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# Multipath Routing of Multiple Description Coded Images in Wireless Networks

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**Abstract** Multiple description coding (MDC) generates multiple decodable bitstreams for a source to combat information loss. In this paper, multipath routing problem for two-description coded images is investigated for traditional and coded wireless networks without and with coding capability at intermediate nodes, respectively. Firstly, we formulate an interference-aware MDC multipath routing for traditional 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. Secondly, for coded networks, we evaluate practical wireless network coding (NC) in delivering descriptions of multiple unicast sessions. While NC increases maximum supporting flow rate of MDC descriptions in wireless networks, possible undecodability of NC mixed information is alleviated by MDC. To minimize achievable distortion, a proposed interference-and-coding-aware MDC multipath routing strikes a good balance between minimizing side effect of wireless interference avoidance and maximizing NC opportunity. Simulation results validate the effectiveness of the two proposed schemes.

**Keywords** multiple description coding, multipath routing, network coding, wireless interference

## 1 Introduction

The fragile wireless links pose a challenge for image transmission in wireless ad hoc networks. To provide continuous media delivery over fragile links without retransmission, multiple description coding (MD coding or MDC)[1] can be used at the source node to generate multiple descriptions for a single source. 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.

Although MDC provides robustness against packet loss in wireless networks, it introduces redundancy among descriptions and thus increases the amount of data to be delivered. Recent development of network coding (NC)[2] shows a great potential in increasing the amount of delivery traffic per unit time in networks. In a traditional network, intermediate nodes adopt the store-and-forward method, which keeps different packets separate and tries to avoid collisions of these packets. In a coded network, intermediate nodes are capable of performing NC operations, like XOR operations or generating linear combinations over a finite field. Mixing of information flows is allowed at intermediate nodes, and those individual flows are deduced at the receiver end. Taking advantage of wireless broadcast nature, an intermediate node in wireless networks can combine different information flows together and broadcast the mixed flow to reduce the overall transmission time[3].

The performance of MD coded media delivery in wireless networks depends on both MD coding efficiency and MDC path selection. In contrast with extensive efforts on MDC codec design[4-15], there is relatively less work on MDC path selection in wireless networks. In this paper, we mainly focus on MDC path selection problem for unicast sessions in two types of wireless networks, namely, traditional wireless networks and coded wireless networks. Studies of multimedia-centric MDC multipath routing in traditional wireless ad hoc networks are presented in [16-20], where video quality

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is optimized via routing operations with respect to available link bandwidth, link "up" probabilities, and average loss burst lengths on links. In those studies, 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. In our previous work[21], we consider interference-aware video communications in a traditional wireless network. In this paper, we consider wireless interference in multipath routing of MD coded image delivery in both types of wireless networks.

NC for multirate video multicast is discussed in [22], where two popular multirate multicast approaches are performing MDC and using multi-resolution codes, respectively. There are a few approaches dedicated to using both MDC and NC for content delivery[22-26]. Shao *et al.*[23] firstly attempted to combine NC with rainbow network flow (RNF or optimal routing of MDC packets) for transmitting MD coded source from multiple encoders to multiple sinks in a general network. Their work shows that performing linear NC at intermediate nodes of a flow path can achieve higher network throughput than the original RNF. In [24], a combination of practical NC and MDC is developed for video multicast in lossless networks, where NC enables the server to provide Quality of Service to users with high bandwidth. In our previous work[27], MD coded image delivery incorporating random NC is considered for image multicast in wireless networks, which is compared with single description coded image delivery with NC as well as MD coded image delivery without NC in terms of decoded image quality, decoding failure rate, and energy consumption. In [28], the authors address the problem of link failure for image unicast from one sender to one receiver through multiple links. NC is used to generate linear combinations of multiple descriptions, which are then transmitted over some additional paths to provide protection against link failures. However, none of these studies consider MDC path selection incorporating wireless NC for unicast sessions, which will be elaborated in the second piece of our work.

In this paper, for traditional wireless networks, we propose an interference-aware MDC multipath routing for image unicast. The routing problem is formulated with a specific treatment of wireless interference. Conflicting wireless links owing to interference are scheduled to be active in different time fractions. We adopt the concept of conflict graph in [29] 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 the minimum achievable distortion of reconstructed image can be obtained for a given wireless network configuration and parameters. The effectiveness of the proposed interference-aware MDC multipath routing is validated by simulation results.

For coded wireless networks, we develop an interference-and-coding-aware MDC multipath routing that maximizes image quality for multiple multipath unicast sessions. The practical wireless NC COPE[3] with opportunistic listening is adopted to enhance the delivery. Compared with the work in [28], as any subset of MDC descriptions can be used to reconstruct an image, no extra protection paths are used. Instead of generating transmission contents for extra paths as in [28], NC is used to increase traffic delivery capacity. With consideration of coded packets, conflict graphs for hypergraph[30-32] can be used to schedule one-to-multiple transmissions. In [32], Traskov *et al.* construct a conflict graph that considers network coding in wireless networks with collisions and with erasures. As opposed to classical link-based scheduling, hyperarc-based scheduling is conducted in [32], where transmissions from a node to all possible subsets of neighbors are considered. Using a time-division broadcast link scheduling method, MDC multipath routing in coded networks strikes a good balance between minimizing the reduction of path flow rate owing to interference avoidance and maximizing NC opportunities, two of which demand different path selections. The resulting optimal path selection can achieve the minimum end-to-end distortion with NC operations performed at intermediate nodes. The successful decoding of an NC mixed flow does depend on not only the receipt of the mixed flow, but also the correct overhearings needed in decoding. Our results show that wireless NC with opportunistic listening only improves end-to-end performance of MD coded image delivery at a high link "up" probability. In the case of high link "up" probability, simulation results demonstrate the effectiveness of the proposed interference-and-coding-aware routing in coded wireless networks.

The remainder of this paper is organized as follows. The backgrounds are provided in Section 2. In Section 3, we discuss and formulate the MDC multipath routing problem in traditional wireless networks. In Section 4, we consider the MDC multipath routing problem in coded wireless networks, where wireless NC with opportunistic listening is adopted to enhance the delivery of multiple MDC unicast sessions. Section 5 presents simulation results, and Section 6 draws a conclusion.

## 2 Backgrounds and Preliminaries

In this section, we describe the backgrounds of practical wireless NC and MD coded image delivery.

### 2.1 Practical Wireless Network Coding

Recent development of NC shows that it can increase traffic delivery capacity of wireless networks. The prior research of NC is mainly theoretical and focuses on multicast traffic, until a practical wireless NC COPE[3] is proposed to address the common case of unicast traffic. The principle of COPE is to learn the state of neighbors, and to mix information at an intermediate node only if its next-hop nodes can decode the mixed flow. In order to maintain backward compatibility with nodes that do not decode, these next-hop nodes decode the mixed information immediately after receiving it, thus COPE is a local NC technique. As delay constraint is one of the aforementioned reasons of choosing MDC, the immediate decoding property and the capability of increasing traffic delivery capacity make COPE a good choice in facilitating the delivery of MDC descriptions.

Opportunistic listening greatly increases NC coding gain of COPE-type NC[3]. Therefore, we adopt COPE with opportunistic listening in this paper. With opportunistic listening, a wireless node overhears the transmissions in the neighborhood and stores the overheard information for a limited time in the buffer to seek an NC opportunity. Utilizing wireless broadcast nature, an intermediate node performing wireless NC mixes multiple flows based on the knowledge of its neighbors' buffer, and then broadcasts the mixed flow which can be decoded by its next-hop nodes. Thus the overall transmission time is reduced resulting in an increased amount of delivery traffic within a prescribed time.

### 2.2 MD Coded Image Delivery over Wireless Networks

Fig.1 shows an MD coded multipath unicast session in a wireless ad hoc network. For each session, multiple paths exist from a source to its corresponding destination with different numbers of hops, maximum flow rates, and path "up" probabilities (successful delivery probabilities of paths). An MDC multipath routing algorithm aims to minimize end-to-end distortion by determining two paths for two descriptions based on rate-distortion function of MDC codec $D(R)$ and collected network information. After selecting two paths which may be disjoint or partially shared, MDC encoder generates two balanced descriptions with description size $R$, whose value is provided by the multipath routing algorithm according to a known delay constraint imposed on the image delivery. These descriptions are then delivered to the destination node along the selected paths. At the destination node, either side decoder or central decoder is used to reconstruct an image according to the number of correctly received descriptions. The expected end-to-end distortion $D^s(R)$ of a unicast session $s$ with description size $R$ can be expressed as follows:

$$\begin{aligned} D^s(R) = {} & (1-p^s_{path_1})(1-p^s_{path_2})d_{null} \\ & + p^s_{path_1}(1-p^s_{path_2})d_s(R) \\ & + (1-p^s_{path_1})p^s_{path_2}d_s(R) \\ & + p^s_{path_1}p^s_{path_2}d_c(R), \end{aligned} \quad (1)$$

where $p^s_{path_i}$ denotes "up" probability (successful delivery probability) of the $i$-th selected path ($i = 1, 2$) for a multipath unicast session $s$, and $d_{null}$, $d_s(R)$, and $d_c(R)$ denote reconstruction distortions corresponding to zero, one, and two successfully received descriptions with a description size of $R$, respectively. As the expected end-to-end distortion $D^s(R)$ is non-increasing with $R$ and $p^s_{path_i}$ [19], we aim to minimize end-to-end distortion through proper design of multipath routing in this paper, taking special consideration of wireless interference.

## 3 Interference-Aware MDC Multipath Routing in Traditional Wireless Networks

In this section, we consider MDC multipath routing in a traditional wireless network, where intermediate nodes are incapable of performing coding operation. In such a network, each node is supported by an omnidirectional antenna and communicates only via wireless medium at the same frequency band. A wireless ad hoc

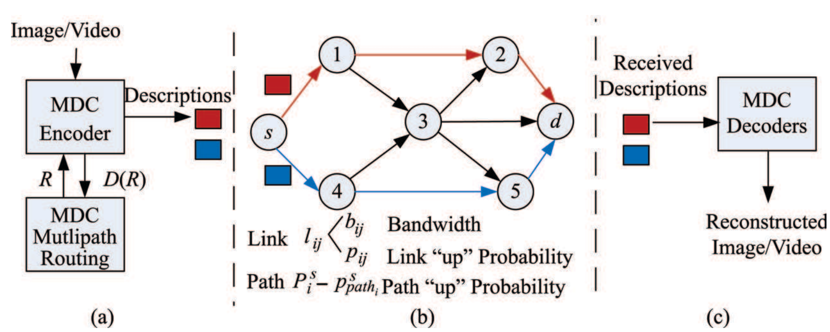


Fig.1. MD coded multipath unicast session in a wireless ad hoc network. (a) At source node. (b) In a wireless ad hoc network. (c) At destination node.

network can be represented by a stochastic directed hypergraph $H = (X, L)$, where $X$ and $L$ denote a set of nodes and a set of hyperedges, respectively. Each node is characterized by its position $(x_i, y_i)$ and a transmission range $R_c$. A wireless link exists between any two nodes whose distance is within $R_c$. Each link $l_{ij}$ is characterized by its link capacity $b_{ij}$ and link "up" probability $p_{ij}$. Owing to wireless broadcast nature, a wireless transmission can be better modeled as a hyperedge $L(i, J)$, which denotes the wireless links from node $i$ to a set of nodes $J$, where $i \in X, J \subseteq X$.

### 3.1 Wireless Interference and Link Scheduling

Wireless communication suffers from wireless interference owing to the broadcast nature of wireless medium. While accurately measuring and estimating wireless interference is a complicated issue, we employ a protocol model in [32] that defines an inference range $R_f$ for wireless nodes and assumes interference to be an all-or-nothing phenomenon. A wireless node causes severe interference within the range of $R_f$ ($R_c \leqslant R_f$) and no interference beyond $R_f$ during transmission. With such a protocol model, a direct transmission from node $i$ to node $j$ is considered to be successful, if: 1) node $i$ can communicate with node $j$ directly, i.e., $d_{ij} \leqslant R_c$; 2) transmissions from any other node $k$ that will cause interference at node $j$, i.e., $d_{kj} \leqslant R_f$, are not happening, where $k \neq i$.

To eliminate interference, a time-division link scheduling method can be developed with the help of conflict graph in [29]. In a conflict graph, vertices correspond to individual links, while an edge between two vertices $l_{ij}$ and $l_{pq}$ means that these two links cannot be active simultaneously owing to interference. An independent set of the graph can be figured out, which is a set of vertices such that there is no edge between any two of the vertices. We assume that a central controller exists, which makes transmissions at the individual nodes finely controlled and scheduled. The implementation of a central controller in a wireless ad hoc network is out of the scope of this paper. By finding the maximal independent sets $I_1, ..., I_n$ in the conflict graph and having each individual set $I_i$ active at its own time fraction $\lambda_i$, wireless links are scheduled to eliminate interference[29]. Maximum output flow rate $f_i$ of a node $i$ is subject to

$$f_i \leqslant \sum_n \lambda_n b_{ik}, l_{ik} \in I_n, \tag{2}$$

$$\sum_{i=1}^{n} \lambda_i \leqslant 1. \tag{3}$$

The problem of maximizing the flow rate can be explored by evaluating the stable set polytope of a conflict graph. The stable set problem of general graphs is NP-hard, except certain classes of graphs including claw-free graphs and perfect graphs. One such special case is a grid graph with two links conflicting if and only if they share an endpoint[29]. The grid graph is a bipartite graph, which is a kind of perfect graphs. However, a conflict graph for a general wireless network may not be claw-free, or perfect. For the conflict graph for a general wireless network, the stable set problem can be solved with some relaxations. For example, the maximum stable set (a stable set with the largest cardinality) constraint is relaxed to the maximal weighted stable set (a stable set that is not contained in any other sets) constraint in [32].

### 3.2 MDC Multipath Routing in Traditional Wireless Networks

With the above link scheduling method, MDC multipath routing for traditional wireless networks is formulated as follows:

Minimize

$$\begin{aligned} D^s(R) = &(1 - p^s_{path_1})(1 - p^s_{path_2})d_{null} \\ &+ p^s_{path_1}(1 - p^s_{path_2})d_s(R) \\ &+ (1 - p^s_{path_1})p^s_{path_2}d_s(R) \\ &+ p^s_{path_1}p^s_{path_2}d_c(R), \end{aligned} \tag{4}$$

subject to (2), (3) and following constraints:

$$p^s_{path_k} = \prod_{l_{ij} \in P^s_k} p_{ij}, \text{ where } k = 1, 2, \tag{5}$$

$$f^s(P) \geqslant R/t, \tag{6}$$

$$\begin{aligned} f_i = &\sum_{s \in S, s=i} \sum_{P \in P^S, l_{ij} \in P} f^s(P) \\ &+ \sum_q \sum_{s \in S} \sum_{P \in P^S, l_{qi} l_{ij} \in P} f^s(P), q \neq j. \end{aligned} \tag{7}$$

The objective function (4) is to minimize the expected end-to-end distortion of a two-description coded image by selection of multipath solution. For each multipath candidate, a decodable description is successfully delivered if all wireless links are "up" along one of two paths as shown in (5), where each path with flow rate $f^s(P)$ has to be able to support delivery of a description with description size $R$ within its delay constraint of $t$ seconds as indicated in (6). The amount of output flow $f_i$ at a node $i$ can be obtained as in (7) which equals the sum of its initial traffic and transit traffic, and it is constrained by (2) and (3) depending on active time and capacities of its output links. For each path, its maximum output flow rate is constrained by a bottleneck link with the minimum achievable rate.

The solution of this problem is a pair of paths from source node $s$ to destination node $dest(s)$ for two balanced descriptions. Given any multipath routing decision, maximal independent sets of its conflict graph can be obtained and wireless links along these paths are scheduled to eliminate interference. The maximum path flow rate for each routing decision is subject to linear constraints (2), (3), (6), and (7), and thus can be obtained using linear programming. We can exhaustively search the solution space to obtain an optimal solution with the minimum expected end-to-end distortion.

## 4 Interference-and-Coding-Aware MDC Multipath Routing in Coded Wireless Networks

Although the broadcast nature of wireless medium causes undesirable interference, this nature can be explored by NC to facilitate the transmission of MDC descriptions for multiple unicast sessions. In this section, we consider routing MDC descriptions in a coded wireless network, where intermediate nodes are capable of performing NC operations.

### 4.1 Routing with Wireless Network Coding

Coding-aware routing[31] considers NC opportunities during routing, which leads to higher throughput than a coding-oblivious routing strategy. It makes routing choice between routing flows "close to each other" for utilizing NC opportunities and "away from each other" for avoiding interference. For the same reason, we extend the proposed interference-aware MDC multipath routing for traditional wireless networks to the one considering both wireless interference and NC opportunities for coded wireless networks. Compared with the work in [31], we explicitly consider the lossy characteristics of coded wireless networks. The work in [31] cares about the throughput of the network, which is the average rate of successful information delivery over a coded wireless network. We focus on the amount of delivery traffic, part of which may not be successfully delivered, and use MDC to combat transmission loss by providing redundancy during source coding. Our MDC multipath routing in coded wireless network cares about the amount of delivery traffic, description decodability, and source decodability. Furthermore, we generalize the coding structures in [31] for pairwise combinations to the case of combinations of $m$ flows ($m \geqslant 2$). The work in [31] only considers the coding case with pairwise combinations. However, Zhao *et al.* analyzed the COPE performance in [34] and found that the main benefit of COPE comes from combinations of three or more packets. In [35], Zhao *et al.* further verified the analysis with the measured performance results in IEEE 802.11 adhoc networks.

As aforementioned, practical wireless NC[3] with opportunistic listening increases the amount of supporting traffic per unit time by broadcasting a decodable mixed flow to several neighbor nodes. However, the increase in traffic delivery capacity comes at a price of information decodability. A native unmixed flow can be decoded if this flow is successfully received, whereas successful decoding of the mixed flow is based on the correct receipt of both the mixed flow and necessary overhearing information. MDC coded source is decodable as long as one of its multiple descriptions is decodable. By blending MDC with NC in fragile wireless networks, possible undecodability of NC mixed information is alleviated by error-resilient MDC. Nevertheless, the impact of NC operations on end-to-end performance of MD coded unicast sessions in a lossy environment still needs to be explored.

As an inter-flow NC, COPE mixes information from different connections together. Thus the first requirement of NC opportunity is that multiple paths delivering MDC descriptions must have common intermediate relay nodes. For example, two flows $s_0 \xrightarrow{f_0} i \rightarrow d_0, s_1 \xrightarrow{f_1} i \rightarrow d_1$ share intermediate node $i$. Secondly, the common intermediate node mixes multiple flows only if the intended receivers know enough to decode the mixed flow. Prior knowledge of the mixed flow at receivers is either from overhearing or previous delivering. In these cases, the intermediate node $i$ can generate a linear combination of $f_0$ and $f_1$ and broadcast a combined flow to both receivers. Link $l_{id_0}$ and link $l_{id_1}$ can be treated as a hyperedge broadcasting from node $i$ to node $d_0$ and node $d_1$ simultaneously. The capacity of a broadcast transmission is restricted to the minimum point-to-point link capacity in this broadcast transmission, while the "up" probabilities of these links remain the same.

To simplify the formulation and avoid buffering packets for longer periods as in [31], NC opportunity is restricted to the case that each destination is the previous-hop node of another flow, or each destination overhears transmission of another flow from its previous-hop node. As an example, the case with two transit flows with different conditions are discussed in the following. For two native transit flows $s_0 \xrightarrow{f_0} i \rightarrow d_0$ and $s_1 \xrightarrow{f_1} i \rightarrow d_1$ at node $i$ as shown in Fig.2(a), an NC opportunity exists at node $i$ if both destination nodes are the previous-hop node of another flow or overhear the transmission of another flow (i.e., $d(s_1, d_0) \leqslant R_c$ and $d(s_0, d_1) \leqslant R_c$). If one of the flows is already a coded flow, e.g., $f_1$ mixed with $f_3$ at $s_1$ as shown in Fig.2(b), node $i$ retrieves $f_1$ instantly according to immediate decoding property of COPE. Suppose an NC opportunity exists at node $i$, $f_0$ and $f_1$ are then mixed at node $i$, and the mixed flow is broadcasted to $d_0$ and $d_1$ simultaneously. If $d_0$ only overhears transmission of a mixed flow of $f_1$ and $f_3$, it cannot decode the received information. $d_0$ has to be the previous node traversed by $f_1$ prior to $i$ which is $s_1$ (i.e., $d(s_1, d_0) = 0$) to know the content of $f_1$ and retrieve $f_0$ from a combined flow of $f_0$ and $f_1$.

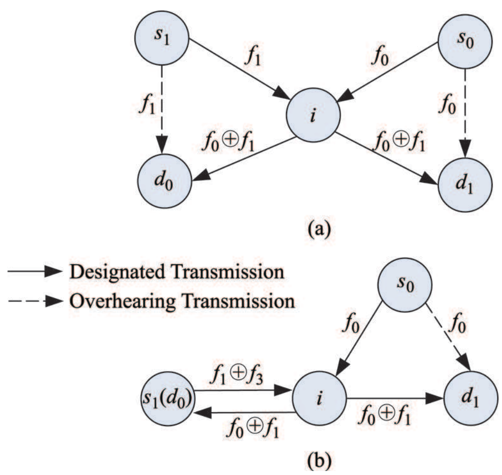


Fig.2. Examples of NC opportunity for two transit flows. (a) Two native flows. (b) A coded flow and a native flow.

To achieve the main benefit of COPE which comes from combinations of three or more packets, coding structure in [31] of two flows is generalized to the case of $n$ flows ($n \geqslant 2$) with $s_1 \xrightarrow{f_1} i \rightarrow d_1, s_2 \xrightarrow{f_2} i \rightarrow d_2, ..., s_n \xrightarrow{f_n} i \rightarrow d_n$ interconnected at node $i$. The algorithm of finding out which transit flows can be coded together is summarized in Algorithm 1, where NC impact coefficient $p'_{id_{c_k}}$ reflects the impact of necessary overhearings on decodability of information transmitted along link $l_{id_{c_k}}$. With NC, the decodability of information transmitted on link $l_{id_{c_k}}$ is changed from $p_{id_{c_k}}$ to $p_{id_{c_k}} p'_{id_{c_k}}$. This coefficient $p'_{id_{c_k}}$ has an initial value of 1, which does not affect information decodability on $l_{id_{c_k}}$ with a multiplication operation. If a coded flow is delivered on $l_{id_{c_k}}$, the value of $p'_{id_{c_k}}$ can be calculated according to Algorithm 1, which represents the probability of successful receipt of all the necessary overhearing information. With a larger number of flows mixed and broadcasted, the necessary overhearings pose severer impact on information decodability of corresponding links.

### 4.2 Link Scheduling with Wireless Network Coding

Conflict graph can be extended to broadcast conflict graph[31] to schedule broadcast transmissions with consideration of coding operation in coded wireless networks. Each node in a broadcast conflict graph represents a broadcast transmission denoted by a hyperedge $l(i, J)$ where $i \in X, J \subseteq X$. An edge exists between two hyperedges $l(i_1, J_1)$ and $l(i_2, J_2)$ in the broadcast conflict graph, if either one of the following conditions holds: 1) node $i_1$ is the same node as node $i_2$; 2) $i_1$ is a node in $J_2$ or node $i_2$ is a node in $J_1$; 3) a node in $J_1$ is within the interference range of node $i_2$ or either node in $J_2$ is within the interference range of node $i_1$. By finding the maximal independent sets $I_1, ..., I_n$ in the broadcast conflict graph and having each individual set $I_i$ active at its own time fraction $\lambda_i$, the constraint of output flow rate of node $i$ becomes

$$f_i \leqslant \sum_{n} \lambda_n \min_{k \in J, (i,J) \in I_n} b_{ik}, \quad (8)$$

$$\sum_{i=1}^{n} \lambda_i \leqslant 1. \quad (9)$$

**Algorithm 1** Algorithm of Finding Subset of Transit Flows at Node $i$ that Can Be Coded Together, out of $n$ Flows $s_1 \xrightarrow{f_1} i \rightarrow d_1, s_2 \xrightarrow{f_2} i \rightarrow d_2, \ldots, s_n \xrightarrow{f_n} i \rightarrow d_n$

**for** $l = 1$ to $n$ **do**
  CodeSet $C = \{l\}$
  **for** $j = 1$ to $n$ with $\forall k \in C, j \neq k$ **do**
    **if** $f_j$ and $f_k$ are both native flows **then**
      **if** $d(s_j, d_k) \leqslant R_c$ AND $d(s_k, d_j) \leqslant R_c$ **then**
        $C = C \cup \{j\}$
      **endif**
    **else**
      **if** $f_j$ is a coded flow and $f_k$ is a native flow **then**
        **if** $d(s_j, d_k) = 0$ AND $d(s_k, d_j) \leqslant R_c$ **then**
          $C = C \cup \{j\}$
        **end if**
      **end if**
    **else**
      **if** $f_j$ is a native flow and $f_k$ is a coded flow **then**
        **if** $d(s_j, d_k) \leqslant R_c$ AND $d(s_k, d_j) = 0$ **then**
          $C = C \cup \{j\}$
        **end if**
      **end if**
    **else**
      **if** $f_j$ and $f_k$ are both coded flows **then**
        **if** $d(s_j, d_k) = 0$ AND $d(s_k, d_j) = 0$ **then**
          $C = C \cup \{j\}$
        **end if**
      **end if**
    **end if**
  **end for**
  $m$ = size of $C$
  **for** $k = 1$ to $m$ **do**
    NC impact coefficient of link $l_{id_{c_k}}$ from node $i$ to the destination of the $k$-th flow in set $C$
    $p'_{id_{c_k}} = p_{s_{c_1} d_{c_k}} \cdots p_{s_{c_{k-1}} d_{c_k}} p_{s_{c_{k+1}} d_{c_k}} \cdots p_{s_{c_m} d_{c_k}}$,
    where $p_{jj} = 1$
    $k \leftarrow k + 1$
  **end for**
  $l \leftarrow l + 1$
**end for**

In a traditional wireless network, tasks on multiple output links of the same intermediate node are conflicting, if these tasks require this node to send out different contents. In a coded wireless network, an intermediate node may find an NC opportunity, and broadcasts the same mixed content to different users performing these tasks simultaneously. Those conflicting output links can be treated as a broadcast link in the conflict graph. Therefore the number of maximal independent sets in the conflict graph can possibly be reduced performing NC, resulting in longer active time for each maximal independent set.

### 4.3 Coding-Aware MDC Multipath Routing

The MDC multipath routing problem for multiple MDC unicast sessions in a coded wireless network can be formulated as follows:

Minimize

$$\begin{aligned}\sum_{s\in S} D^s(R) = \sum_{s\in S} [&(1-p^s_{path_1})(1-p^s_{path_2})d_{null}\\ &+ p^s_{path_1}(1-p^s_{path_2})d_s(R)\\ &+ (1-p^s_{path_1})p^s_{path_2}d_s(R)\\ &+ p^s_{path_1}p^s_{path_2}d_c(R)], \end{aligned} \quad (10)$$

subject to (8) and (9), where

$$p^s_{path_k} = \prod_{l_{ij}\in P^s_k} [p_{ij}p'_{ij}], \text{ where } k=1,2, \quad (11)$$

$$f^s(P) \geqslant R/t, \quad (12)$$

$$\begin{aligned} f_i = &\sum_{s\in S, s=i} \sum_{P\in P^S, l_{ij}\in P} f^s(P)\\ &+ \sum_q \sum_{s\in S} \sum_{P\in P^S, l_{qi}l_{ij}\in P} f^s(P), q\neq j. \end{aligned} \quad (13)$$

Compared with routing in traditional wireless networks, the formulation of MDC multipath routing for coded wireless networks differs in several ways. Firstly, a decodable description is successfully delivered in a coded network, if all the links along the path are "up" and overhearings required in decoding NC mixed information are successful as shown in (11). If $l_{ij}$ delivers a coded flow, NC impact coefficient $p'_{ij}$ in (11) can be calculated according to Algorithm 1; otherwise, $p'_{ij}$ has a value of 1. Secondly, the elements in broadcast conflict graph are changed owing to NC. The number of maximal independent sets can probably be reduced resulting in different interference constraints (8) and time fraction constraint (9). Lastly, delivering capacity of a wireless link is affected if it belongs to a broadcast link owing to NC. The capacity of a broadcast link is restricted to the minimum output link capacity of this broadcast transmission as expressed in constraint (8).

The solution of MDC multipath routing in coded wireless network is a pair of paths for each MDC session. Given a multipath routing decision, intermediate nodes performing NC can be figured out based on traffic pattern and their positions. The output wireless links of an intermediate node broadcasting NC mixed information are represented by a hyperedge from this node to a set of neighbors. These hyperedges and the remaining links delivering descriptions are scheduled to eliminate interference, and maximal independent sets of the corresponding broadcast conflict graph can be obtained. The constraints of maximum flow rate (8), (9), (12), and (13) for a routing decision are linear, and thus maximum flow rate can be obtained using linear programming. The whole solution space can be exhaustively searched to get a solution with the minimum overall expected distortion of several unicast sessions.

## 5 Simulation Results

In the simulation, performance of MDC multipath routing is evaluated in three randomly generated wireless ad hoc networks as shown in Fig.3. In each network, 15 nodes are randomly placed with a uniform distribution in an area of $500\times500$ square. Transmission range of wireless nodes $R_c$ is a fixed value to ensure that average node degree is at least 3. Interference range $R_f$ has the same value as 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 [0.5, 2] Mb/s with a step size of 0.25 Mb/s. Source nodes and destination nodes for MDC unicast sessions are randomly chosen among 15 nodes.

The proposed MDC multipath routing schemes generate optimal routing solutions for delivery of two MDC descriptions from a source to its corresponding destination in these networks, and specify the maximum description size for MDC encoder. Although the two proposed schemes are independent of specific MDC techniques, a JPEG 2000-based MDC image codec[36] is used in the simulation, whose codes can be downloaded from its website (http://www.telematica.polito.it/sas-ipl/download.php). The standard images "Lena.bmp" and "Peppers.bmp" of dimension $512\times512$ are used in the simulation. With a maximum description size $R$ specified in the optimal routing solution, two balanced descriptions with 25% redundancy between them are generated for each image, by grouping code-blocks of JPEG 2000 under two different bit rates into two sets with similar rate-distortion performance. These descriptions are delivered to the destinations along optimal selected paths yielded by the proposed MDC

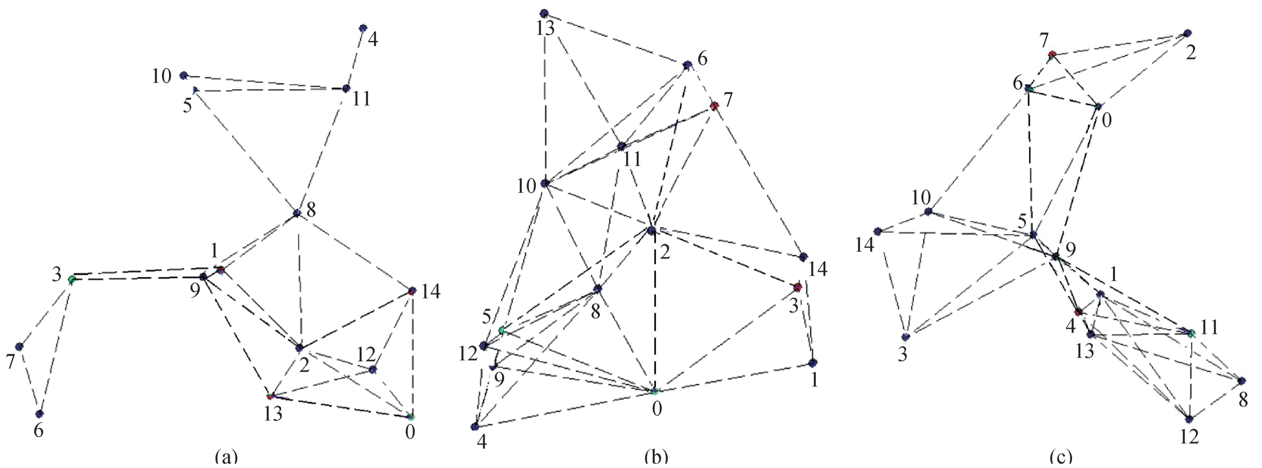


Fig.3. Topologies of three randomly generated wireless networks. (a) Network 1. (b) Network 2. (c) Network 3.

multipath routing within a prescribed time between [0.1, 0.8] seconds. We assume each description is completely lost or received. Lost information will not be retransmitted. At destination nodes, MDC decoder in [36] is used to reconstruct the image, based on the number of correctly received descriptions within the prescribed time.

### 5.1 Performance of Interference-Aware MDC Multipath Routing

In this subsection, different MDC multipath routing methods are used to generate two paths for one MDC unicast session in traditional wireless networks. Interference-aware MDC multipath routing in Section 3 is compared with $k$-shortest paths[37] and MDC multipath routing algorithm without considering wireless interference[18]. 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 MDC multipath routing without considering interference is termed as interference-oblivious multipath routing, which minimizes average end-to-end distortion by finding paths with large flow rate and high link "up" probability like those in wired networks.

We exhaustively search all the paths from the source to destination within 6 hops to obtain these results. Maximum path flow rates can be obtained solving linear programming (LP) problems. There are a variety of effective methods including simplex method, ellipsoid algorithm, and projective interior point algorithm[38]. The computational complexity of linear programming in practice is in order of $n^2m$[39], where $n$ and $m$ are the number of maximal independent sets and the number of active links plus one (time fraction constraint), respectively. For simplicity and convenience, we use a Matlab linear programming function which uses a variation of simplex method for medium-scale optimization.

Table 1 shows the routing decisions of 2-shortest paths, interference-oblivious multipath and interference-aware multipath in three traditional wireless networks, when two descriptions of "Lena.bmp" have to be delivered within 0.1 seconds. End-to-end distortion comparisons of using different multipath routing decisions in terms of average peak signal-to-noise ratio (PSNR) of reconstructed image are shown in Fig.4 and Fig.5, where "Lena.bmp" and "Peppers.bmp" are delivered with varying delay constraint in the network 1 and network 2 correspondingly. These algorithms find different paths supporting different amounts of delivery traffic within a same prescribed time. With a JPEG-2000 based MDC technique, different rates result in different source encoding distortions, although both descriptions are received. It can be seen that the interference-aware MDC multipath routing shows a great potential to achieve end-to-end performance gain in terms of average reconstructed image quality by considering wireless interference.

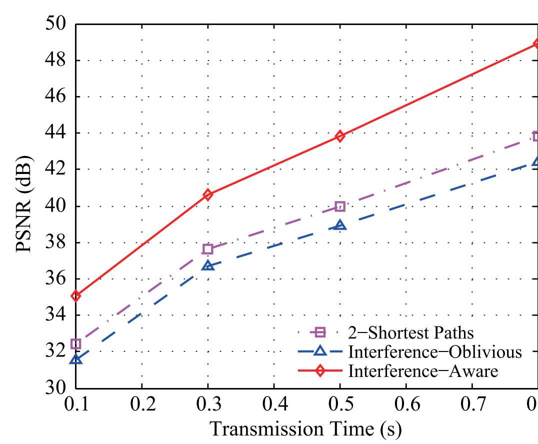


Fig.4. End-to-end PSNR performance comparison in delivering "Lena.bmp" with varying delay constraint in the traditional wireless network 1.

**Table 1.** End-to-End Performance Comparison in Three Traditional Wireless Networks

| | | Path 1 | Path 2 | Path 1 "up" Probability (%) | Path 2 "up" Probability (%) | Maximum Flow Rate (Mb/s) | Average PSNR (dB) |
|---|---|---|---|---|---|---|---|
| Network 1 | 2-shortest paths | 0→2→1 | 0→13→1 | 99.00 | 99.00 | 0.28 | 32.45 |
| | Interference-oblivious | 0→13→9→2→1 | 0→13→9→8→1 | 98.01 | 98.01 | 0.23 | 31.57 |
| | Interference-aware | 0→13→1 | 0→14→8→1 | 99.00 | 98.51 | 0.49 | 35.05 |
| Network 2 | 2-shortest paths | 13→6→2→0 | 13→10→2→0 | 98.51 | 98.51 | 0.23 | 31.42 |
| | Interference-oblivious | 13→10→1→2→0 | 13→11→10→12→0 | 98.01 | 98.01 | 0.28 | 32.46 |
| | Interference-aware | 13→6→2→0 | 13→10→12→0 | 98.51 | 98.51 | 0.38 | 33.99 |
| Network 3 | 2-shortest paths | 11→1→5→0→7 | 11→9→0→7 | 98.01 | 98.51 | 0.14 | 29.58 |
| | Interference-oblivious | 11→4→5→6→7 | 11→9→5→6→7 | 98.01 | 98.01 | 0.25 | 31.88 |
| | Interference-aware | 11→9→0→7 | 11→9→10→6→7 | 98.51 | 98.01 | 0.30 | 32.69 |

Note: Two descriptions of "Lena.bmp" are delivered within 0.1 seconds with a link "up" probability of 0.995.

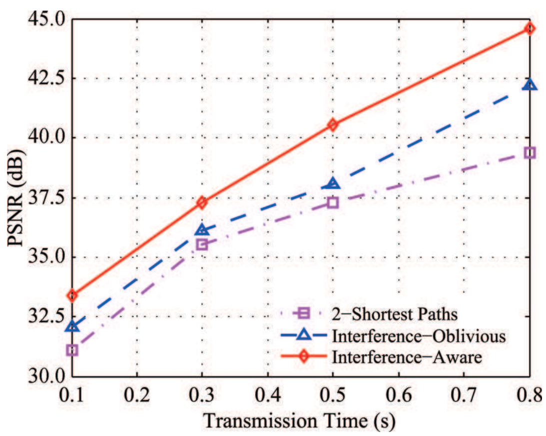


Fig.5. End-to-end PSNR performance comparison in delivering "Peppers.bmp" with varying delay constraint in the traditional wireless network 2.

## 5.2 Performance of Wireless Network Coding in MDC Multipath Routing

In this subsection, performance of wireless NC with opportunistic listening is evaluated for two MD coded unicast sessions. MDC descriptions are sent along the same set of paths in traditional networks and coded networks. These two types of networks have the same topology and configurations, except coding capability at intermediate nodes. Table 2 presents performance comparison of same routing decision in two types of networks, transmitting "Lena.bmp" within 0.1 seconds with a link "up" probability of 0.995. Result of network 1 in Table 2 indicates that, with no NC opportunity (no common intermediate node among different flows), delivery in a traditional network achieves the same performance as transmission in a coded network. Results of network 2 and network 3 in Table 2 show that, with NC opportunity, delivery in coded networks results in higher path flow rate and lower path "up" probability than the case in traditional networks. Fig.6 and Fig.7 show the reconstructed images of the traditional network 2 and the coded network 2, respectively, when the delay constraint is 0.1 seconds. With wireless network coding performed at intermediate nodes, the coded network 2 has a larger traffic delivery capacity compared with the traditional network 2. Therefore image delivered in the coded network 2 is associated with a larger description size resulting in a higher PSNR value. Although NC increases path flow rate at a price of decodability, smaller overall expected distortion can be achieved with NC, when "up" probability of link has a reasonable high value of 0.995.

Fig.8 shows performance comparison of the traditional network 2 and the coded network 2 with varying link "up" probability between [0.86, 1], where identical routing decisions are used in these networks as shown in Table 2. It can be seen from the figure that NC with opportunistic listening improves end-to-end performance at a high link "up" probability, but worsens the end-to-end performance at a relatively low link "up" probability. The observed result is reasonable, as a native unmixed flow can be decoded if this flow is successfully received, while the successful decoding of a mixed flow requires correct overhearings besides successful receipt of the mixed flow. If a coded network is in a bad condition, an increase in the flow rate at a huge price of decodability is not worthwhile. In this case, we can further improve the performance of routing MDC with

NC by designing an MDC multipath routing that allows intermediate nodes to perform NC operations conditionally. Currently in this paper, MDC multipath routing problem is formulated for coded networks with a

**Table 2.** End-to-End Performance Comparison Using the Same Routing Decision in the Two Types of Networks

| | | Path 1 for Session 1 | | Path 2 for Session 1 | |
|---|---|---|---|---|---|
| | | Path | "up" Probability (%) | Path | "up" Probability (%) |
| Network 1 | W/O NC | 0→2→1 | 99.00 | 0→14→8→1 | 98.51 |
| | With NC | 0→2→1 | 99.00 | 0→14→8→1 | 98.51 |
| Network 2 | W/O NC | 13→6→2→0 | 98.51 | 13→10→12→0 | 98.51 |
| | With NC | 13→6→2→0 | 98.01 | 13→10→12→0 | 98.01 |
| Network 3 | W/O NC | 11→4→5→6→7 | 98.01 | 11→9→0→7 | 98.51 |
| | With NC | 11→4→5→6→7 | 97.04 | 11→9→0→7 | 98.51 |

| | | Path 1 for Session 2 | | Path 2 for Session 2 | | Maximum Flow Rate (Mb/s) | Average PSNR (dB) |
|---|---|---|---|---|---|---|---|
| | | Path | "up" Probability (%) | Path | "up" Probability (%) | | |
| Network 1 | W/O NC | 3→1→13 | 99.00 | 3→9→13 | 99.00 | 0.17 | 30.30 |
| | With NC | 3→1→13 | 99.00 | 3→9→13 | 99.00 | 0.17 | 30.30 |
| Network 2 | W/O NC | 5→2→6 | 99.00 | 5→10→6 | 99.00 | 0.21 | 31.14 |
| | With NC | 5→2→6 | 99.00 | 5→10→6 | 98.51 | 0.29 | 31.81 |
| Network 3 | W/O NC | 7→6→5→4 | 98.51 | 7→6→5→9→4 | 98.01 | 0.16 | 30.01 |
| | With NC | 7→6→5→4 | 97.52 | 7→6→5→9→4 | 98.01 | 0.17 | 30.29 |

Note: "Lena.bmp" is delivered within 0.1 seconds with a link "up" probability of 0.995.

(a) (b) (c)

Fig.6. Possible reconstructed images using the obtained routing decision in Table 2 for network 2 without NC. The probabilities of obtaining these images are 1.47%, 1.47%, 97.04% for unicast session 1 and 0.99%, 0.99%, 98.01% for unicast session 2, respectively. (a) PSNR = 27.74 dB. (b) PSNR = 27.74 dB. (c) PSNR = 31.23 dB.

(a) (b) (c)

Fig.7. Possible reconstructed images using the obtained routing decision in Table 2 for network 2 with NC. The probabilities of obtaining these images are 1.95%, 1.95%, 96.06% for unicast session 1 and 1.47%, 0.99%, 97.52% for unicast session 2, respectively. (a) PSNR = 28.93 dB. (b) PSNR = 28.72 dB. (c) PSNR = 32.59 dB.

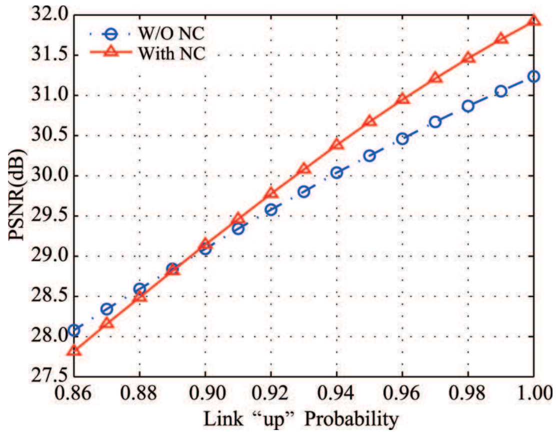


Fig.8. End-to-end PSNR performance comparison using identical routing decisions for the traditional network 2 and the coded network 2, where "Lena.bmp" is delivered within 0.1 seconds with varying link "up" probability.

high link "up" probability where the performance of wireless NC with opportunistic listening is guaranteed, and an intermediate node performs NC whenever an NC opportunity appears.

### 5.3 Performance of Interference-and-Coding-Aware Multipath Routing

In this subsection, link "up" probability is fixed to a reasonable high value 0.995 to ensure the performance of NC with opportunistic listening. Different MDC multipath routing methods are used to generate paths for two MDC unicast sessions in a coded wireless network. Each session is not aware of delivering content on the other session. These two MDC unicast sessions deliver descriptions in opposite directions, where NC opportunities are likely to exist among different sessions through proper path selection. In the real network traffic today, NC opportunities can be found easily between unicast traffic in large networks or with a large number of unicast sessions.

Interference-and-coding-aware MDC multipath routing in Section 4 is compared with $k$-shortest paths[37], MDC multipath routing without considering interference[18], and interference-aware MDC multipath designed for traditional wireless networks. All the simulation results below are obtained in coded wireless networks. An intermediate node in such networks performs COPE-type wireless NC whenever a coding opportunity arises. Paths within five hops for the coded network 1 and network 3, and paths within four hops for the coded network 2 are exhaustively searched to obtain results. Maximum flow rate on each path can be obtained using linear programming after scheduling wireless links along four paths for two MDC unicast sessions. Table 3 shows the routing decisions and performance comparison of four algorithms in transmitting "Lena.bmp" within 0.1 seconds, with end-to-end performance comparison of transmitting "Lena.bmp" at varying delay constraint summarized in Fig.9. It can be seen that the interference-and-coding-aware MDC multipath routing can at least perform as well as the other three routing methods, better than them most of the time in terms of average expected distortion by considering both wireless interference and NC opportunity.

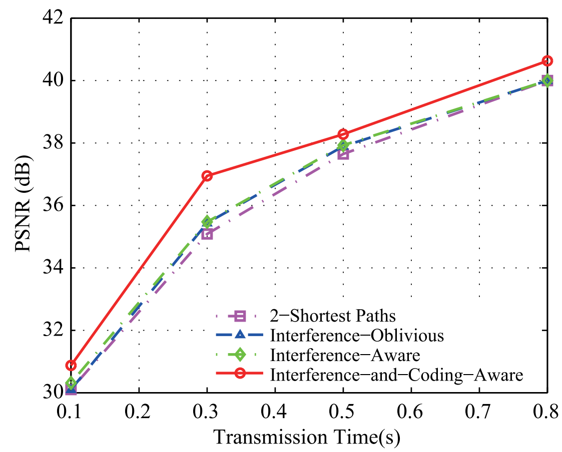


Fig.9. End-to-end PSNR performance comparison in delivering "Lena.bmp" with varying delay constraint in the coded wireless network 1.

## 6 Conclusion

In this paper, we investigated path selection problem for two-description coded images in two types of wireless networks. In these networks, wireless interference is an important factor affecting optimal path selection, which is not explicitly or adequately addressed in most existing work of MDC multipath routing. For traditional wireless networks with no coding capability at intermediate nodes, we formulated an interference-aware MDC multipath routing under a protocol model of interference. Time-division link scheduling is employed to eliminate interference. The proposed interference-aware MDC multipath routing generates optimal paths that maximize the average decoded quality. In a coded wireless network with coding capability at intermediated nodes, we considered and evaluated COPE-type wireless NC with opportunistic listening, while delivering MDC descriptions of multiple unicast sessions. By exploiting wireless broadcast nature, several output links of an intermediate node can be treated as a broadcast link with NC. Similarly, using a time-division broadcast link scheduling method, interference-and-coding-aware MDC multipath routing takes into account of both minimizing side effect of wireless interference avoidance and maximizing NC opportunity, two of which request

**Table 3.** End-to-End Performance Comparison in the Three Coded Wireless Networks

| | | Path 1 for Session 1 | Path 2 for Session 1 | Path 1 for Session 2 | Path 2 for Session 2 | Maximum Flow Rate (Mb/s) | Average PSNR (dB) |
|---|---|---|---|---|---|---|---|
| Network 1 | 2-shortest paths | 0→2→1 | 0→13→1 | 3→1→13 | 3→9→13 | 0.16 | 30.09 |
| | Interference-oblivious | 0→2→1 | 0→13→1 | 3→1→13 | 3→9→13 | 0.16 | 30.09 |
| | Interference-aware | 0→2→1 | 0→14→8→1 | 3→1→13 | 3→9→13 | 0.17 | 30.30 |
| | Interference-and-coding-aware | 0→2→1 | 0→14→8→9→1 | 3→9→2→0→13 | 3→9→13 | 0.19 | 30.85 |
| Network 2 | 2-shortest paths | 13→6→2→0 | 13→10→2→0 | 5→2→6 | 5→10→6 | 0.20 | 30.87 |
| | Interference-oblivious | 13→6→2→0 | 13→10→2→0 | 5→2→6 | 5→10→6 | 0.20 | 30.87 |
| | Interference-aware | 13→6→2→0 | 13→10→12→0 | 5→2→6 | 5→10→6 | 0.29 | 31.81 |
| | Interference-and-coding-aware | 13→6→2→0 | 13→10→12→0 | 5→2→6 | 5→10→6 | 0.29 | 31.81 |
| Network 3 | 2-shortest paths | 11→1→5→0→7 | 11→9→0→7 | 7→0→5→4 | 7→0→9→4 | 0.10 | 29.02 |
| | Interference-oblivious | 11→4→5→6→7 | 11→9→5→6→7 | 7→6→5→4 | 7→6→5→13→4 | 0.16 | 30.02 |
| | Interference-aware | 11→4→5→6→7 | 11→9→0→7 | 7→6→5→4 | 7→6→5→9→4 | 0.17 | 30.29 |
| | Interference-and-coding-aware | 11→4→5→6→7 | 11→13→5→6→7 | 7→2→6→5→4 | 7→6→5→4 | 0.19 | 30.67 |

Note: "Lena.bmp" is delivered within 0.1 seconds with a link "up" probability of 0.995.

dissimilar path selections. In this way, an optimal trade-off is stricken to yield path selection with minimum distortion of reconstructed images. Simulation results under our analytical formulations have shown effectiveness of the proposed MDC multipath routing in the two types of networks for achieving end-to-end distortion reduction in a prescribed time.

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