Multiple Description Coded Video Streaming with Multipath Transport in Wireless Ad Hoc Networks

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Abstract. Multiple description coding (MD coding or MDC) generates multiple decodable bitstreams for a single source to combat packet loss, which is suitable for video streaming in error-prone wireless ad hoc networks. In this paper, two problems are investigated for MD coded video streaming in wireless ad hoc networks. The first problem addresses multipath selection for balanced two-description coded video streaming. We formulate an interference-aware MDC multipath routing for single-radio networks by employing a time-division link scheduling method to eliminate wireless interference, and ultimately obtain an optimal path selection corresponding to the minimum achievable distortion. A heuristic solution is developed for the interference-aware multipath routing, by defining a path metric taking into account interference, link bandwidth and link "up" probability. The second problem addresses MDC redundancy control according to varying channel conditions of multiple paths. We design an unbalanced redundant slice based two-description video coding, which optimally selects the amount of inserted redundancy for each description. Simulation results demonstrate the effectiveness of the proposed MDC multipath routing scheme and the unbalanced MD video coding approach over heterogeneous paths.

Keywords: Multiple description video coding, multipath routing, wireless ad hoc networks, wireless interference.

1 Introduction

Wireless ad hoc networks consist of wireless nodes, which exchange data without infrastructures support. The lack of infrastructure support poses a great challenge for multimedia applications in wireless ad hoc networks, especially for delay-sensitive and high bandwidth-demanding video streaming services. Video traffic may suffer from great packet losses due to the varying network topology and fragile wireless links. Retransmission of loss packets is sometimes undesirable due to the mobility of source node, delay constraint or congestion control. To provide continuous video delivery over fragile links without retransmission, multiple description coding (MD coding or MDC) [1] can be used to generate

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different decodable bitstreams for a single source, where each bitstream is called a description. Each description is delivered along its own path and can provide a coarse version of source independently, while more descriptions result in a finer quality of reconstruction. By transmitting multiple descriptions over multiple paths, bandwidth of wireless paths is aggregated. Unless all the paths fail simultaneously, MDC coupled with multipath transport can provide continuous delivery of source content.

The performance of MD coded video streaming in wireless ad hoc networks depends on both MD coding efficiency and MDC path selection. Extensive efforts have been devoted to MDC codec design [2, 3, 4, 5, 6, 7, 8, 9]. Recently, a multiple description video coding (MDVC) technique [10] makes use of redundant slice representation option of H.264/AVC video coding standard [11], and generates two balanced descriptions by interlacing primary slices and redundant slices of each frame. This MDVC approach is fully compatible with the H.264/AVC standard. The two descriptions for two paths are equally protected with the same amount of inserted redundancy. However, multi-hop paths in wireless ad hoc networks are heterogeneous. Packets transmitted in different paths are likely to encounter different packet loss rates.

Compared with works on MDC codec design, there is relatively less work on MDC path selection. Without support of fixed base stations or wired backbone networks, routing becomes a crucial issue for the design of wireless ad hoc networks. Studies of multimedia-centric MDC multipath routing in wireless ad hoc networks are presented in [12, 13, 14, 15], where video quality is optimized via routing operations with respect to available link bandwidth, link "up" probabilities and loss burst length on links. In those works, wireless links are modeled as point-to-point channels in wired networks for simplicity and convenience, where interference which is a fundamental issue of wireless networks is either implicitly or inadequately considered. There are a few network-centric approaches addressing the inference issue, e.g. WCETT [16], MIC [17], iAWARE [18]. Nevertheless, these works are designed for single path routing in multi-radio wireless networks, and focus on network criteria rather the received video quality.

In this paper, we focus on two problems of MD coded video streaming in wireless ad hoc networks, which are multipath routing for balanced two-description coded video and MDC redundancy control for heterogenous paths. For the first problem, we formulate an interference-aware MDC multipath routing for video unicast services. Conflicting wireless links due to interference are scheduled to be active in different time fractions. We adopt the concept of conflict graph in [19] to obtain a schedulable maximum flow rate on each path subject to interference constraint. Based on maximum flow rates and estimated "up" probabilities of multiple paths, optimal path selection with minimum achievable distortion of reconstructed video can be obtained for a given wireless network. We also develop a heuristic solution for interference-aware MDC multipath routing. A new path metric is defined considering both video streaming characteristics and network-centric criteria. For the second problem, an unbalanced MDVC scheme is designed for multiple paths with varying channel conditions. MDVC inserts different amounts of redundancy into two descriptions according to varying channel conditions of their selected paths.

The remainder of this paper is organized as follows. The background of MDC and MDC multipath routing is provided in Section 2. In Section 3, we discuss and formulate interference-aware MDC multipath routing, and develop a heuristic solution. In Section 4, we consider the unbalanced MDVC design. Section 5 presents simulation results of MDC multipath routing, and evaluates the performance of unbalanced MDVC. Section 6 draws a conclusion.

2 Background and Preliminaries

2.1 Multiple Description Coding

MDC is a promising technique to combat transmission error by generating multiple decodable descriptions for a single source. Reconstructed quality can be refined as the number of received descriptions increases. Various MDC methods can be classified into preprocessing-based MDC, encoding-based MDC and postprocessing-based MDC, depending on which stage the one-to-multiple mapping occurs at [9]. In the preprocessing-based MDC, the original source is split into multiple subsources before encoding, and then subsources are encoded separately to generate multiple descriptions, e.g., subsampling based MDC in the temporal and spatial domains [7]. For encoding-based MDC, the one-to-multiple mapping is performed by dedicated coding techniques, such as MD scalar quantization [4], MD lattice vector quantization [6, 8], and MD correlating transform [5]. The postprocessing-based MDC realizes the one-to-multiple mapping in the compression domain by transforming an encoded bit stream into multiple streams, for instance, FEC-based MDC [3]. The redundant slice based MDVC in [10] is a kind of postprocessing-based MDC.

Generally the decoding of one or partial descriptions is known as side decoding corresponding to side distortion d_s, while the decoding of all the descriptions is central decoding resulting in a smallest central distortion d_c. If none of the descriptions is received, distortion d_{null} can be calculated according to a specific error concealment technique ($d_{null} > d_s > d_c$). We focus on two-description coding in this paper. Till now, the entire achievable MD rate-distortion region is only known for two-description coding with quadratic Gaussian source [20]. The distortions of zero-mean Gaussian source satisfy [21]

$$d_{s1} \geq \sigma^2 2^{-2R_{s1}}, \tag{1}$$

$$d_{s2} \geq \sigma^2 2^{-2R_{s2}}, \tag{2}$$

$$d_c \geq \frac{\sigma^2 2^{-2(R_{s1}+R_{s2})}}{1-(\sqrt{\Pi}-\sqrt{\Delta})^2}, \tag{3}$$

where $\Pi = (1-\frac{D_{s1}}{\sigma^2})(1-\frac{D_{s2}}{\sigma^2})$, and $\Delta = (\frac{D_{s1}D_{s2}}{\sigma^4}) - 2^{-2(R_{s1}+R_{s2})}$. R_{si}, d_{si} are bitrate and side distortion corresponding to description i, respectively. Rate-distortion region for a specific MDC codec can be estimated or obtained empirically.

2.2 MDC Multipath Routing

Given a source and a destination, an MDC multipath routing generates two paths for MDC descriptions. More than two paths may exist between the source and the destination. The MDC multipath routing computes paths that minimize expected distortion of two-description coded video. MDC multipath routing in wireless ad hoc networks can be described as follows.

$$\begin{aligned} \text{Minimize } D^s(R_{s1}, R_{s2}) = &(1 - p^s_{path1})(1 - p^s_{path2})d_{null} \\ &+p^s_{path1}(1 - p^s_{path2})d_{s1}(R_{s1}) \\ &+(1 - p^s_{path1})p^s_{path2}d_{s2}(R_{s2}) \\ &+p^s_{path1}p^s_{path2}d_c(R_{s1}, R_{s2}), \end{aligned} \tag{4}$$

where $D^s(R_{s1}, R_{s2})$ is expected distortion of a unicast session s, and p^s_{pathi} is successful delivery probability of ith path P^s_i. As MDC introduces redundancy between descriptions, it is usually coupled with best-effort transmission which implies no retransmissions. A description is successfully delivered to the destination, if all wireless links along the transmission path are "up", $p^s_{pathi} = \prod_{l_{jk} \in P^s_i} p_{jk}$, where p_{jk} is "up" probability of link l_{jk}. Link may be "down" due to mobility of nodes, energy shortage or connection errors. Different paths differ in their "up" probabilities and maximum supporting flow rates R_i, which cause different expected distortions at the destination as shown in (4).

3 Interference-Aware MDC Multipath Routing

In this section, we focus on MDC multipath routing in single-radio wireless ad hoc networks. With special consideration of wireless interference, an interference-aware multipath routing problem is formulated. A heuristic solution is developed at the end of this section.

3.1 Wireless Interference and Link Scheduling

Assume that each node in a wireless ad hoc network is supported by an omnidirectional antenna and communicates only via wireless medium at the same frequency band. These nodes are distributed in the physical space. They assume to stay at their own locations during a video streaming session. A communication range R_c can be defined for each wireless node. Two nodes can communicate directly through a wireless link, if they are within each other's communication ranges. Each link l_{ij} is characterized by its maximum capacity b_{ij} and link "up" probability p_{ij}. Packet losses on a link are assumed to be independent.

Due to broadcast nature of wireless medium, transmission on one link interferes with transmissions on its neighboring links. While accurately measuring and estimating wireless interference is a complicated issue, we use a protocol model in [22] assuming interference to be an all-or-nothing phenomenon.

An interference range R_f is defined for each wireless node ($R_c \leq R_f$). An actively transmitting node causes severe interference within its interference range R_f and no interference outside range R_f.

To eliminate interference in a shared wireless medium, transmissions on wireless links in the neighborhood have to be scheduled in a time-division manner. A direct transmission from node i to node j is considered to be successful if: (1) a wireless link exists between node i and node j, i.e. $d_{ij} \leq R_c$, where d_{ij} is the distance from node i to node j; (2) transmissions from other node k causing interference at node j, i.e. $d_{kj} \leq R_f$, are not happening, where $k \neq i$ [19].

Conflict graph in [19] can be used to model interference between links, whose vertices correspond to individual links. An edge exists between two vertices l_{ij} and l_{pq} in the conflict graph, if two links l_{ij} and l_{pq} cannot be active simultaneously due to interference, i.e. $d_{iq} \leq R_f$ or $d_{jp} \leq R_f$. Maximal independent sets $I_1, .., I_n$ can be found in the conflict graph, where no edge exists between any two of the vertices in an independent set. By including every active link in one of the maximal independent sets, and having each individual set I_i active at its own time fraction λ_i, wireless links are scheduled to eliminate interference [19]. The maximum output flow rate of node i is subject to

$$f_i \leq \sum_n \lambda_n b_{ik}, l_{ik} \in I_n, \tag{5}$$

$$\sum_{i=1}^{n} \lambda_i \leq 1. \tag{6}$$

Note that, although we use protocol model of wireless interference for simplicity, the proposed scheme can be generalized to a more practical physical model [19] of interference as well. With the physical model, signal strength and signal to interference plus noise ratio (SINR) of each transmission are calculate at the receiver. If the receiver receives the signal at or above its sensitivity level, the transmission is successful. Similarly, conflict graph and maximal independent sets can be obtained using the physical model, and wireless links are scheduled to eliminate interference.

3.2 Problem Formulation

With the aid of conflict graph, wireless links delivering multiple descriptions to the destination are carefully scheduled to eliminate interference. An interference-aware multipath routing for balanced MDC can be formulated as follows:

$$\begin{aligned} \text{Minimize } D^s(R) = &(1 - p^s_{path1})(1 - p^s_{path2}) d_{null} \\ &+ p^s_{path1}(1 - p^s_{path2}) d_s(R) \\ &+ (1 - p^s_{path1}) p^s_{path2} d_s(R) \\ &+ p^s_{path1} p^s_{path2} d_c(R), \end{aligned} \tag{7}$$

subject to

$$f_i \leq \sum_n \lambda_n b_{ik}, l_{ik} \in I_n, \tag{8}$$

$$\sum_{i=1}^{n} \lambda_i \leq 1, \tag{9}$$

where

$$f^s(P) = R, \tag{10}$$

$$f_i = \sum_{s=i, l_{ij} \in P_i^s} f^s(P) + \sum_q \sum_{l_{qi} l_{ij} \in P_i^s} f^s(P) - \sum_{dest(s)=i, l_{qi} \in P_i^s} f^s(P), q \neq j, \tag{11}$$

$$p^s_{pathi} = \prod_{l_{jk} \in P_i^s} p_{jk}. \tag{12}$$

The optimization problem aims to minimize expected distortion of a two-description coded video unicast session initiated from source s to destination $dest(s)$ with respect to link capacities and "up" probabilities as shown in (7). Maximum output flow rate f_i of a node depends on active time and capacities of its output links b_{ik} as given in (8). Interference between links is eliminated using a time-division scheduling method that gives a constraint on time fractions (9). One of the two balanced description with bitrate R has to be delivered on each path as indicated in equation (10). Equation (11) guarantees that the amount of output flow at node i equals the sum of flows initiated from node i and transit flows at node i, excluding traffic flows ending at node i, where $l_{qi} l_{ij} \in P_i^s$ means l_{qi} and l_{ij} are two consecutive links along path P_i^s.

The solution of this problem is a pair of paths from source s to destination $dest(s)$ for two balanced descriptions. These two paths may be disjoint or partly shared. Given any multipath routing decision, maximal independent sets of its conflict graph can be obtained, and wireless links along these paths are scheduled accordingly to eliminate interference. The maximum path flow rate for each routing decision is subject to linear constraints (8-11), thus can be obtained using linear programming. Therefore a schedulable maximum flow rate on each path within interference constraint can be obtained. The maximum flow rate is achieved with an ideal media-access-control protocol, which finely controls and schedules transmissions at the individual nodes. The design of such a media-access-control protocol in wireless ad hoc networks is very challenging, and is out of the scope of our research. With maximum flow rates and path "up" probabilities, we can obtain the corresponding distortion. A global optimal solution with the minimum expected distortion can be found by exhaustively searching all the combinations of two qualified path candidates.

3.3 Heuristic Routing Solution

In this subsection, a heuristic routing solution is developed for solving the aforementioned interference-aware multipath routing problem. For computational purpose, we consider the subset of MD achievable region of zero-mean Gaussian source where three inequalities in (1) are all active. Thus rate-distortion of Gaussian source can be approximated as

$$\begin{aligned} D_{s1} &= \sigma^2 2^{-2R_{s1}}, \\ D_{s2} &= \sigma^2 2^{-2R_{s2}}, \\ D_c &= \frac{\sigma^2 2^{-2(R_{s1}+R_{s2})}}{2^{-2R_{s1}} + 2^{-2R_{s2}} - 2^{-2(R_{s1}+R_{s2})}}. \end{aligned} \tag{13}$$

Substituting (13) into (7), we can have $\frac{\partial D}{\partial R_{s1}} \leq 0$, $\frac{\partial D}{\partial R_{s2}} \leq 0$, $\frac{\partial D}{\partial p^s_{path1}} \leq 0$, $\frac{\partial D}{\partial p^s_{path2}} \leq 0$ [15]. Therefore, D is non-increasing with R_{s1} and R_{s2}. Assuming packet losses are independent, D is non-increasing with p^s_{path1} and p^s_{path2}.

We define a conflict factor $n^{f_n}_{ij}$ for a link l_{ij} delivering flow f_n, where the value of $n^{f_n}_{ij}$ equals the number of active links that are conflicting with the delivery of f_n on l_{ij}. Note that the same link l_{ij} carrying another flow f_m $(m \neq n)$ increases $n^{f_n}_{ij}$ by 1. Conflict factor measures both intra-path interference and inter-path interference. Larger value of $n^{f_n}_{ij}$ indicates severer interference, probably leads to shorter active time. However, short active time can be compensated by large link bandwidth. Therefore, a path metric $I(P, f_i)$ can be defined for a path P carrying flow f_i as follows,

$$I(P, f_n) = (1-\alpha) \prod_{l_{ij} \in P} p_{ij} + \alpha \sum_{l_{ij} \in P} \frac{b_{avg}}{b_{ij}} \frac{n^{f_n}_{ij}}{N}, \tag{14}$$

where b_{avg}, N are the approximate average link bandwidth in the network and number of all the active links, respectively. The value of α is tunable, where $0 \leq \alpha \leq 1$. Larger α helps to find paths with greater flow rate, while lower α results in more reliable paths.

The proposed path metric $I(P, f_n)$ is non-isotonic, which is not suitable for link-state routing protocols to find loop-free and minimum weighted paths. However, on-demand distance vector or source routing protocols can use non-isotonic metrics to find efficient paths [17]. To find two paths P^s_1 and P^s_2 for one MDC video streaming session, we search all paths connecting source node s and destination $dest(s)$. The path with the minimum $I(P, f_1)$ is selected as P^s_1. Then $I(P, f_2)$ path metric for f_2 is updated counting in interference caused by P^s_1. We search in the rest of paths and choose the one with the minimum updated $I(P, f_2)$ to be P^s_2.

4 Unbalanced Multiple Description Video Coding

In [10], redundant slices based MDVC aims to produce two balanced descriptions for a video sequence. These descriptions are of the same size and correspond to the same side distortion. However, there are hardly any identical multi-hop paths between a source and a destination in wireless ad hoc networks. Descriptions transmitted in different channels encounter different degrees of packet losses, thus should be unequally protected. In this section, we present an unbalanced redundant slice based MDVC technique, which adjusts the amount of inserted redundancy in each description according to channel condition of its own path.

4.1 Unbalanced MDVC Scheme

The concept of redundant slice defined in the H.264/AVC standard [11] represents an alternative representation of a picture. When normally coded primary slice cannot be decoded correctly, the decoder will replace it with the corresponding correctly decoded redundant slice. By interlacing primary slices and redundant slices, two descriptions can be generated as shown in Fig. 1. As in [10], only primary slices are used as references for motion predication of subsequent pictures. The primary and redundant representations of the same slice are transmitted in different channels to provide robustness against loss. While MDVC in [10] codes redundant slices in a picture with the same quality, we tune the quality of these redundant slices according to their allocated channels. The quality of slices can be controlled by employing different values of quantization parameter (QP).

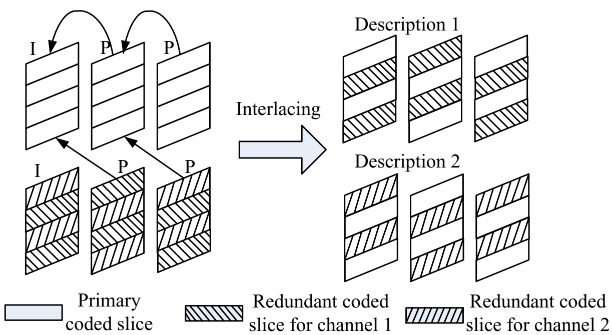

Fig. 1. Unbalanced redundant slices based MDVC

4.2 Optimal Redundancy Allocation

When redundant slice replaces primary slice at the decoder, an error is introduced in prediction loop due to the mismatch between primary and redundant representations. This mismatch error propagates to the subsequent frames. If we consider transmitting primary representation of kth slice in path 1 with successful probability p^s_{path1}, and redundant representation in path 2 with p^s_{path2}. According to [10], expected distortion of slice k can be evaluated as

$$\begin{aligned} d_{k,1} &= p^s_{path1} d_{p,k} + p^s_{path2}(1 - p^s_{path1})\phi_i d_{r,k,2} + (1 - p^s_{path1})(1 - p^s_{path2}) d_{0,k} \\ &\approx p^s_{path1} d_{p,k} + p^s_{path2}(1 - p^s_{path1})\phi_i d_{r,k,2}, \end{aligned} \tag{15}$$

where slice k belongs to ith picture $i = M(k)$, and $d_{p,k}$, $d_{r,k,2}$, $d_{0,k}$ represent encoding distortion of kth primary slice, encoding distortion of kth redundant slice allocated to channel 2, and distortion of kth slice losing both representations, respectively. In (15), mismatch and propagation errors due to redundant slice are captures by ϕ_i, which is the summation of power transfer functions $\phi_i = \sum_{n=0}^{N-M(k)} e^{-\alpha n} = (1-e^{-\alpha(N-i+1)})/(1-e^{-\alpha})$. The term $(1-p^s_{path1})(1-p^s_{path2})d_{0,k}$ can be ignored at a low packet loss probability.

$$d_{k,1} \approx p^s_{path1} d_{p,k} + p^s_{path2}(1-p^s_{path1})\phi_i d_{r,k,2}. \tag{16}$$

If primary slice is transmitted in path 2, the expected distortion becomes

$$d_{k,2} \approx p^s_{path2} d_{p,k} + p^s_{path1}(1-p^s_{path2})\phi_i d_{r,k,1}. \tag{17}$$

We aim to minimize expected distortion of N frames by adjusting the amount of inserted redundancy, where bitrate of each description is constrained by maximum flow rate of its path. The allocation problem can be formulated as

$$\begin{aligned}
\text{Minimize} \quad & \sum_{i=1}^{N} \sum_{k:M(k)=i} d_k = \sum_{i=1}^{N} \Big(\sum_{k:M(k)=i,(k+i)\%2=1} d_{k,1} + \sum_{k:M(k)=i,(k+i)\%2=0} d_{k,2} \Big) \\
& \approx \sum_{i=1}^{N} \sum_{k:M(k)=i,(k+i)\%2=1} (p^s_{path1} d_{p,k} + p^s_{path2}(1-p^s_{path1})\phi_i d_{r,k,2}) \\
& + \sum_{i=1}^{N} \sum_{k:M(k)=i,(k+i)\%2=0} (p^s_{path2} d_{p,k} + p^s_{path1}(1-p^s_{path2})\phi_i d_{r,k,1})),
\end{aligned} \tag{18}$$

subject to

$$\sum_{i=1}^{N} \Big(\sum_{k:M(k)=i,(k+i)\%2=1} R_{p,k} + \sum_{k:M(k)=i,(k+i)\%2=0} R_{r,k,1} \Big) \le R_1, \tag{19}$$

$$\sum_{i=1}^{N} \Big(\sum_{k:M(k)=i,(k+i)\%2=0} R_{p,k} + \sum_{k:M(k)=i,(k+i)\%2=1} R_{r,k,2} \Big) \le R_2. \tag{20}$$

The optimization problem can be solved by minimizing the cost function

$$\begin{aligned}
L = & \sum_{i=1}^{N} \sum_{k:M(k)=i} d_k + \lambda_1 \Big(\sum_{i=1}^{N} \Big(\sum_{k:M(k)=i,(k+i)\%2=1} R_{p,k} + \sum_{k:M(k)=i,(k+i)\%2=0} R_{r,k,1} \Big) - R_1 \Big) \\
& + \lambda_2 \Big(\sum_{i=1}^{N} \Big(\sum_{k:M(k)=i,(k+i)\%2=0} R_{p,k} + \sum_{k:M(k)=i,(k+i)\%2=1} R_{r,k,2} \Big) - R_2 \Big),
\end{aligned} \tag{21}$$

where λ_1 and λ_2 is the Lagrangian multiplier. As we task for allocation of redundant slices, constant QP is used for all the primary slices ($QP_{p,k} = QP_p$). Using the standard H.264 R-D approximation $\frac{\partial D}{\partial R} = -0.85 \times 2^{(\frac{QP-12}{3})}$ [23], optimal QPs of redundant slices can be obtained:

$$QP_{r,k,1} = QP_p + 3\log_2^{(\frac{1}{(1-p^s_{path2})\phi_i})}, \quad (22)$$

$$QP_{r,k,2} = QP_p + 3\log_2^{(\frac{1}{(1-p^s_{path1})\phi_i})}. \quad (23)$$

5 Simulation Results

5.1 Performance of Interference-Aware MDC Multipath Routing

In the simulation, performance of MDC multipath routing is evaluated in randomly generated wireless ad hoc networks. In each network, wireless nodes are randomly placed with a uniform distribution in an area of 500 × 500 square. During a video session, these nodes remain at the same locations. Transmission range of wireless nodes R_c is a fixed value to ensure that average node degree is at least 3. Interference range R_f is a fixed value larger than transmission range R_c. If the distance between two nodes is within the transmission range, a wireless link exists between these nodes. Each wireless link l_{ij} has a fixed link "up" probability $p_{ij} = 0.995$, while its maximum capacity $b_{i,j}$ is randomly selected within the range of [0.25, 1] Mb/s with a step size of 0.125 Mb/s. Source node and destination node for each MDC unicast session are randomly chosen among these nodes.

In Table 1, different multipath routing algorithms are used to select two paths for one MD coded video streaming session in two 15-node networks and two 30-node networks. The proposed interference-aware MDC multipath routing is compared with k shortest paths [24] and interference-oblivious MDC multipath routing algorithm ignoring wireless interference. The scheme of k shortest paths is a popular network-centric routing algorithm connecting a source and a destination with k paths that have minimum hops. The interference-oblivious MDC multipath routing minimizes average end-to-end distortion by finding paths with large bandwidth and high link "up" probability like those in wired networks, and the work in [14] adopts a similar approach.

Global optimal solution of interference-aware MDC multipath routing can be obtained by exhaustively searching all the combinations of two paths, where each path has a restricted number of hops. Maximum flow rate on each path is obtained under linear constraints using a linear programming function in MATLAB. As we can see from Table 1, the global optimal solution of proposed interference-aware outperforms the two existing algorithms. We also compare our heuristic solution of interference-aware routing with the global optimal solution, 2 shortest paths [24] and interference-oblivious routing. The heuristic solution is obtained by searching paths within certain hops to obtain one path with minimum value of path metric $I(P, f_1)$, and a second path with minimum updated $I(P, f_2)$. It can be observed from Table 1 that, the heuristic routing solution generally achieves better performance compared with two existing algorithms.

Table 1. Comparison of average distortion using different routing solutions

Topology	I (15-node)	II (15-node)	III (30-node)	IV (30-node)
2 shortest paths	0.804	0.687	0.776	0.799
Interference-oblivious	0.729	0.669	0.735	0.712
Global optimal	0.686	0.618	0.708	0.689
Heuristic solution	0.686	0.629	0.730	0.708

In Fig. 2, we compare reconstructed quality of individual frames of Foreman QCIF sequence using different routing solutions in Topology I. The redundant slice based MDVC in [10] is used to generate two balanced descriptions for each sequence. The video sequence is encoded at 30 frames per second using "IPP..P" coding structure with an intra period of 50 frames. Each coded slice is packed into a packet. Reconstructed quality of individual frames is measured in peak-to-noise ratios (PSNRs). The proposed solution achieves 3.96dB and 1.27dB gains in average over 2 shortest paths and its interference-oblivious counterpart, respectively. Reconstructed frame samples of Foreman sequence using different schemes in Topology I are shown in Fig. 3, while frame samples of Mobile QCIF sequence using different routing solutions in Topology II are shown in Fig. 4.

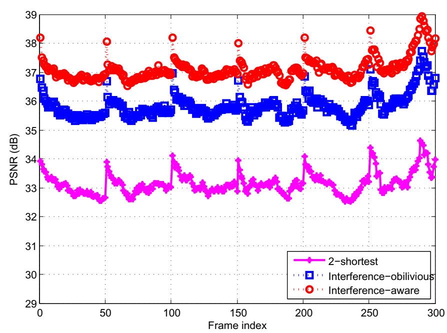

Fig. 2. Comparison of reconstructed "Foreman.qcif" using different routing solutions

5.2 Performance of Unbalanced MDVC

We compare the proposed unbalanced redundant slice based MDVC with balanced version of MDVC in [10]. The successful probabilities of two paths are set to 0.99 and 0.95, respectively. Each primary slice or redundant slice is packed into a packet for transmission. The proposed MDVC adds more redundancy to the description transmitted in the worse path, while balanced MDVC in [10] equally protects these description according to an average path successful probability. In Fig. 5, with the same QP for primary slices, the proposed MDVC generates

(a) 2 shortest paths (PSNR = 32.60 dB) (b) Interference-oblivious (PSNR = 35.45 dB) (c) Interference-aware (PSNR = 36.65 dB)

Fig. 3. Reconstructed 45^{th} frames of "Foreman.qcif" using different routing solutions

(a) 2 shortest paths (PSNR = 28.67 dB) (b) Interference-oblivious (PSNR = 29.39 dB) (c) Interference-aware (PSNR = 30.26 dB)

Fig. 4. Reconstructed 135^{th} frames of "Mobile.qcif" using different routing solutions

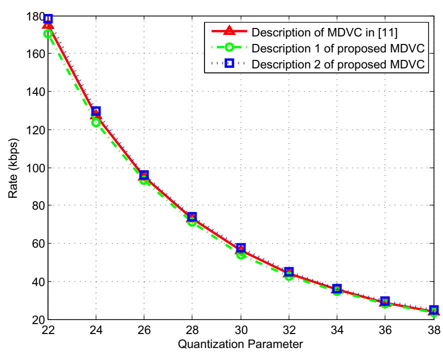

Fig. 5. Comparison of coding rate of Foreman QCIF video sequence

two descriptions whose bitrates are close to average bitrate per description of balanced MDVC. Decoded quality of individual frames using different MDVC schemes is compared with a same transmission trial in Fig. 6. It can be seen that the unbalanced MDVC gets better reconstructed images than balanced MDVC

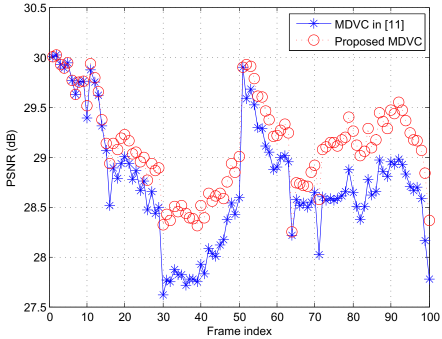

Fig. 6. Comparison of reconstructed Foreman.qcif in the same transmission trial

(a) MDVC in [10] (PSNR = 27.77 dB)

(b) Proposed MDVC (PSNR = 28.42 dB)

Fig. 7. Reconstructed 31^{th} frames of Foreman.qcif using different MDVC schemes

with biased error protection. Fig. 7 shows the reconstructed frame samples using different MDVC schemes.

6 Conclusion

In this paper, we investigate two problems of two-description coded video streaming in wireless ad hoc networks, namely, multipath selection and MDC redundancy allocation. Firstly, we formulate an interference-aware MDC multipath routing in single-radio networks with a time-division link scheduling method. The proposed MDC multipath routing generates optimal paths that maximize average decoded quality. A heuristic solution is developed for the proposed interference-aware multipath routing, by defining a new path metric considering intra-path and inter-path interference. Secondly, we design an unbalanced MDVC scheme for multiple paths with different channel conditions, where the amount of redundancy of each description is optimally selected according to condition of its selected path. Simulation results verify the proposed MDC multipath routing scheme and the proposed unbalance MDVC approach.

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