On The Effects of Path Correlation in Multi-Path Video Communications using FEC over Lossy Packet Networks

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***Abstract*—In this paper, we investigate the effect of path correlation on video communications when path-diversity routing techniques are employed together with forward error correction (FEC). We study the statistical properties of packet losses when correlation between paths exists and demonstrate that the effects of path correlation on received video quality depend on various factors, such as the effectiveness of error control strategies (passive error concealment, FEC, etc.) and the existing channel conditions. We demonstrate that, contrary to common belief, path correlation need not be detrimental to the system performance. The results are expected to have some impact on the development of explicit multi-path routing strategies.**

***Keywords*—Path correlation, Joint links, Path diversity, FEC, Channel coding, Error concealment, Video quality.**

I. Introduction

Diversity techniques have been used at the physical layer in wireless communications for many years as a means of improving end-to-end communication performance. Recently, path-diversity-based routing schemes for video transmission have been proposed for packet networks as well [1, 3, 5, 9]. The use of diversity in this case is partly motivated by the observation that if the loss patterns on different paths are independent, then large burst losses are less likely to occur. However, the assumption of path independence is rarely warranted on the Internet. For example, two different Internet paths might share one or more joint links somewhere in the network, which may introduce path correlation between their respective loss processes. To avoid this, methods have been proposed to choose paths with a minimal number of joint links [2, 5].

Most of the proposed schemes (with a notable exception in [4]) assume that correlation among packet losses on different paths (spatial correlation) will degrade system performance. Certainly, this may be true for some specific choices of source coding, error control and transmission schemes, but is it really true in general? Our goal in this paper is to test this assumption using a relatively simple video transmission system that employs a standard H.264 video coder and conventional FEC coding scheme. We hope that such investigation will provide some guidelines for future design of diversity-based multimedia transmission systems. In summary, our results point to the following:

- The effects of path correlation depend on the properties of the video coder, the encoded sequences and the error control methods used (i.e., passive error concealment, intra-updating and FEC coding) – correlation will not always degrade the performance; this observation agrees with the results presented in [4].
- The block error probability distribution of the packet loss process shifts towards the extremes with increasing path correlation – that is, the probability of having a larger number of losses in a given block of packets increases (as also demonstrated in [5]), but so does the probability of having a smaller number of losses in the same block of packets. Due to this shift, path correlation may benefit uncoded transmission or the use of weak FEC codes, while it usually degrades the performance using strong FEC codes.
- On average, path correlation has little effect in the case of sequences in which errors are easy to conceal, such as low-motion scenes, regardless of whether FEC is used or not, while it usually degrades the performance in the case of sequences that are difficult to conceal, such as high-motion scenes, especially under high loss conditions and when stronger FEC codes are used.

The rest of the paper is organized as follows: in Section II, we describe the path correlation model and the transmission scheme we employ in this paper; in Section III, we analyze the effect of path correlation for packet transmission; results of video experiments are presented in Section IV. Finally, we conclude the paper in Section V.

II. Preliminaries

In this section, we first describe the correlation model employed in this paper to investigate the effects of path correlation in diversity-based lossy-packet networks. Then we describe our transmission scheme for the purpose of multi-path video transmission.

A. Path Correlation Model

We assume there are two alternative paths from sender to receiver, each of which is composed of several intermediate links modeled as independent Gilbert channels. If the two paths have no links in common, as shown in Fig. 1(a), the loss processes on the two paths are clearly independent. However, path correlation exists when the two paths share one or more lossy-packet links as shown in Fig. 1(b).

Consider one of the two paths. Let P_L^i and L_B^i be the average packet loss rate and average burst length for the i-th link along the path. Then, because of the independence among all the links on the path, the end-to-end packet loss process of the path consisting of L links can be modeled as a Gilbert channel, with average packet loss rate (P_L) and average burst length (L_B) given by

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$$P_L = 1 - \prod_{i=1}^{L} \pi^i(g), \tag{1}$$

and

$$L_B = (1 - \prod_{i=1}^{L} \pi^i(g)) \Big/ \left(\prod_{i=1}^{L} \pi^i(g) \right) \left(1 - \prod_{i=1}^{L} (1 - p_i) \right), \tag{2}$$

where $\pi^i(g)$ is the steady state probability of being in the reception state for intermediate link i and p_i is the transition probability from the reception state to the loss state [8].

Let random sequences X and Y be the indicator functions for the successful packet reception on the two paths, respectively, where 0 represents packet loss and 1 represents successful packet reception. Then the path correlation is defined as the correlation coefficient between X and Y according to

$$\rho = \frac{\operatorname{cov}(X, Y)}{\sqrt{Var(X) Var(Y)}}. \tag{3}$$

By varying the number of joint links, we can control the correlation between the two paths from 0 to1.

B. Transmission Scheme

We employ a transmission scheme similar to that used in [1]. As shown in Fig. 2, video packets pass through the channel encoder which creates FEC parity packets. The resulting packet stream is split into two substreams consisting of the even- and odd-numbered packets, respectively. The two substreams are then sent over separate paths.

III. Effect of Path Correlation On Packet Transmission

In our simulations we assume there are five (L=5) intermediate links on each of the two paths[1]. Each intermediate link is independently modeled by a Gilbert channel with P_L^i and L_B^i given as 1.44 % and 3.85, respectively. Therefore, according to (1) and (2), the corresponding end-to-end P_L and L_B are 7% and 4, respectively, for each path.

When choosing the appropriate (n, k) block code for FEC, we are interested in the probability that the number of losses in a block of n packets is less than the error-correcting capability of the code. Hence, one of the metrics we use to evaluate the effects of path correlation is the block error probability $P_e(n, k)$ - the probability of having k errors in a block of n packets. We start by examining the patterns of block error probability for packet transmission without channel coding and then examine the case where channel coding is used.

A. Packet Transmission without Channel Coding

In Fig. 3 we show $P_e(20, k)$ for two different values of path correlation, achieved by varying the number of joint links between the two paths. To aid with the explanation, we show the probability mass function (PMF) in the left part of the figure and the cumulative distribution function (CDF) of block errors in the right part of the figure. In Fig. 3 (a), the number of joint links is 5, i.e., the path correlation is 1. Observe that error-free blocks occur more frequently when the paths are correlated - the probability of error-free block in the correlated case is near 0.8

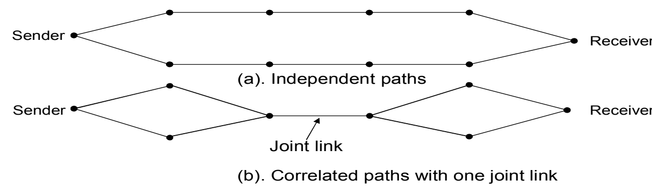


Fig. 1. Path correlation model.

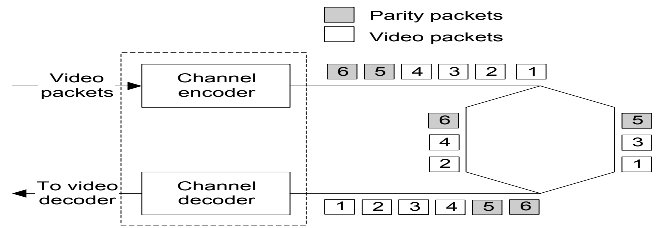
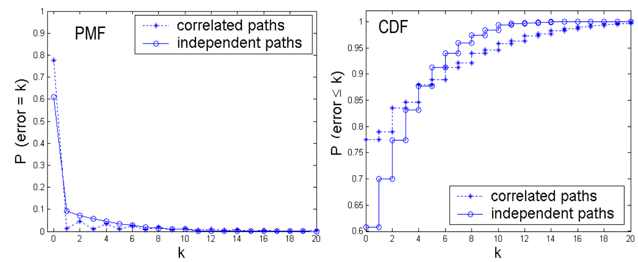
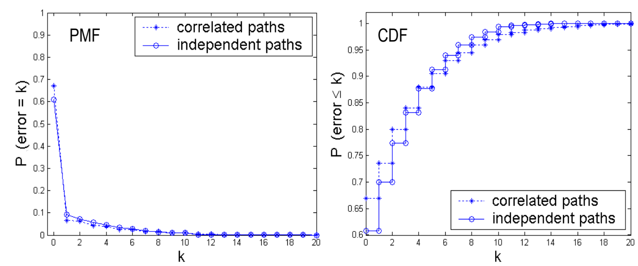


Fig. 2. Transmission scheme.



(a). PMF and CDF for the distribution of blocks with *k* errors; 5-joint links for correlated paths.



(b). PMF and CDF for the distribution of blocks with *k* errors; 2-joint links for correlated paths.

Fig. 3. Distribution of blocks of size 20 with k errors for different degrees of path correlations (P_L=7% and L_B=4).

while for the independent case as also shown in the same figure, it is about 0.6. Indeed, with reference to Fig. 2, when the paths are perfectly correlated we have

$P_e(20, 0) = P(0$ *losses in block of 10 packets on one path*),

while for independent paths we have

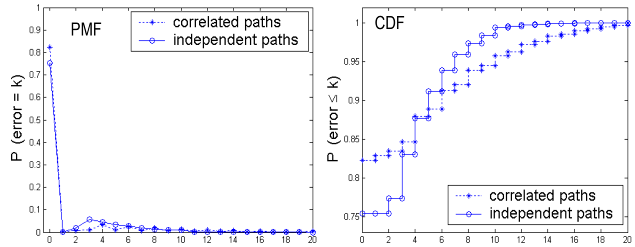
$P_e(20, 0) = P(0$ *losses in block of 10 packets on one path*$)^2$.

On the other hand, the probability of having a large number of losses (e.g., $k > 8$) in a block of 20 packets increases with path correlation compared to the independent case– this is more clearly seen in the CDF plot.

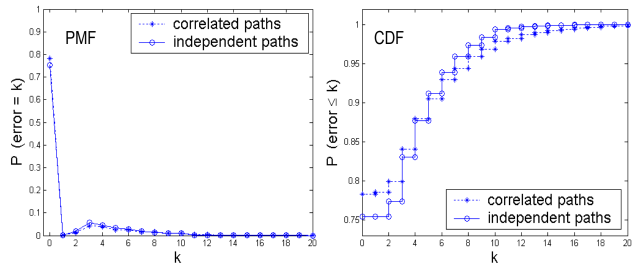
Now consider the CDF plot in Fig. 3 (a). If we were to use a RS(20,18) code whose erasure correcting capability[2] is 2, about 86% of 18-packet information blocks would be error-free after channel decoding in the case of correlated paths, compared to about 77% in the independent case. However, if we use a much stronger RS(20, 10) code, the percentage of error-free blocks would be about 95% in the correlated case, compared to about

[1] In order to simplify the simulation, in this paper we model the intermediate links using independent Gilbert channels each with the same parameters.

[2] The error correcting capability for a RS(n, k) code is $n - k$ provided the positions of lost packets are known.



(a). PMF and CDF for the distribution of blocks with *k* errors; 5-joint links for correlated paths.



(b). PMF and CDF for the distribution of blocks with *k* errors; 2-joint links for correlated paths.

Fig. 4. Distribution of blocks of size 20 with *k* errors for different degrees of path correlations (P_L=7%, L_B=4, RS(22, 20) code).

98% in the independent case. Hence, the performance with weaker codes may be improved if the paths are correlated, while the performance with stronger codes is somewhat degraded.

The plots in Fig. 3 (b) show the results obtained with 2 joint links, corresponding to ρ = 0.383. The trends are similar to those in Fig. 3(a). But as the correlation decreases, the plots of PMF and CDF approach those obtained in the case of independent paths. Therefore, the performance gap between partly-correlated cases and the independent case is getting smaller when path correlation decreases.

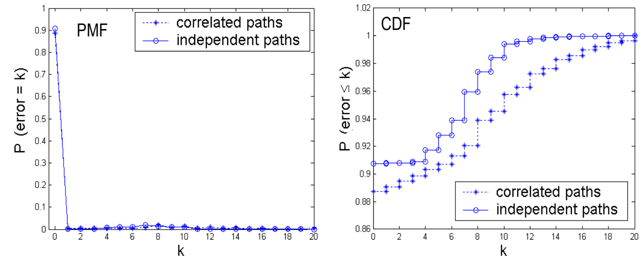
For different pairs of P_L and L_B, we observe similar trends as shown in Fig. 3 for (P_L, L_B) = (7%, 4).

B. Packet Transmission with Channel Coding

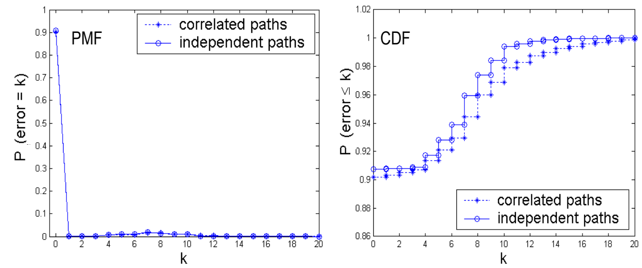
In this section we present the results obtained with two different Reed-Solomon codes: the relatively weak RS(22, 20) code which can correct two losses in a block of 22 packets, and the stronger RS(26, 20) code which is capable of correcting 6 losses in a block of 26 packets. We repeat the same scenarios (5 joint links and 2 joint links) as in the previous case, except here we measure the block error distribution within the systematic part of the codeword after channel decoding. The results are shown in Fig.'s 4 and 5.

When the weak RS(22, 20) code is used, as seen in Fig. 4, the trends are similar to the uncoded case. Again, error-free blocks occur more frequently with correlated paths than with independent paths, but the number of blocks with a large number of losses is also larger for the correlated paths than for the independent paths. The gaps between the correlated case and the independent case are smaller for both the PMF and CDF plots compared to the uncoded case.

However, when the stronger RS(26, 20) code is used, the situation is changed as shown in Fig. 5. Here, the independent case outperforms the correlated cases in terms of frequencies of occurrence of blocks with small numbers of errors. This is clearly seen from the CDF plots in Fig. 5, where the curves for the independent case lie above the curves for the correlated case over the entire graph.



(a). PMF and CDF for the distribution of blocks with *k* errors; 5-joint links for correlated paths.



(b). PMF and CDF for the distribution of blocks with *k* errors; 2-joint links for correlated paths.

Fig. 5. Distribution of blocks of size 20 with *k* errors for different degrees of path correlations (P_L=7% , L_B=4, RS(26, 20)).

TABLE I

Residual Packet Loss Rates (P_r) with FEC; J is the number of joint links, ρ is the path correlation and n represents the block size of RS(n, 20) code.

J	P_L = 7%, L_B = 4			P_L = 3%, L_B = 4		
	ρ	RS(22,20)	RS(26,20)	ρ	RS(22,20)	RS(26,20)
0	0	6.27%	3.41%	0	2.39%	1.04%
1	0.186	6.30%	3.71%	0.197	2.43%	1.22%
2	0.383	6.31%	4.02%	0.392	2.47%	1.38%
3	0.589	6.34%	4.36%	0.596	2.51%	1.56%
4	0.794	6.42%	4.73%	0.799	2.54%	1.72%
5	1	6.47%	5.07%	1	2.58%	1.89%

Another factor which can affect the system performance is the residual packet loss rate P_r after channel decoding. In Table I, we show P_r for two different channel conditions: (1) (P_L, L_B) = (7%, 4); and (2) (P_L, L_B) = (3%, 4). In case (1), when the weak RS(22, 20) code is used, there is almost no difference in terms of P_r between the independent and correlated cases. However, when the strong RS(26, 20) code is used, P_r is up to 1.7 percentage points lower for independent paths compared to the case of highly correlated paths. On the other hand, in scenario (2), the variation of P_r is below 1 percentage point over the entire range of correlations, even when the strong channel code is used. In general, when a strong channel code is used, correlated paths will result in higher residual packet loss rate, but the difference with respect to independent paths need not be significant–it depends on channel conditions as shown in Table I.

Observe that the increased burstiness of packet loss and increased residual packet loss rate with the number of joint links were also reported in [5] for the relatively strong RS(30,23) code. However, as demonstrated above, these negative impacts of path correlation are less significant when weaker codes are used. Further, we have yet to examine the resulting impact on received video quality – we will do this in the following section.

IV. EFFECT OF PATH CORRELATION ON VIDEO QUALITY

In this section, we demonstrate the effects of path correlation upon transmitted video quality. We used the ITU-JVT JM3.9 version of the new H.264 video codec. The results are based on two standard QCIF test sequences: *Susie* and *Foreman*. Both are 30 fps and consist of 150 frames. The *Susie* sequence has low motion and the background tends to remain constant, while the *Foreman* sequence exhibits increased activity and frequent scene changes. Both are coded at constant bit rates specified by using the associated H.264 rate control scheme [6]. The first frame of the sequence is intra-coded and the rest of the frames are inter-coded as *P* frames with an intra-updating rate of one slice every two frames. In our packetization scheme, every QCIF frame is packetized into 20 RTP packets. For the channel coding strategy, we make use of RS(n, k) codes, with k=20, to combat the packet losses.

We first show the results of the video experiments for the *Susie* sequence. Again, we examine two sets of end-to-end channel parameters: (1) (P_L, L_B) = (7%, 4); and (2) (P_L, L_B) = (3%, 4). We assume each link has a bandwidth of 96 Kbps, so the available bit rate for source-channel encoding is 192 Kbps. All the simulations in what follows are done with 20 iterations in order to obtain statistically meaningful results.

In Table's II and III, we show the results for the *Susie* sequence for different degrees of path correlations and different channel codes. In Table II where (P_L, L_B) = (7%, 4), we can see that when no FEC is used, the correlated paths can, on average, achieve a slightly better reconstructed video quality than independent paths. For example, with 5 joint links between the two paths (i.e., correlation 1), the performance gain is about 0.5 dB compared to the case of independent paths. The reason is that blocks with a small number of losses occur more frequently with correlated paths, so the passive error concealment (PEC) and intra-updating can work more effectively, and result in a slightly better performance when no channel coding is used. Although blocks with a large number of losses also occur more frequently with correlation, the probability differences are so small that the net results are negligible. Thus, the performance gain achieved by PEC and intra-updating for the correlated case may outperform the performance drop due to the corresponding higher frequencies of occurrence of a large number of losses in a block. Therefore, in the absence of channel coding, the reconstructed video quality can be better with correlated paths than with independent paths.

When the relative weak RS(22,20) code is applied, some losses can be recovered. From the previous section, the residual packet loss rate for independent paths is slightly smaller than for correlated paths. Thus, the performance gain achieved by PEC for correlated pairs of paths is overcome to some extent by the slightly higher residual packet loss rate, so for the case of the RS(22, 20) code, we can observe that the performance with independent paths is almost the same as with correlated paths. However, with the stronger RS(26, 20) code, the difference in residual packet loss rates between the independent case and the correlated cases is relatively large, so the performance with correlated paths is slightly worse than with independent paths.

TABLE II
Performance comparison in PSNR between different number of joint links; for the QCIF Susie sequence; P_L=7% and L_B = 4; R_{tot} = 192 Kbps.

# of joint links	No FEC	RS(22, 20)	RS(26, 20)
0	33.8	33.7	34.8
1	34.1	33.7	34.6
2	34.3	33.9	34.7
3	34.4	33.9	34.6
4	34.4	33.9	34.4
5	34.3	33.7	34.2
Lossless Case	38.4	37.8	36.7

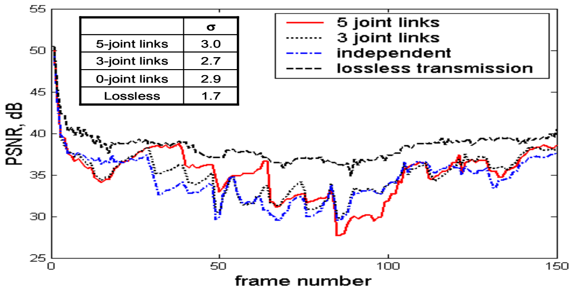
TABLE III
Performance comparison in PSNR between different number of joint links; for the QCIF Susie sequence; P_L=3% and L_B = 4; R_{tot} = 192 Kbps.

# of joint links	No FEC	RS(22, 20)	RS(26, 20)
0	36.5	35.8	35.8
1	36.5	35.7	35.7
2	36.6	35.8	35.7
3	36.6	35.8	35.7
4	36.6	35.8	35.6
5	36.6	35.7	35.6
Lossless Case	38.4	37.8	36.7

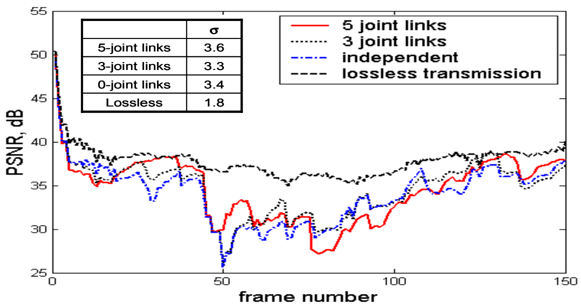
Table III corresponds to (P_L, L_B) = (3%, 4), and the trends are similar as in Table II. However, due to better channel conditions, the performance difference between correlated paths and independent paths is smaller than in Table II.

In Fig. 6 we show the ensemble average PSNR values for each frame of the *Susie* sequence for (P_L, L_B) = (7%, 4). Observe that the video quality is sometimes better with correlated paths, while at other times it is better with independent paths. For example, in Fig. 6 (c) which shows the performance when the RS(26,20) code is used, we see that independent paths give better performance between frames 50 and 80, due to the increased residual packet loss rates when correlation exists. However, the average PSNR results are fairly similar, as shown in Table II. Figure 6 also shows the standard deviation (σ) in PSNR, which measures the variation in video quality from frame-to-frame. Observe that standard deviations obtained with correlated paths are similar to those obtained with independent paths.

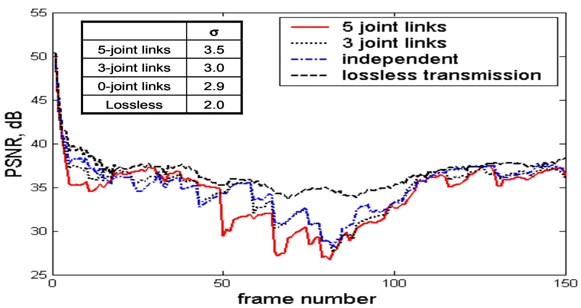
We repeated the same experiments with the *Foreman* sequence that exhibits somewhat higher motion than *Susie*. The results are tabulated in Tables IV and V. In Table IV, the experimental configurations are the same as for Table II. For uncoded transmission, we again see that the correlated paths can provide a slightly better video quality than independent paths, but the differences are now smaller than those in Table II. However, for the coded case, especially with the strong channel code, the performance with independent paths is better than with correlated paths. For example, with the relative strong RS(26, 20) code, the performance degradation between independent paths and correlated paths with 5-joint links is about 1.2 dB. The main reason is the higher motion activity in the *Foreman* sequence, which results in less effective PEC performance. Thus, when FEC coding is applied, the independent case would exhibit better performance. Although the performance gap between completely correlated paths and independent paths is relatively large (about 1.2 dB with the RS(26, 20) code), the gaps between lightly correlated or even



(a). Packet transmission without channel coding.



(b). Packet transmission with RS(22, 20) code.



(c). Packet transmission with RS(26, 20) code.

Fig. 6. Performance comparison between different number of joint links; for the QCIF Susie sequence; P_L=7% and L_B = 4; R_{tot} = 192 Kbps.

moderately correlated paths and independent paths are not as large.

Table V tabulates the results for the case (P_L, L_B) = (3%, 4). Note that, due to the relatively good channel conditions compared to that of Table IV, the performance differences between independent paths and correlated paths are not significant, even when the strong channel code is used.

V. Conclusions And Future Work

Based on the results presented here, we conclude that path correlation has a significant impact on video communications using FEC across multiple paths only when: (1) passive error concealment is not effective, for example when the motion level of the transmitted video is high, (2) channel conditions are severe, and (3) strong FEC codes are used. If any of these conditions are not satisfied, the effect of path correlation on the received video quality seems to be rather insignificant. In fact, correlated paths can sometimes provide a better average video quality than independent paths.

This means that when a multi-path routing algorithm searches for appropriate paths to stream the video to the destination, it may not be necessary to find completely disjoint paths, or even least correlated paths. Thus, multi-path routing discovery might

TABLE IV

Performance comparison in PSNR between different number of joint links; for the QCIF Foreman sequence; P_L=7% and L_B = 4; R_{tot} = 192 Kbps.

# of joint links	No FEC	RS(22, 20)	RS(26, 20)
0	29.7	29.8	30.1
1	29.7	29.8	29.8
2	29.8	29.6	29.3
3	29.9	29.6	29.5
4	30.0	29.4	29.2
5	29.8	29.2	28.9
Lossless Case	34.5	33.8	32.4

TABLE V

Performance comparison in PSNR between different number of joint links; for the QCIF Foreman sequence; P_L=3% and L_B = 4; R_{tot} = 192 Kbps.

# of joint links	No FEC	RS(22, 20)	RS(26, 20)
0	32.1	32.1	31.6
1	32.2	32.1	31.4
2	32.3	32.2	31.1
3	32.3	32.1	31.2
4	32.3	32.0	31.1
5	32.2	31.9	30.8
Lossless Case	34.5	33.8	32.4

be substantially simplified without sacrificing received video quality. However, if our goal is to find an optimal collection of paths that maximizes the received video quality, then multiple factors (not just path correlation) need to be considered, including rate-distortion characteristics of the video, the existing channel conditions as well as source and channel coding strategies employed.

Note that the Gilbert channel models end-to-end packet loss behavior without distinguishing the causes of loss, such as transmission errors, buffer overflows, and losses due to excessive delay, etc. In future work, we aim to investigate the effects of path correlation using more powerful packet loss models and real network experiments.

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