Flow routing results in terms of (a) average min PSNR, (b) average PSNR variance, and (c) average sum PSNR, with CRVC-D. ($N = 40$, 50, and 60, $HL = 5$, and $PEP = 0.0001$).

performance using CRVC-D is better than it is with non-CRVC for all cases in terms of the min PSNR and PSNR variance. Min PSNR, the objective value to be maximized in the problem formulation, is improved by up to 14.6% using CRVC-D compared to non-CRVC. The average PSNR variance also decreases by approximately 30–40% when taking into account video complexity by using CRVC-D. We surmise that there are two main reasons for the result. First, in wireless communication environments that are good enough not to realize any failure in video connection for streaming, it is appropriate to focus on improving the tentative video session of the minimum PSNR. Assigning high priority to fast-motion videos during path determination helps them to reserve sufficient resources prior to the

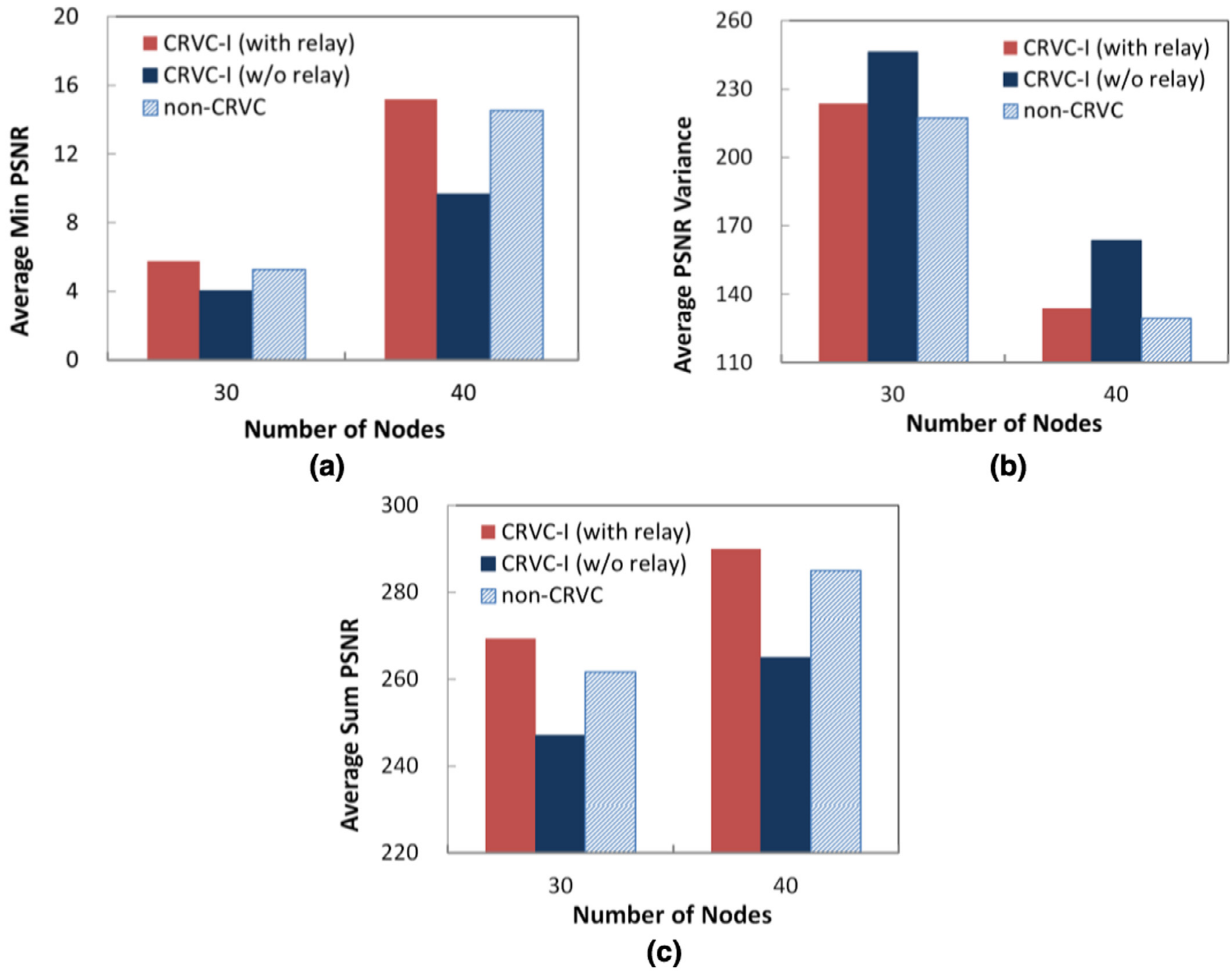

Fig. 3. Flow routing results in terms of (a) average min PSNR, (b) average PSNR variance, and (c) average sum PSNR, with CRVC-I. ($N = 30$ and 40, $HL = 6$, and $PEP = 0.0005$).

slow-motion videos; therefore, distortion of fast-motion videos tends to decrease. This finally improves the minimum PSNR because the distortion of a fast-motion video is greater than that of a slow-motion video. Second, in non-CRVC simulations, the path of the actual lowest PSNR may not be assigned CRs during Phase 3, because the video complexities of all videos are assumed to be the same. Therefore, Phase 3 has no positive effect to increase the minimum PSNR in non-CRVC. The result also shows that there is no noticeable sacrifice of average sum PSNR from the payment of user fairness improvement as shown in Fig. 2(c). The values of average sum PSNR using CRVC-D and non-CRVD have only very slight differences when N is 40 and 60, and the difference when N is 50, about 1.1%, seems to be ignorable.

The same simulation was repeated for Condition 2 using CRVC-I and non-CRVC, where N, HL, and PEP were set to 30 and 40, 6, and 0.0005. Each experiment was also repeated 200 times, and the average was used as the evaluation value. The simulation result has a few differences from the case of Condition 1: a little improvement in min PSNR and sum PSNR, and slight damage in PSNR variance, to give a brief explanation. The average min PSNR and average sum PSNR improved by up to 10 and 3%, respectively when N was 30 and 40 when using CRVC-I as compared to non-CRVC, as shown in Fig. 3(a). However, average PSNR variance increased up to 3% in CRVC-I, meaning that user fairness declined rather slightly, as shown in Fig. 3(b), contrary to the improvement in average min PSNR. Taking all the results together, we conclude that there are slight improvements in both user fairness and sum PSNR. When wireless communication environments are not good enough, it is suitable to maximize the number of successful video streams because failure in video streaming has a negative effect on user fairness and min PSNR. In CRVC-I, slow-motion videos get higher priority in selecting an available routing path. Typically, the number of successful communication paths tends to increase when providing higher priority for selecting available paths to the data streams requiring less data rate. We surmise that the improvement in min PSNR and sum PSRN in the simulation proceeded from the growth in the number of successful video streams using CRVC-I. However, providing higher priority to slow-motion videos may increase the PSNR variance because slow-motion videos originally gain higher PSNR than fast-motion videos and obtain higher PSNR from the priority of path selection.

5.2. Effect of cooperative relay

The modified algorithm CRVC-D w/o relay was used to evaluate the effect of CRs in Condition 1. The improvements in min PSNR and PSNR variance were as high as 30 and 55%, respectively. The result confirms that CRs can have significant positive effects on network performance, as is well known (see Fig. 2). The sum PSNR increased by approximately 4–5%. CRVC-I w/o relay was also simulated to

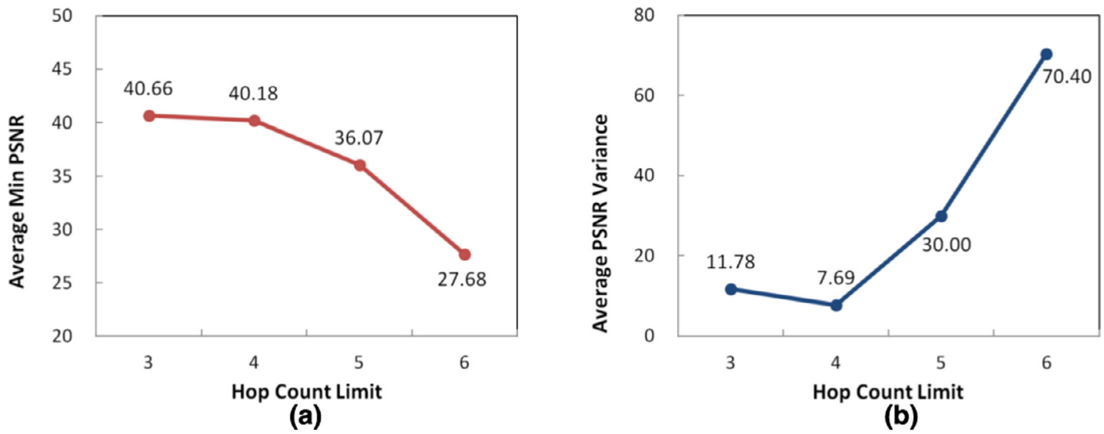

Fig. 4. Effect of hop-count limit in terms of (a) average min PSNR, (b) average PSNR variance, with CRVC-D ($N = 50$, $PEP = 0.0001$).

quantify the effect of CRs in Condition 2. The result also shows significant improvement in min PSNR, incremented by 30 and 42%. PSNR variance and sum PSNR also improved by as much as 20 and 8%, respectively.

5.3. *Effect of hop count limit*

It can be seen that the hop-count limit can significantly improve the performance under certain conditions (see Fig. 4). When the limit is three, the min PSNR improved by 47% compared to when the limit is six. The PSNR variance decreased but improved by 89% when hop count was limited from six to four. We surmise that two main reasons account for the result. The proposed algorithm seeks to find the path with the highest capacity during the path determination phase. However, an unnecessarily high number of links causes increased delay and packet errors, and finally reduces the PSNR of the video stream. In that respect, an appropriate hop-count limit can improve min PSNR. This result also comes from fair utilization of transmission resource—relay nodes in this paper. By limiting hop count, the number of relays a path utilizes is also limited. Therefore, after a path is determined, the next path has more available relays to utilize, and may finally improve the PSNR of the video sequence on the path. We conclude that fair utilization of relay nodes increases user fairness in terms of both min PSNR and PSNR variance. Although hop-count limitation may significantly improve the performance, an excessively tight hop-count limit will instead impair the result by preventing the use of relay nodes, which are necessary to improve the performance. When hop-count limit is tightened from four to three, PSNR variance increases from 7.7 to 11.8 although min PSNR improved slightly. This denotes that the quality of one or more sessions among the eight sessions degrades as a result of the tightening of hop-count limit from four to three.

6. Conclusion

As more multimedia contents are consumed on mobile devices, streaming traffic over wireless networks have been growing exponentially. However, wireless networks often suffer unpredictable failures such as high packet-loss ratio and transmission path disconnection. Multi-hop cooperative relay networking is a promising solution proposed to transmit video streams more stably over wireless networks.

Although many studies have been conducted on how to improve the performance of video streaming over multi-hop cooperative relay networks, they have largely focused on fundamental approaches such as cross-layer design, and relay network scheduling. In this paper, a novel approach for video flow routing that takes video complexity into account was presented. A proposed video distortion model was developed for heterogeneous motion-level video streams, because video complexity is one of the main characteristics of video sequences. The proposed flow routing algorithms, CRVC-D and CRVC-I, are comprised of three phases: path determination, CR assignment, and rate assignment. The proposed algorithm considers the video complexities of heterogeneous motion-level video sequences during path determination and rate assignment. The simulation results show that providing high priorities to fast- or slow-motion videos for selection of an available routing path in the different communication conditions improves the performance in terms of min PSNR and PSNR variance without impairment of the total PSNR. It was also shown that the support of CRs and an appropriate hop-count limit improves performance.

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