

Mesh Routing for Error Resilient Delivery of Multiple-Description Coded Image/Video Content

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Abstract—Multiple Description (MD) source coding is a technique that breaks a media stream into equally important sub-streams which can be sent over different paths for protection against channel errors in wireless networks. In this paper, we explore the possibility of sending the descriptions through different paths and intermediately merging them to exploit recovery of the corrupted descriptions from the uncorrupted ones before reaching the destination, thereby increasing the quality of received media at the destination. We first analytically model the end-to-end distortion of MD coded multipath transmission as a function of the path parameters and prove that intermediate recovery achieves an improvement of up to 9.2% in end-to-end distortion compared to traditional multipath transport. We then formulate the mesh route construction as a cross-layer optimization problem. Since the problem is highly complex, we propose an efficient heuristic routing strategy. We show that using this routing strategy, good paths (with up to 2 intermediate recovery nodes) can be constructed to achieve a lower distortion compared to the case without intermediate recovery.

Index Terms—Multiple description coding, multipath routing, intermediate recovery, multi-hop wireless networks

I. INTRODUCTION AND MOTIVATION

Wireless ad hoc networks have the characteristics of being scalable and dynamic and hence are widely popular in the present day. The nodes themselves form a network, behaving as source/destination/routers wherever necessary. However, the wireless communication channel is highly unreliable and error prone. The transmission of content-rich multimedia, with delay-sensitive information, is challenging because retransmission of error prone packets is infeasible. Further, due to the techniques used in compression of video, an error in one frame is propagated to many frames. Finding suitable coding techniques in order to provide protection against the unreliable channels is a widely researched area.

Multiple Description Coding (MDC) is a source coding technique that splits the media streams into equally important sub streams and transmits them to the destination through different paths. Any subset of the descriptions can be used to decode the stream, and the quality of the received data depends on the number of received sub-streams. When the descriptions are sent over disjoint multipath, the transmission errors tend to be independent. In [1], it was shown that multi-stream coding with multipath transport (MPT) is an effective means to overcome the transmission errors in ad hoc networks. A comprehensive review of several contemporary MDC techniques for video was presented in [2].

In the MDC schemes, the descriptions are constructed in a way to have some of correlation (artificial or natural) among them, such that at the receiver the corrupted descriptions can be reconstructed using the uncorrupted ones. Instead of recovering the lost descriptions at the destination (as in Fig. 1(a)), if one can do it intermediately, there is a high

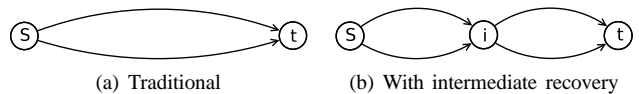


Fig. 1. Examples of MD coded transmission over multiple paths.

chance that the recovery performance will improve. If we were to construct paths for transmitting all the descriptions in such a way that they are edge disjoint but merge at specific nodes (as in Fig. 1(b)), we could use the correlation information among the packets to reconstruct the corrupted packets. The intermediate recovery concept was explored in [3] by using a spatial interpolation technique on lost descriptions. However, the routing performance and optimization studies over random network topologies, which we consider a critical practical consideration for image/video content delivery over multihop mesh networks, were not conducted. Also, the performance gain was not backed up by any analysis, and the signal errors due to wireless channel properties were not accounted. Overall, to our best knowledge a detailed analytic study on the MD coded transmission over meshed multipath routes in an ad hoc network to optimize the cost performance of image/video content delivery has not been done in the literature.

In this paper, we explore the optimal mesh routing strategy in a random network setting for efficient delivery of MD coded image/video data. Specifically, we investigate via mathematical analysis and cross layer optimization the gain associated with multipath routing strategy over wireless ad hoc network for a reduced distortion in end-to-end delivery of image/video content. Our key contributions are as follows: (i) We first develop an analytical model to quantify the quality of image/video content delivery in a fading channel environment in terms of mean square error (MSE) distortion in an MDC-MPT system with intermediate recovery. (ii) We then present a cross-layer optimization formulation for meshed multipath route construction to aid intermediate recovery. (iii) We also propose an intermediate recovery aware heuristic route construction technique for a two description (2D) MDC system. We show that the performance gain with intermediate recovery is higher when the error correction capability of the coding scheme is increased. Our analytic results indicate that, having one recovery stage leads to about 9% decrease in the end-to-end distortion. Our mesh routing study in a random network environment verifies our analytic claim, where it is also shown that the intermediate recovery performance gain increases with network density.

II. DISTORTION ANALYSIS

We consider a 2D MDC for image/video transmission because most of the popular MDC techniques used currently are

2D systems. Our consideration on 2D system is also motivated by [4], where the authors demonstrated that the increase in performance gain slows down significantly as the number of descriptions is increased beyond two. The quality of video at the destination can be suitably described using MSE distortion as the performance metric.

In [5], the end-to-end distortion of MDC-MPT system was modeled as a function of link bandwidth, packet loss probability, minimum delay between two nodes, and delay jitter. In [6], the distortion was modeled as a function of available bandwidth of a link, probability that a link is up, average burst length for the packets, and rates of coding. In contrast to the approaches in [5], [6], we model the MDC-MPT system with intermediate recovery using various physical layer wireless link parameters in a meshed network scenario.

In a 2D MDC system, let d_0 , d_1 , d_2 , and d_3 be the respective distortion values when at the destination both the descriptions are available for decoding, only description 1 is available, only description 2 is available, and none are available. Denoting the corresponding occurrence probabilities as P_{00} , P_{01} , P_{10} , and P_{11} , the average end-to-end distortion is given by:

$$D = P_{00}d_0 + P_{01}d_1 + P_{10}d_2 + P_{11}d_3 \quad (1)$$

For analysis of the 2D MDC-MPT performance, we consider a technique for video, called multiple description transform coding (MDTC) [7]–[9]. In this form of MDC, some amount of redundancy is introduced in the two (uncorrelated) descriptions so as to correlate them. One description can be recovered from the other using the correlation information. Intermediate recovery system would achieve a lower distortion as compared to the traditional one, irrespective of the coding technique used, as long as the condition $d_0 \ll d_1, d_2 \ll d_3$ holds. In any MDC scheme, the distortion introduced when no descriptions are lost is much less than the distortion when one description is lost. But, the method of recovery of a lost description and the associated amount of distortion introduced depend on the particular scheme in hand.

A. Network model:

We model a network (say, a mobile ad hoc network) as a stochastic directed graph $G(V, E)$, where V is the set of nodes and E is the set of edges. The nodes are numbered from 1 to n . A directed edge from node i to j is denoted by (i, j) . Let the cost (in terms of delay) associated with using the edge (i, j) be c_{ij} . Let the respective paths taken by descriptions 1 and 2 be \mathcal{P}_1 and \mathcal{P}_2 . For the analytic exposition, we assume the number of nodes encountered by the two descriptions (i.e., the number of hops) along the source-to-destination path are equal. If there are N intermediate recovery nodes from a source to its destination for a given path pair, each of the paths in the pair is divided into $N + 1$ segments. A segment is a path fraction between a source (respectively, an intermediate recovery node) to an intermediate recovery node (respectively, the destination). The k th segment in the l th path is denoted by H_k^l , for $k = 1$ to $N + 1$, $l = 1, 2$.

We account for small-scale Rayleigh fading in every link (i, j) , wherein the signal experiences rapid fluctuations in a small period of time or space. We also assume the fading to be a slowly-varying process with respect to the data transmissions rate. In this case the success/failure of consecutive bits of data

are not independent. It was shown [10], the transmission errors in such a fading channel follow a two state Markov model. The channel can be seen as a two state Gilbert Channel, with states Good (G) and Bad (B) (see Fig. 2(a)). For simplicity of the analysis we assume bit error probability in Good state is 0 and that in Bad state is 1. Over a link (i, j) , if a_{ij} is the transition probability from Good to Bad state and that from Bad to Good state is b_{ij} , with fading margin F (the power threshold above which decoding process is assumed error free), Doppler frequency f_d , and sampling interval T , we have the steady state link error probability as [10]:

$$\phi_{ij} = 1 - \frac{b_{ij}}{a_{ij} + b_{ij}} = 1 - e^{-\frac{1}{F}},$$

$$b_{ij} = \frac{Q(\theta, \rho\theta) - Q(\rho\theta, \theta)}{e^{1/F} - 1}.$$

Here Q is the Marcum- Q function, $\theta = \sqrt{\frac{2/F}{1-\rho^2}}$, and $\rho = J_0(2\pi f_d T)$. f_d depends on the relative velocity between the nodes i and j , v , and the signal wavelength λ as: $f_d = \frac{v}{\lambda} \cos \phi$, where ϕ is the angle of incidence of the wave with respect to the relative movement direction of the receiver.

B. Description error probability:

We consider a 2D transmission scenario, where the two transmission paths are designated by the superscript l ($= 1, 2$). A description packet is corrupted and unusable when more than τ bits in a packet are in error. This threshold τ depends on the error correction capability of the coding scheme. Referring to Fig. 2(a), over a link (i, j) , the fraction of time spent in Bad state is ϕ_{ij} . Since the transmission across the segment

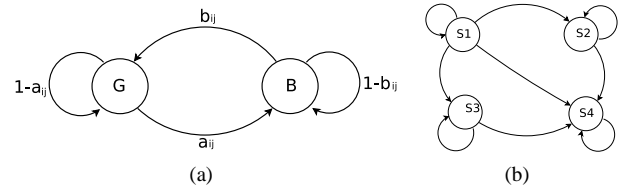


Fig. 2. (a) Gilbert channel model, (b) Intermediate recovery system state transition diagram.

H_k^l , $k = 1$ to $N + 1$, $l = 1, 2$, is successful only if all the links $\{(i, j) \in H_k^l\}$ are in Good state, the $2^{|H_k^l|}$ channel states (two corresponding to each link) can be lumped in one Good and one Bad state. The aggregated Bad state corresponds to all the cases where there is at least one link in Bad state. Let the transition probability from the aggregated Good state to aggregated Bad state, aggregated Bad state to aggregated Good state, and the fraction of time spent by the segment H_k^l in the aggregated Bad state be a_k^l , b_k^l , and ϕ_k^l , respectively. The transition probabilities of the aggregate model are obtained as follows:

$$a_k^l = 1 - \prod_{(i,j) \in H_k^l} (1 - a_{ij}), \quad (2a)$$

$$\phi_k^l = 1 - \prod_{(i,j) \in H_k^l} (1 - \phi_{ij}), \quad (2b)$$

$$b_k^l = \frac{(1 - \phi_k^l) a_k^l}{\phi_k^l} \quad (2c)$$

Say, an error correction code can resolve upto τ errors in a description. Then a description is considered useless if the total number of bit errors in it is greater than or equal to τ . If there are a total of n_t bits in the description, let the probability of n_f of those flipping be denoted by $P(n_f, n_t)$. The expression for $P(n_f, n_t)$ in terms of Gilbert channel parameters was obtained in [11]. The probability that a description is corrupted is given by:

$$Pr(errors \geq \tau) = \sum_{n_f=\tau}^{n_t} P(n_f, n_t) \quad (3)$$

C. Modeling of MDC-MPT with intermediate recovery:

The error state model of the intermediate recovery system is represented by the state transition diagram in Fig. 2(b). The states of the system at an intermediate recovery node can be: S1 (both descriptions are uncorrupted/recoverable), S2 (description 1 is uncorrupted/recoverable and description 2 is corrupted/unrecoverable), S3 (description 2 is uncorrupted/recoverable and description 1 is corrupted/unrecoverable), and S4 (both the descriptions are corrupted/unrecoverable).

The system begins at state S1 at the source. If along the path between source and the next intermediate recovery node one of the descriptions gets corrupted beyond recovery, the system moves into S2 or S3 (depending on which description is lost). If both the descriptions are lost simultaneously the system moves to S4. Once the system moves to either S2 or S3, the system can either stay in itself or go to S4. If the system reaches state S2 or S3, the lost description is estimated and transmitted. This estimated description is in a way the best estimate of the lost original description given the other, and is a duplicate of the original uncorrupted description. The system cannot go back from S2/S3 to S1 because there is loss of information which can be only partially recovered by the estimate. Once the system reaches S4, it remains there for all subsequent state transition opportunities, in which case the mean of the data is transmitted in place of the data itself here. If the probability of loss of a description in a segment H_k^l is P_k^l , for $k = 1$ to $N + 1$, $l = 1, 2$, the transition probability matrix U_k is given by:

$$\begin{pmatrix} (1 - P_k^1)(1 - P_k^2) & P_k^2(1 - P_k^1) & P_k^1(1 - P_k^2) & P_k^1 P_k^2 \\ 0 & 1 - P_k^1 P_k^2 & 0 & P_k^1 P_k^2 \\ 0 & 0 & 1 - P_k^1 P_k^2 & P_k^1 P_k^2 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The value of P_k^l can be obtained from (2) and (3). The transition probability matrix U for the overall path is given by

$$U = \prod_{k=1}^{N+1} U_k$$

Since the system starts in state S1 at the source, P_{00} , P_{01} , P_{10} , and P_{11} are given by the elements of first row of U taken in order of the column number. With this formulation of end-to-end description error probability over a given pair of paths, we address the mesh route construction problem in the next section.

III. MESHED MULTIPATH CONSTRUCTION FOR ROUTING

We formulate the multipath construction for intermediate recovery as a cross-layer optimization problem in which the objective is a complex function of several parameters of the wireless channel.

A. Optimization problem formulation

Let $D = [d_0 \ d_1 \ d_2 \ d_3]$ and $P = [P_{00} \ P_{01} \ P_{10} \ P_{11}]$. Two flow variables x_{ij}^l , $l = 1, 2$ for every $(i, j) \in E$ are introduced:

$$x_{ij}^l = \begin{cases} 1 & \text{if } (i, j) \in \mathcal{P}_l, \\ 0 & \text{otherwise} \end{cases}$$

where \mathcal{P}_l is the path taken by the corresponding description. Also define a set S which contains all the intermediate recovery nodes and the source as follows:

$$S = \left\{ i : \sum_{l;j:(i,j) \in E} x_{ij}^l = 2 \right\}$$

Any path in the network can be characterized using the introduced variables. Through out this section we assume that the processing delay experienced at every node is negligible. This is a reasonable assumption owing to the high processing capability current routers have. In practice, the time taken by both the descriptions to reach the recovery node is different. This means that the description that has arrived earlier has to wait for the other description to arrive so that the process of recovery can begin. Therefore, the total source (s) to destination (t) end-to-end delay is:

$$\text{Delay} = \sum_{k=1}^{N+1} \max \left\{ \sum_{(i,j) \in H_k^1} c_{ij}, \sum_{(i,j) \in H_k^2} c_{ij} \right\}$$

We now state the path construction problem OPT-DIST as:

$$\begin{aligned} & \text{Minimize: } \mathcal{D} = DP' \\ \text{s.t. } & \sum_{j:(i,j) \in E} x_{ij}^l - \sum_{j:(i,j) \in E} x_{ji}^l = \begin{cases} 1, & i = s, i \in V, l = 1, 2 \\ -1, & i = t, i \in V, l = 1, 2 \\ 0, & \text{otherwise} \end{cases} \\ & \sum_{j:(i,j) \in E} x_{ij}^l = \begin{cases} \leq 1, & \text{if } i \neq t, i \in V, l = 1, 2 \\ 0, & \text{if } i = t, i \in V, l = 1, 2 \end{cases} \\ & x_{ij}^1 x_{ij}^2 = 0, \forall (i, j) \in E \\ & |S| = N + 1 \\ & x_{ij}^l \in \{0, 1\}, \forall (i, j) \in E, l = 1, 2 \\ & \text{Delay} < T \end{aligned}$$

where P' is the transpose of matrix P . The first constraint defines the flow for each particular description at source, destination, and other nodes over each of the paths. The difference between the outgoing and incoming flow (for each description) is negative at the destination and positive at the source. At all other nodes, whether they are recovery nodes or not, this difference is zero. The second constraint enforces the fact that, at the destination there is no outgoing flow (for each description). It also makes sure that at all nodes other than the destination, the outgoing flow (for each description) is less

than one. These two constraints are required to obtain simple paths. The third constraint ensures that the paths obtained are link disjoint (since a link can be used by only one of the two descriptions at a time along its path, the product of the flow variables over link is zero). Almost all multimedia applications related to video are delay sensitive. Hence the last constraint.

Similarly, to minimize delay subject to a constraint on distortion, an optimization problem OPT-DELAY can be defined.

The objective function in the above optimization problem is highly complex function of the path parameters. More specifically, OPT-DIST is a complex ratio of higher order exponentials in path variables with non-linear constraints. In Section III-B, a simple heuristic routing strategy is discussed that gives paths with a low distortion.

B. Development of a practical routing strategy

The routing strategy that we develop is based on the intuitive understanding that the distortion should increase with the number of hops traversed by the description from the source to destination. Fig. 3 shows the distortion plotted for the Doppler spread and symbol duration product $f_d T_s = 0.0004128$, $F = 25$ dB for symmetric paths (without any intermediate recovery nodes) ranging from 0 to 30 hops. It can be seen that the distortion clearly increases with the number of hops. In this paper we omit the rigorous proof of the result. So,

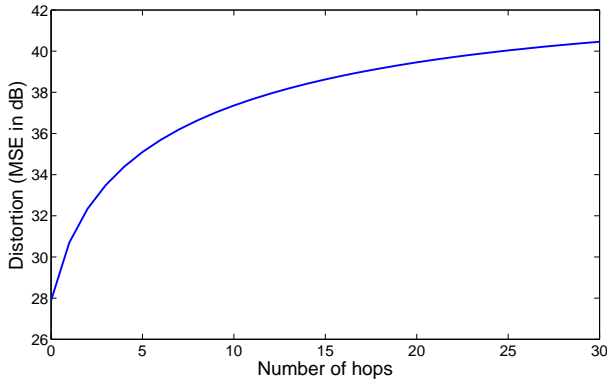


Fig. 3. Variation of distortion with the number of hops. $F = 25$ dB, $f_d T_s = 0.0004128$, $L = 1000$ bits, $\tau = 25$ bits.

considering a homogeneous error rate encountered along each link across the network, a path pair that minimizes the total number of hops taken by both the descriptions would be a good path that gives a low distortion.

An algorithm was developed in [12] to compute k -disjoint paths from a source s to a destination t in a non negatively weighted directed graph that have the minimum total cost (sum of costs of all links in the path pairs) using k Dijkstra's like computations. The above algorithm was later modified in [13] to calculate two disjoint paths with a minimum total length from a node to all other nodes in the network using a simple single Dijkstra like computation, i.e., in $O\left(m \log_{1+\frac{m}{n}} n\right)$ time where m is the number of edges and n is the number of nodes in the network. Since Dijkstra's algorithm can be implemented in $O\left(\min\left\{m + n \log n, m \log \log C, m + (n \log C)^{0.5}\right\}\right)$, where C represents the largest edge cost in graph G , using

the technique in [13], the disjoint path problem from a single node to all destinations with total minimum cost can be solved in the same time. There is a parallel version [14] that implements the same algorithm in $n^3/\log n$ processors and $O(\log^2 n)$ time. A distributed algorithm was presented in [15] to compute shortest disjoint pair of paths from s to t with an implementation on a network having unit edge costs, achieving communication and time complexities $O(m + \Delta n)$ and $O(\Delta_2)$, respectively, where Δ is the network diameter, and Δ_2 is the maximum over all nodes i , of the total number of links in the shortest pair of disjoint paths from i to t .

Algorithm 1 Routing Strategy: MIN-DIST

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H ▷ It is the array containing the shortest pair of disjoint
paths from every node to every other node in G
procedure FINDPATH(G, s, t, N)
  minDist ← −1
  path ← NULL
  for all ( $v_1, \dots, v_N$ ) ∈  $V^N$ ,  $v_i \neq v_j, \forall i \neq j, v_i \neq s, t$  do
    currPath ← {H[s][v1], H[v1][v2], ⋯, H[vN][t]}
    currDist ← Distortion(currPath)
    if minDist == −1 || currDist ≤ minDist then
      path ← currPath
      minDist ← currDist
    end if
  end for
  return path
end procedure

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Algorithm 1 captures the developed heuristic routing strategy MIN-DIST. It is based on initially calculating the shortest pair of disjoint paths (in terms of number of hops) between all pairs of nodes in the network. This information is passed onto all the nodes. A node thereafter iterates over all possible N -tuples (for N intermediate recovery nodes) to find the tuple that minimizes distortion. The matrix H in MIN-DIST can be computed in $O(nS(n, m))$ time if $S(n, m)$ is an efficient upper bound for Dijkstra's computation. This cost is incurred only once in the initial stages. The iteration step takes $O(n^N)$ time. Clearly, if the number of intermediate recovery nodes is increased, the iteration step becomes more time consuming.

A heuristic routing strategy MIN-DELAY that minimizes delay can be designed in a similar fashion as MIN-DIST. The shortest pair of disjoint paths are the paths having a minimum total end-to-end delay in this case.

C. Possible improvements

If the number of nodes in a network is very large, the above routing technique is not suitable as it iterates over all possible combinations of intermediate recovery nodes. If we knew the ideal location of these nodes before hand, the complexity could be reduced significantly. The ideal position of these nodes between the source and destination that minimizes the distortion is studied in this section.

Consider the case of a single intermediate recovery node between source-destination pair. If this recovery node is placed close to the source, the descriptions in error can be recovered quickly. However, there is a high chance of corruption in the long distance between the recovery node and the destination. So, intuitively, the intermediate recovery nodes should be

placed equidistant from the source and the destination. In this paper, the analytical proof is presented for the two simple cases. In both the cases, we assume that there is only one intermediate recovery node at r hops away from the source, and the paths from the source to destination for both the descriptions are homogeneous in terms of error rate and have equal (κ) number of hops. In a symmetric MDC, the two descriptions are equally important and hence the loss of description 1 or description 2 results in the same amount of distortion.

1) *Case 1: When the probability of corruption of a description is constant and the channel is memoryless:* For the sections of path between source-to-intermediate recovery node and intermediate recovery node-to-destination, let the probabilities of corruption of a description be P_1 and P_2 . If p is the probability of corruption of a description on a single hop, $P_1 = 1 - (1 - p)^r$, $P_2 = 1 - (1 - p)^{\kappa - r}$. End-to-end distortion \mathcal{D} as a function of r in terms of P_1 and P_2 is:

$$\begin{aligned} \mathcal{D}(r) = & (1 - P_1)^2(1 - P_2)^2 d_0 + [P_1^2 + P_2^2 - P_1^2 P_2^2] d_3 \\ & + 2[(1 - P_1)(1 - P_2)(P_1 + P_2)] d_1 \end{aligned}$$

The value of p can be obtained as a special case from the Gilbert channel model (using (2) and (3)).

In order to find the minimum, $\mathcal{D}(r)$ is treated as a continuous function of r in the interval $[1, \kappa]$. It can be easily shown that $\frac{d\mathcal{D}(r)}{dr}$ has a zero at $r = \frac{\kappa}{2}$ and the sign of double derivative of \mathcal{D} with respect to r is positive for $d_3 \gg d_1$.

2) *Case 2: Description contains $L > 1$ bits, error threshold τ is 1:* This case corresponds to a situation in which the description is discarded whenever there is a bit error. With the assumption of homogeneous error rate along all links, $a_{ij} = a$; $b_{ij} = b \forall (i, j) \in E$. Let $p = \frac{a}{a+b}$. Then, the corruption probabilities of the descriptions P_1 and P_2 are given by $P_1 = 1 - (1 - p)^r (1 - a)^{(L-1)r}$, $P_2 = 1 - (1 - p)^{\kappa - r} (1 - a)^{(L-1)(\kappa - r)}$. As in Case 1, it can be easily shown that the first derivative of \mathcal{D} has a zero at $r = \frac{\kappa}{2}$ and the second derivative at that particular value of r is positive under the assumption that $d_3 \gg d_1 \gg d_0$.

3) *Case 3: Packet Contains $L > 1$ bits and error threshold $\tau > 1$:* The analytic proof in this case is lengthy and involved, and hence omitted here. Fig. 4 shows the numerically computed end-to-end distortion, plotted against the position of intermediate recovery node for $\kappa = 11$. Clearly, the distortion is minimized when the recovery node is approximately equidistant between the source and destination.

The proof for a general case with $N > 1$ number of intermediate recovery nodes is straightforward from this point. Given the ideal locations of recovery nodes, instead of iterating over all possible nodes, we can iterate over all nodes in specific locations in the network.

IV. RESULTS AND DISCUSSION

In this section we study the performance of MDC intermediate recovery system in comparison to the traditional MDC-MPT system. Throughout this section we assume that the paths taken by the descriptions are present beforehand. In the numerical results, we assume that the path taken by the description has 33 intermediate nodes and with homogeneous link error rate, i.e., each link has the same Gilbert channel parameters. Unless specified otherwise, we consider a wireless

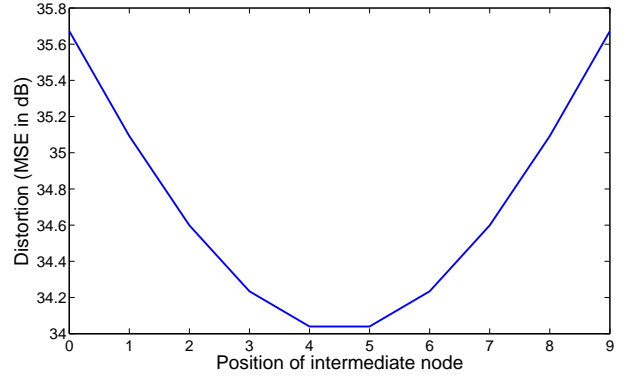


Fig. 4. $F = 25$ dB, $f_d T_s = 0.0004128$, $L = 1000$ bits, $\tau = 25$ bits.

system with each link having a Doppler spread and symbol time product $f_d T_s = 0.0004128$. This corresponds to a system with a Data rate = 13 kbps, carrier frequency = 1850 MHz, and the velocity of the mobile = 120 kmph. The ratio of variances of both the descriptions is taken to be 453. The MDTC transform matrix used is $\begin{bmatrix} \frac{6}{5}, \frac{5}{12}; -\frac{6}{5}, \frac{5}{12} \end{bmatrix}$. The average distortion in (1) is plotted in terms of $10 \log_{10}(\text{MSE})$.

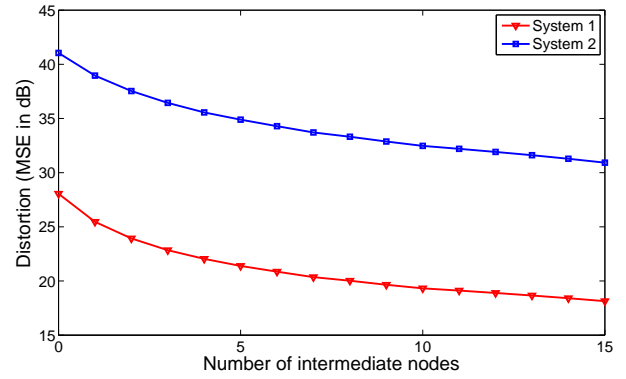


Fig. 5. Variation of average distortion with the number of intermediate recovery nodes.

Fig. 5 shows the average distortion versus number of intermediate recovery nodes for two different system configurations. System 1 corresponds to the default system and System 2 is a system with a data rate = 54 Mbps, carrier frequency = 2.4 GHz, velocity of mobile = 120 kmph. The error threshold τ was taken to be 5% (i.e., 50 bits in a total of 1000 bits). The intermediate recovery nodes were distributed uniformly and symmetrically. The case of zero intermediate recovery nodes corresponds to the traditional MDC-MPT. Compared to the traditional MDC-MPT, the intermediate recovery approach in System 2 offers a gain about 9.2% with one intermediate recovery stage. The gain however reduces as the number of recovery stages increases. For example, with two intermediate recovery stages, the additional gain (over one recovery stage) is about 6%. Fig. 6 shows the average distortion plotted against the fading margin for traditional MDC-MPT and MDC-MPT with one intermediate recovery stage. The error threshold used here was 2.5% (25 bits in a 1000 bit packet). Intermediate recovery works for links with fading margin over 15 dB.

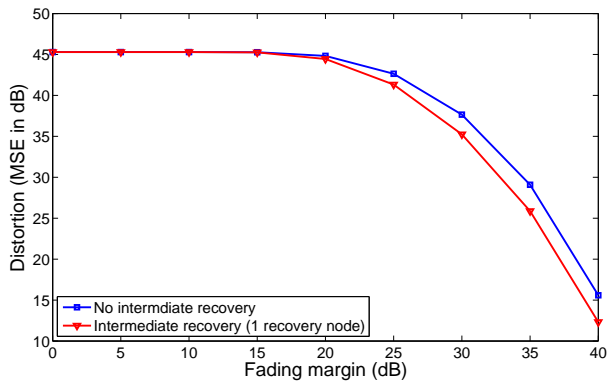


Fig. 6. Comparison of MDC with intermediate recovery with traditional MDC-MPT for different fading margins.

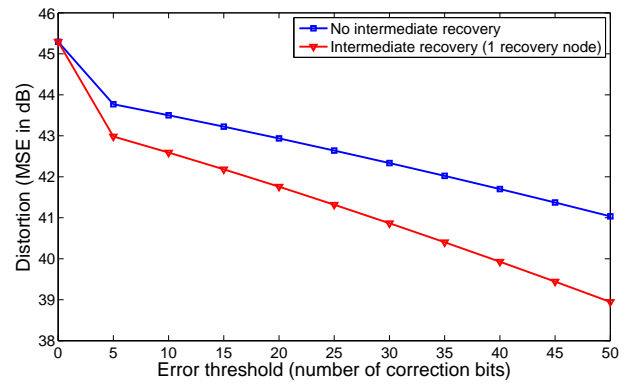


Fig. 8. Comparison of MDC with intermediate recovery with traditional MDC-MPT for different error thresholds τ .

The fraction of time the channel spends in the Bad state of Gilbert model increases with an increase in fading margin. So, for lower fading margins, the probability of losing both the descriptions is high. Intermediate recovery cannot take place when both the descriptions are lost along the way.

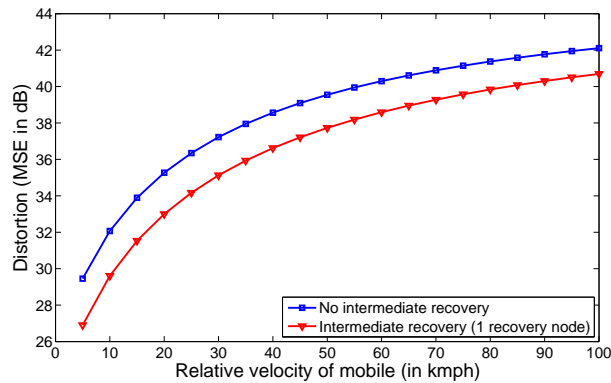


Fig. 7. Comparison of MDC with intermediate recovery with traditional MDC-MPT for different mobile relative speeds.

Fig. 7 shows the average distortion plotted against the different mobile speeds for MDC-MPT and MDC-MPT with one intermediate recovery stage. The error threshold was set to 2.5% (25 bit errors in 1000 bits). If the velocity of the receiver increases the Doppler spread increases, thereby increasing the chance of error. Hence the distortion when it comes to larger velocities is larger. It can be observed from Fig. 7 that the effect of increasing the mobile speed on distortion decreases as we move to higher velocities. Fig. 8 shows the average distortion plotted against the different error thresholds for MDC-MPT and MDC-MPT with one intermediate recovery stage. It is obvious that increasing the error tolerance of the system should decrease the distortion (since we discard the description sooner for a fewer number of bit errors if the threshold is low). However, the MDC with intermediate recovery performs better than traditional MDC, i.e., the distortion has a greater degree of descent in MDC with intermediate recovery.

A. Performance of mesh routing strategy

We implemented the routing strategy on networks of sizes 50, 75, 100, and 150. The nodes were distributed using an

uniform random distribution in a 100×100 square units area. All nodes within 15 units of each other were assumed to be directly connected. The routing strategy was tested for every source-destination pair in which the nodes are at least 60 units apart. Table I shows the % of path pairs that achieve a decrease

TABLE I
PERFORMANCE OF ROUTING STRATEGY (100 NODES).

	% of connections achieving reduction in distortion
From 0 to 1 recovery node	100%
From 1 to 2 recovery nodes	46.875%
From 2 to 3 recovery nodes	0%

TABLE II
PERFORMANCE GAIN FOR ONE INTERMEDIATE RECOVERY STAGE.

Number of nodes	Decrease in distortion
50	0.79 dB
75	0.80 dB
100	0.72 dB

in the distortion when the number of intermediate recovery nodes are increased for 100 nodes. The number of path pairs achieving a decrease in distortion when the intermediate recovery nodes are higher is significantly low. This is mainly because the total number of edges in the path increases as the number of recovery nodes increases the distance between them decreases the edge disjoint paths get longer.

Fig. 9 shows the % of connections for which the routing strategy achieves a reduction in the distortion plotted against different node densities (number of nodes). The routing was tested for all nodes that are at least 30 units apart in this case. The error threshold was taken to be 1%. When the node density is low the routing strategy fails to find suitable edge disjoint paths such that the distortion is decreased. Testing for globally optimum paths to check the efficiency of our routing scheme is not feasible due to its computational complexity. Table II shows the decrease in distortion for a single stage intermediate recovery system when compared to a system in which there is no intermediate recovery (0.5 dB improvement in distortion is discernible in multimedia applications). By the

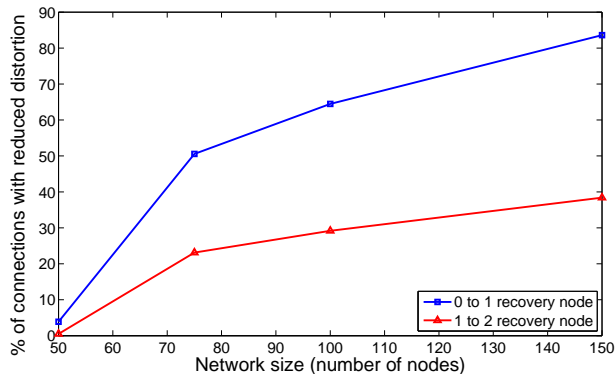


Fig. 9. Performance in intermediate recovery versus network size.

application of a better routing strategy that can find paths that are of equal length as that of a traditional MDC-MPT system, the performance is expected to increase.

B. Effect of randomness on the heuristic algorithms

Intuitively, minimizing the distortion (i.e. total path length) should also minimize the delay. So, it is expected that the path obtained from the MIN-DIST version of the heuristic algorithm will have a reasonably small delay. To test the above hypothesis, a *similarity index* was used. Similarity index at a delay threshold is defined as the percentage of connections having delay less than or equal to that threshold. Fig. 10

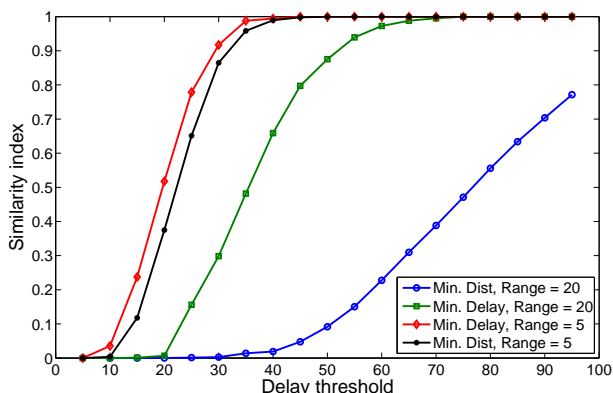


Fig. 10. Similarity index comparison under different network conditions.

shows the similarity index plotted for different variances of link weights of a 150 node network deployed in 100×100 units area. It can be observed that, when the variance is low, minimizing distortion or delay is essentially the same thing. However, when the variance is high, there is a huge gap in the similarity indices. So, in networks that are more random in link performance characteristics, minimizing either of distortion/delay does not guarantee that the other variable is bounded. This observation calls for alternative improved solutions for joint guarantee of delay and distortion bounds.

V. CONCLUSION

In this paper, we studied end-to-end distortion of MDC-MPT systems in a random wireless ad hoc network using physical layer channel parameters, without as well as with

intermediate recovery. Via analytic modeling, we showed that intermediate recovery achieves good performance gains in comparison to the traditional multipath system, and thereby we proved that the proposed intermediate recovery technique can be used for robust transmission of video over multihop wireless networks. We formulated a cross-layer optimization problem to construct meshed multiple paths with either distortion or delay minimization criteria. To reduce complexity, we proposed a simple heuristic routing strategy that gives good quality paths with intermediate recovery stages. To address the practical utility of the proposed routing heuristics in terms of jointly achieving distortion and delay bounds, we further studied the delay (respectively, distortion) performance of the network when distortion (respectively, delay) minimization is targeted under varied link conditions (costs). We observed that, the two minimization criteria are not jointly achieved if the link costs vary widely. We are currently working on genetic algorithm based routing optimization solutions to address the joint delay and distortion optimization under acceptably bounded time complexity.

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REFERENCES

- [1] S. Mao, S. Lin, S. Panwar, Y. Wang, and E. Celebi, "Video transport over ad hoc networks: multistream coding with multipath transport," *IEEE J. Sel. Areas Commun.*, vol. 21, no. 10, pp. 1721–1737, Dec. 2003.
- [2] Y. Wang, A. Reibman, and S. Lin, "Multiple description coding for video delivery," *Proc. of the IEEE*, vol. 93, no. 1, pp. 57–70, Jan. 2005.
- [3] P. De, N. Banerjee, and S. De, "Error-resilient image transmission over multihop wireless networks," in *Proc. COMSNETS*, Bangalore, India, Jan. 2011.
- [4] E. Setton, Y. Liang, and B. Girod, "Adaptive multiple description video streaming over multiple channels with active probing," in *Proc. Intl. Conf. Multimedia and Expo*, Baltimore, MD, USA, Jul. 2003.
- [5] A. Begen, Y. Altunbasak, and O. Ergun, "Multi-path selection for multiple description encoded video streaming," in *Proc. IEEE ICC*, Anchorage, AK, USA, May 2003.
- [6] S. Mao, Y. Hou, X. Cheng, H. Sherali, S. Midkiff, and Y.-Q. Zhang, "On routing for multiple description video over wireless ad hoc networks," *IEEE Trans. Multimedia*, vol. 8, no. 5, pp. 1063–1074, Oct. 2006.
- [7] V. Goyal and J. Kovacevic, "Optimal multiple description transform coding of Gaussian vectors," in *Proc. Data Compression Conf.*, Snowbird, UT, USA, Mar. 1998.
- [8] Y.-C. Lee and Y. Altunbasak, "A collaborative multiple description transform coding and statistical error concealment method for error resilient video streaming over noisy channels," in *Proc. IEEE ICASSP*, Orlando, FL, USA, May 2002.
- [9] V. Goyal, J. Kovacevic, R. Aream, and M. Vetterli, "Multiple description transform coding of images," in *Proc. Intl. Conf. on Image Process.*, Chicago, IL, USA, Oct. 1998.
- [10] M. Zorzi, R. Rao, and L. Milstein, "ARQ error control for fading mobile radio channels," *IEEE Trans. Veh. Technol.*, vol. 46, no. 2, pp. 445–455, May 1997.
- [11] J. R. Yee and E. J. Weldon, Jr., "Evaluation of the performance of error-correcting codes on a Gilbert channel," *IEEE Trans. Commun.*, vol. 43, no. 8, pp. 2316–2323, 1995.
- [12] J. W. Suurballe, "Disjoint paths in a network," *Networks*, vol. 4, no. 2, pp. 125–145, 1974.
- [13] J. W. Suurballe and R. E. Tarjan, "A quick method for finding shortest pairs of disjoint paths," *Networks*, vol. 14, no. 2, pp. 325–336, 1984.
- [14] S. Banerjee, R. K. Ghosh, and A. P. K. Reddy, "Parallel algorithm for shortest pairs of edge-disjoint paths," *J. Parallel Distrib. Comput.*, vol. 33, pp. 165–171, Mar. 1996.
- [15] R. Ogier and N. Shacham, "A distributed algorithm for finding shortest pairs of disjoint paths," in *Proc. IEEE INFOCOM*, Ottawa, Canada, Apr. 1989.