The Impact of Inter-layer Network Coding on the Relative Performance of MRC/MDC WiFi Media Delivery

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ABSTRACT

A primary challenge in multicasting video in a wireless LAN is to deal with the client diversity – clients may have different channel characteristics and hence receive different numbers of transmissions from the AP. A promising approach to overcome this problem is to combine scalable video coding techniques such as MRC or MDC, which divide a video stream into multiple substreams, with inter-layer network coding. The fundamental challenge in such an approach is to determine the strategy of coding the packets across different layers that maximizes the number of decoded layers at all clients. In [7], the authors showed that inter-layer NC indeed helps the delivery of MRC coded media over the WiFi, and proposed how to efficiently search for the optimal coding strategies online.

In this paper, we study (1) how NC can help with WiFi delivery of MDC media, and (2) in particular, due to the different decoding requirements of MDC from MRC, whether WiFi delivery of MDC media can benefit more from NC compared to that of MRC media. Our simulation results are somewhat surprising. Even though MDC is generally shown to outperform MRC in lossy channels, most of the benefit of MDC over MRC is lost after applying NC to both schemes.

Categories and Subject Descriptors

C.2.1 [**Computer Communication Networks**]: Network Architecture and Design—*Wireless Communication*

General Terms

Design, Performance

Keywords

streaming media, MDC, MRC, network coding, WiFi

1. INTRODUCTION

As both media content (e.g. youtube videos) over the Internet and wireless devices (e.g. smartphones) become increasingly popular, scalable delivery of rich media content over wireless heterogeneous links, e.g., with varying Packet Delivery Ratios (PDRs), is quickly becoming one of the most important applications today.

A promising approach to dealing with receiver diversity is to exploit source-coding techniques such as Multi-Resolution Coding (MRC) [2] (also referred to as layered coding) and Multiple Description Coding (MDC) [4]. In contrast to a conventional media coder that generates a single bitstream, MRC and MDC encode a media source into multiple substreams and reception of more substreams generally improves the video quality. MRC divides the video into a base layer and multiple enhancement layers. The base-layer can be decoded to provide a basic quality of video while the enhancement layers are used to refine the quality of the video. If the base-layer is corrupted, the enhancement layers become useless, even if they are received perfectly. In contrast, in MDC, the substreams (or descriptions) are mutually refining, equally important, and independent. When the decoder receives more descriptions, the quality can be gradually increased no matter which description is received first.

In case of multiple clients, with diverse network conditions, the individual clients can independently decide how many substreams (layers or descriptions) to receive from the server according to their individual available bandwidth from the server. In a wireless network, however, all substreams transmitted share the medium; sending higher layers or more descriptions reduces the bandwidth available for sending lower layers/fewer descriptions.[1]

A promising approach to overcome the client diversity problem in delivering media content over WiFi is to combine using MRC/MDC streams with inter-layer network coding (NC) to maximize the number of useful layers that can be retrieved by the wireless receivers. In [7], the authors showed that inter-layer NC indeed helps the delivery of MRC coded media over the WiFi, and proposed how to efficiently search for the optimal coding strategies online.

The fundamental reason that inter-layer coding improves the number of decoded layers even for a single receiver is that it allows retrieving useful layers from more combinations of received transmissions; a scheme without coding could decode more layers by adjusting individual transmissions based on feedback after each transmission, which is costly and impractical when there are multiple clients. Further, this fundamental reason implies that inter-layer coding can also improve the case for multiple clients, which may have different combinations of received transmissions.

1.1 Related work

Several performance comparisons between MRC and MDC have been reported in the literature (e.g., [12, 11, 14, 8]). Summarizing

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[1] For simplicity, we will use the term "layer" for both MRC layers and MDC descriptions in the remaining of the paper.

the findings from these studies, one can conclude that MDC outperforms MRC for networks with no feedback, long RTTs, or high loss rates.

MRC combined with network coding has been studied in the early years of the development of network coding. Recent analytical results focus on sustaining the largest possible rates for the MRC video applications with intra-layer (e.g [13]) or inter-layer network coding, both centrally [1] and distributively [6]. However, most results have focused on the wireline networks (or they convert the wireless network into its equivalent wireline counterpart), an approach which does not take into account randomness, one of the critical features of a wireless network. Recently, there have also been a few practical works that demonstrated the effectiveness of combining MRC video streaming with network coding in multihop wireless networks [3, 5], using simple heuristic coding strategies. In [7], the authors showed that such simple heuristics can perform poorly even for a single client, and proposed how to efficiently search for the optimal coding strategies online.

In contrast to MRC, to our best knowledge, almost no effort of combining MDC with network coding has been reported so far, with the exception of two recent, preliminary works [10, 9] focusing on wireline networks.

1.2 Problem Formulation

In this paper, we study (1) how NC can help with WiFi delivery of MDC coded media, and (2) in particular, due to the different decoding requirements of MDC from MRC, whether WiFi delivery of MDC media can benefit more from NC compared to that of MRC media. Intuitively, this appears to be the case; since there is no inter-layer dependence in MDC, receiving any K layers can lead to better quality of video compared to receiving less than K layers. In contrast, in MRC, receiving the Kth layer is only helpful if the previous $K-1$ layers have been received. This second question is of particular interests as it will answer the question of practical importance: *whether MDC coupled with NC can lead to more efficient video delivery compared to MRC combined with NC.*

2. BACKGROUND

In popular video coding schemes such as H.264/AVC, the video content is partitioned into sequences of pictures, referred to as groups of pictures (GOPs), each beginning with an independently decodable intra-coded picture. A typical duration for a GOP is 1 to 2 seconds. Each GOP contains many pictures or frames. A GOP is divided into a sequence of packets for delivery over the network. Although a single frame may span multiple packets, or a single packet may contain more than one frame, we can assume that there will be multiple packets for a GOP, and in the case of constant bitrate video coding, the number of packets per GOP will be constant throughout a sequence.

We focus on network coding within each GOP. Let L be the number of layers/descriptions (typically 2-6) and Q be the number of packets per layer in a GOP. The value of Q depends on the streaming rate of the video. For example, an HD video of 12 Mbps coded in 4 layers, using 1000-byte packets corresponds to 375 packets per layer per (1-second) GOP.

Since Q can potentially be large, we divide up the Q packets per layer per GOP into multiple segments, so that the number of packets per segment (per layer) N is on the order of 8. This ensures that even when we code the packets from segments from all layers, the total number of packets is in the order of 32 (e.g. for 4 layers), which will not result in high coding/decoding overhead. Let X be the total number of transmissions the AP can have within the deadline of frames corresponding to the $N \cdot L$ packets for the L layers.

2.1 NC Helps Delivery of MRC

In [7], the authors showed that inter-layer network coding helps the delivery of MRC coded media over the WiFi, and proposed how to efficiently search for the optimal coding strategies online. We briefly review these results below.

Efficient Search of Optimal Strategies under MRC The primary challenge in combining inter-layer coding with MRC for WiFi delivery is how to find the optimal inter-layer coding strategy for a given channel condition, determined by the number of transmissions the AP can send before the deadline of a set of frames, and the packet deliver ratio (PDR) at the receiver(s). The most intuitive heuristic is to estimate the number of layers that can be decoded based on the expected number of received transmissions, and code packets from those many layers for all transmissions. While this strategy is expected to be optimal for the average cases (of reception outcomes), when dealing with small numbers of transmissions, due to the binomial distribution of reception outcomes, a carefully chosen strategy can outperform this simple though intuitive strategy.

[7] shows the naive way of searching all strategies for the optimal strategy has a complexity of $2^{LX} \cdot 2^{X} \cdot O((N \cdot L)^3)$. [7] then presents several optimizations that together enable efficient search of the optimal inter-layer coding strategies in real time, for practical scenarios, i.e., 4 layer segments with 8 packets per segment.

We first observe that since the X transmissions are assumed to be independent Bernoulli trails, the ordering in sending individual packets does not matter. Hence, two strategies are equivalent if their matrix presentations are the same after some row swapping. This suggests we just need to search among all the strategies that are not equivalent. Since there are only 2^L possible row vectors, or "bins", the total number of nonequivalent strategies is the same as the number of unique ways of assigning X transmissions to the 2^L bins, $\begin{pmatrix} X-1+2^L \\ 2^L-1 \end{pmatrix}$. This is a drastic reduction from 2^{LX}.

Optimization 1: The main optimization is instead of searching for all possible 2^L coding strategies for each of the X transmission, we only need to consider the following L ways of coding packets from the L layers: the kth way being coding the first k layers, for $k = 1, ..., L$. Such a scheme can be denoted as $(x_1, ..., x_L)$, where $\sum_{i=1}^{L} x_i = X$, and x_i denotes the number of packets that code the first i layers. This optimization reduces the number of strategies to be searched down to $\begin{pmatrix} X-1+L \\ L-1 \end{pmatrix}$. We will call a scheme that only considers the triangular canonical form of strategies **Canonical triangular scheme (Canonical-L)** in the remaining of the paper.

Optimization 2: The second optimization is to consider group transmission into groups of R packets, with each group always assigned the same coding strategy. This further reduces the number of coding strategies to $\begin{pmatrix} Z-1+L \\ L-1 \end{pmatrix}$, where $Z = \frac{X}{R}$.

Optimization 3: The final optimization is to avoid Gaussian Elimination in calculating the number of layers that can be decoded for each outcome, using a simple calculation with a complexity of $O(L^2)$. This optimization takes advantage of the fact that all transmissions follow the canonical triangular coding scheme. [7] shows with these three optimizations, the time to search the optimal strategy is 0.13 seconds for $(L, N, X, R) = (4, 8, 64, 4)$.

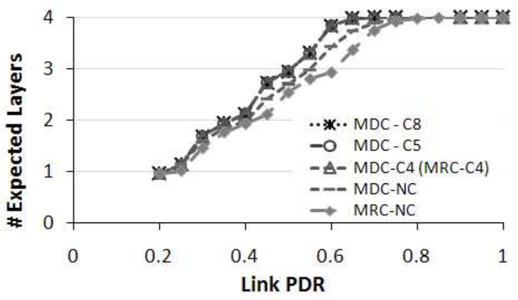


Figure 1: Performance comparison of different schemes for varying PDRs.

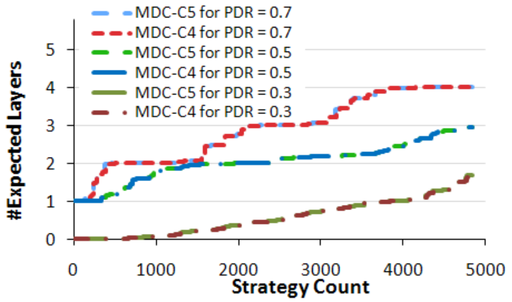


Figure 2: CDF for all the strategies at PDR = 0.7, 0,5 and 0.3 for MDC-C4 and MDC-C5.

3. HOW TO APPLY NC TO MDC

We first consider the case where the AP is trying to delivery an MDC video to a single client only. We then consider the case with multiple clients in the next section.

3.1 MDC vs. MRC

We first compare the performance of the two video encoding schemes without NC. We consider $(L, N, X, R) = (4, 8, 64, 4)$, (*i.e.*,, we assume the two schemes have the same coding efficiency) and vary the PDR p at the client.

The two lower curves of Figure 1 (MRC-NC and MDC-NC) plot the average (out of all possible reception outcomes) number of decoded layers under the best transmission strategy, using MRC and MDC, respectively, with **N**o (Network) **C**oding. We observe that MDC outperforms MRC by as much as 17%. In MDC, there is no inter-layer dependency, and hence, receiving any K layers can lead to better quality of video compared to receiving less than K layers. In contrast, in MRC, the Kth layer is only helpful if the previous $K - 1$ layers have been received.

Given that (i) MDC outperforms MRC and (ii) NC improves the performance of MRC ([7]), intuitively one would expect NC to also boost the performance of MDC and most importantly, MDC to benefit more from NC compared to MRC. In the following, we are we are trying to answer these two questions.

3.2 Adding NC to MDC

The intuition for the optimal coding strategy under MRC being of canonical triangular form comes from the very nature of MRC encoding: as mentioned before, receiving the Kth layer is only helpful if the previous $K - 1$ layers have been received. For example, there is no need to deliver the second layer by itself, since if the first layer is received, delivering coded first and second layers is no different from delivering the second layer by itself; and if the first layer is not received, delivering the second layer is useless.

The above reasoning does not work for MDC, as receiving any descriptions contributes to the final quality of the video. Therefore, in principle, we need to consider all strategies, which can be prohibitively costly to search. We propose two heuristic schemes, in addition to **Canonical-L**, that exploit the nature of MDC to search more strategies than the canonical triangular scheme.

Canonical-(L+1): This scheme considers $(L + 1)$ ways of inter-layer coding: in addition to the L canonical ways of coding, *i.e.*,, the first K layers each, for $K = 1, ..., L$, it also considers layer 2 alone. The rational is to exploit the delivery of layer 2 by itself, since receiving layer 2 is as productive as receiving layer 1, under MDC. Complexity-wise, there are a total of $\binom{X+L}{L}$ unique ways of assigning X packets to the $(L + 1)$ ways of generating the coded packets in this scheme.

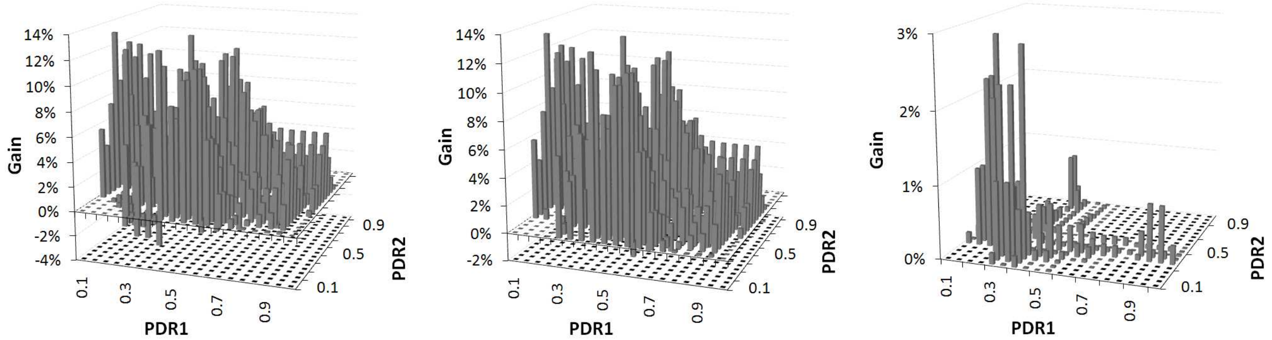
Canonical-(L+4): This scheme considers $(L + 4)$ ways of inter-layer coding: in addition to the L ways in Canonical-L, it also considers layer 2 alone, layer 3 alone, coded layers 1 and 3, and coded layers 2 and 3. Complexity-wise, there are a total of $\binom{X+L+3}{L+3}$ unique ways of assigning X packets to the $(L + 5)$ ways of generating the coded packets in this scheme. For the typical values of $(L, N, X, R) = (4, 8, 64, 4)$, the above three schemes will explore 969, 4845, 245157 strategies, respectively.

Comparing different NC schemes for MDC We first compare the performance of different NC schemes with MDC for a single client. The goal is to evaluate the benefit of considering more strategies for NC-based MDC videos. We denote MDC combined with Canonical-4, Canonical-5, and Canonical-8 as MDC-C4, MDC-C5, and MDC-C8, respectively. The three upper curves of Figure 1 plot the average (out of all possible reception outcomes) number of decoded layers under the best transmission (coding) strategy, using MDC-C4, MDC-C5, and MDC-C8, respectively. We observe that, the performance benefit of MDC-C5 and MDC-C8 over MDC-C4 is negligible; the maximum gain is less than 0.5%.

The reason for the negligible performance gain of MDC-C5 and MDC-C8 over MDC-C4, in spite of considering many more coding strategies, is that, for every PDR, *the maximum number of decoded layers with MDC-C4 is the same (or almost the same) as the maximum number of decoded layers with MDC-C5 for at least one strategy*. This is observed in Figure 2, which plots the average number of decoded layers for each MDC-C4 and MDC-C5 strategy under three different PDRs. MDC-C5 strategies cover all the MDC-C4 strategies and each MDC-C4 strategy is plotted against the MDC-C5 strategy it matches. Since the graphs overlap for a given PDR, there is no performance benefit in using MDC-C5 than MDC-C4.

Does NC help MDC? Figure 1 shows that NC helps MDC but the gains are moderate. MDC-C4 outperforms MDC-NC by 0-13.25%.

Does NC help MDC more compared to MRC? We saw that, when applying NC to MDC videos in the case of a single client, it is sufficient to use the triangular scheme Canonical-4 which has been shown in [7] to be optimal for MRC videos. This observation has an important implication. **Assuming that MDC and MRC have the same coding efficiency, i.e., they share the same parameters L and N per delivery segment within which we perform NC, the benefit of applying NC is the same for both schemes.** In other words, MDC-C4 is exactly the same as MRC-C4 and the results for MDC-C4 apply in the same way to MRC-C4 too. This can be explained by the properties of the canonical scheme. If any higher numbered layer is decoded by MDC-C4, all layers below it are also



(a) MDC-C4 vs. MDC-NC (b) MDC-C5 vs. MDC-NC (c) MDC-C5 vs. MDC-C4

Figure 3: The benefit of applying NC to MDC in the case of 2 clients.

decoded due to NC, which is true for MRC-C4 too. In the rest of the paper, the results for MDC-C4 also apply to MRC-C4 with the same efficiency. Hence, *the benefit of MDC over MRC in the case of a single client is lost when we apply NC to both schemes.* In Figure 1, we have included MRC-C4 in parentheses next to MDC-C4. From now one, we will use these two terms interchangeably.

The next question is whether these conclusions hold when a video is multicast to more than one client with a diverse set of PDRs. In such a cases, for an MRC video, we are still limited to the Canonical-4 scheme. However, for an MDC video it may be worth using a higher complexity coding scheme (Canonical-5 or Canonical-8) which provides more strategies to choose from and hence, greater flexibility in dealing with heterogeneous clients.

4. MULTIPLE CLIENTS

In case of multiple clients, we multicast the network coded packets using 802.11 broadcast. As the PDR can be different for different clients, the number of decoded layers will also be different. This is effectively a multi-objective optimization problem as suggested in [7]. The server scans through all the strategies and selects a strategy that maximizes the objective function. In this paper, we consider the objective function of maximizing the sum of decoding layers for all the clients.

4.1 Does NC help MDC more with multiple clients than with a single client?

Figures 3(a) and 3(b) compare the performance of MDC-C4 over MDC-NC and MDC-C5 over MDC-NC, respectively, in the case of two clients. The height of each bar shows the gain in terms of the average number of decoded layers under the best coding strategy (*i.e.,* the one that optimizes the sum of the decoded layers for the two clients) for a given PDR pair.

MDC-C4 vs. MDC-NC. From Figure 3(a) we observe that MDC-C4 outperforms MDC-NC for most PDR pairs with the performance benefit being as high as 13%. Generally, this is consistent with Section 3.2, where we saw that the gain of MDC-C4 over MDC-NC varies from 0-13.5% for a single client. However, it should also be noted that MDC-C4 performs worse than MDC-NC for some PDR pairs, especially at low PDRs.

MDC-C5 vs. MDC-NC From Figure 3(b), we observe that the performance gain of MDC-C5 over MDC-NC can be as high as 13%, *i.e.,* similar to that of MDC-C4 over MDC-NC. However, overall the performance is improved and MDC-C5 outperforms MDC-NC for most of the PDR pair where MDC-NC outperforms MDC-C4. This is because, MDC-C5 has an additional option to transmit layer 2 packets alone at the lower PDRs, which is similar to MDC-NC.

4.2 Does NC help MDC more than MRC with multiple clients?

In the case of a single client, we have seen that the benefit of MDC over MRC is lost when we apply NC to both schemes. Figure 3(c) compares the performance of MDC-C5 vs. MRC-C4 (which is equivalent to MDC-C4) for two clients. We observe that the conclusion for the single client case generally holds true for two clients as well. The benefit of MDC-C5 over MRC-C4 is always less than 3%. As we saw in Figure 2, the additional strategies considered by MDC-C5 do not provide any significant benefit for any PDR compared to the best MDC-C4 strategy. MDC-C5 only performs slightly better than MRC-C4 at lower PDRs. At the lower PDRs, the server mostly sends packets with 1 or 2 layers coded. To send 2 layers, MRC-C4 needs to code packets from layer 2 and layer 1, whereas MDC-C5 has an additional option to send layer 2 packets without coding with packets from layer 1. This way, MDC-C5 behaves more or less like MDC-NC.

5. ONLINE WIFI MULTICAST OF MDC MEDIA USING NC

In the previous two sections we assumed that the AP had perfect knowledge of the PDR of each client and the transmission budget X. In practice, the AP learns these parameters through feedback from the clients. In this section, we evaluate the benefits of applying NC to MDC in an online multicast system. In [7], the authors presented an online video delivery scheme, Percy, deployed at a proxy behind the AP of a WLAN. The proxy in real time collects loss rates for different clients, searches for the optimal NC strategy (assuming MDC or MRC coded video), and generates coded packets for the AP to broadcast. In Section 5.1, we give a brief overview of Percy's main components. We then describe the evaluation methodology in Section 5.2, and evaluate the performance of Percy with MDC and MRC videos using simulations in Sections 5.3 and 5.4.

5.1 Percy overview

Percy consists of 3 main building blocks:

PDR feedback from clients The AP transmits each packet it receives from the proxy using 802.11 broadcast. The clients periodically send feedback to the proxy to allow it to obtain an estimate of their PDRs. We use a lightweight scheme in which each client reports every 200 ms the *total* number of packets since the last report. These feedback messages are forwarded by the AP to the proxy.

Online Estimation of X and PDRs The proxy (1) continuously monitors the number of transmissions X' it can make in each GOP. The total transmission X' is divided equally among the segments constituting the GOP, i.e., X per segment; and (2) receives the periodic PDR feedbacks from each client, which are sent back to the proxy at fixed instants during every GOP.

At the end of GOP i, the proxy uses the measured X and PDRs as the predicted values for GOP $i+1$, to calculate a Strategy Performance Table (SPT) that lists the number of layers decoded for all possible strategies for the given L and X, using resolution $R = 4$, for all PDRs ranging from 5% to 100% with increments of 5%. As shown in [7], this calculation can be finished in less than 0.13 sec for typical values of (L, N, X, R), e.g. (4,8,64,4).

Calculating the optimal coding strategy For any given objective function, e.g., the sum of the layers that can be retrieved at each client, the proxy scans through all the coding strategies in the SPT, and finds the one that maximizes the objective function for the set of clients, based on their PDRs. This strategy is then used for all the segments consisting the next GOP.

5.2 Evaluation Methodology

We used the Glomosim simulator [15]. We placed an AP in the center of the simulation area and the clients uniformly on a circle around the AP. To evaluate the performance of the protocols under different loss scenarios, the clients were placed close to the AP and we generated link loss rates in a controlled manner, by artificially dropping packets at each client following a Bernoulli model.

We used the 802.11 MAC layer with a fixed bitrate of 5.5Mbps and RTS/CTS disabled, as in most operational networks. Data packets were broadcast at the MAC layer. The feedback messages sent by Percy clients were unicast at the MAC layer for increased reliability.

The video stream was a constant bit rate (CBR) traffic over UDP at 2.56 Mbps for a duration of 100 sec. The GOP duration was set to 1 sec. The stream consisted of $L = 4$ layers. Each layer included 80 1000-byte packets and was divided into 10 segments of $N = 8$ packets each.

5.3 Evaluation with a Single Client

Figure 4 shows the average number of decoded layers under different media coding schemes (MDC or MRC), with or without NC. We make the following observations: (i) Without network coding, MDC outperforms MRC. The gain of MDC-NC over MRC-NC is 0-25.08%. (ii) NC improves the performance of MDC. The gain of MDC-C4 and MDC-C5 over MDC-NC is 24.3% and 28.7% respectively. These gains are higher than the gains we observed in Section 3. (iii) The gain of MDC over MRC is lost when we apply NC to both schemes. The gain of MDC-C5 over MRC-C4 is at most 4.3%. Even though this is slightly higher compared to the offline gain in Section 3, it is still too low to justify using MDC-C5 instead of MDC-C4.

5.4 Evaluation with Multiple Clients

Applying NC to MDC Figures 5(a), 5(b) show the gain of MDC-C4 and MDC-C5 over MDC-NC, respectively. In Figure 5(a), we observe that MDC-C4 outperforms MDC-NC by up to 19%. This is higher than the offline analysis gain (up to 13.5%) in Section 4. Similar to Figure 3(a), there are a few cases where MDC-NC performs better than MDC-C4 by up to 3.28%. Figure 5(b) shows that MDC-C5 improves the performance in most of the cases where MDC-C4 performs worse than MDC-NC. However, the maximum gain of MDC-C5 over MDC-NC is 19%, equal to the maximum gain of MDC-C4 over MDC-NC.

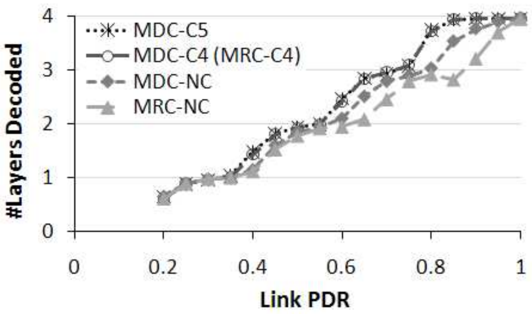


Figure 4: Performance comparison of different schemes in Glomosim for a single client.

Comparing different NC schemes for MDC Figure 5(c) shows the gain of MDC-C5 over MRC-C4. MDC-C5 outperforms MRC-C4 by up to 8.5%. Our offline analysis in Section 4 showed that the gain was always lower than 3%. Note that MDC-C5 outperforms MRC-C4 mostly at low PDRs. The lack of inter-layer dependency of MDC makes it more resilient to imperfect PDR and bandwidth estimation, which is unavoidable in an online system.

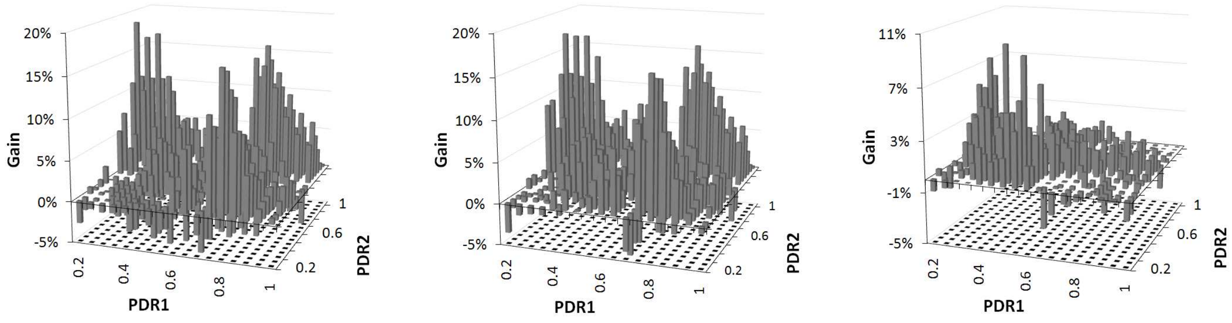
Of course, the 8.5% gain of MDC-C5 comes at the cost of increased complexity. Our measurements in [7] show that an SPT for MRC(MDC)-C4 can be constructed in less than 0.13 sec. The construction of an SPT for MDC-C5 takes much longer. However, in cases when the bandwidth does not change rapidly, one may not have to recalculate the SPT at the beginning of each GOP. In those cases, MDC-C5 can be used in place of MDC-C4 to increase performance by up to 8.5%.

Varying the number of clients We also evaluate the performance gain of network coding when the number of clients varies from 2 to 6 clients. For each case, we ran 100 different simulation scenarios; in each scenario the client PDRs are chosen uniformly randomly from the range [0.2, 0.9]. Figures 6(a), 6(b) and 6(c) plot the CDF of the gain of MDC-C5 and MDC-C4 over MDC-NC for 2, 4 and 6 clients respectively. Similar to 2 clients, MDC-C4 and MDC-C5 outperform MDC-NC for 4 and 6 clients but the benefit is small and it reduces with the number of clients (up to 18% for 4 clients and up to 13% for 6 clients). Also, the benefit of MDC-C5 over MRC-C4 is always negligible.

6. CONCLUSION

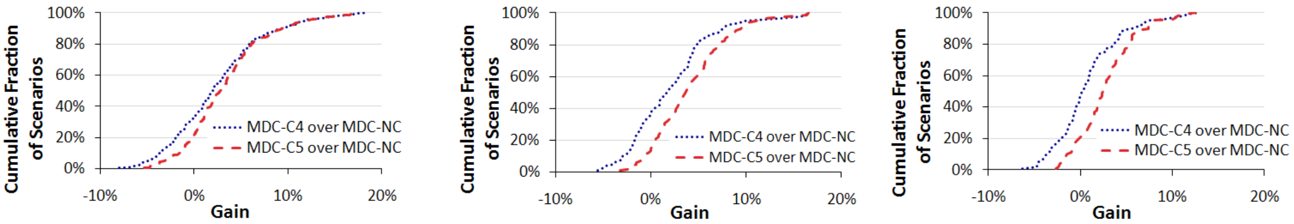
Motivated by the result of [7] (NC can help the delivery of MRC coded media over WiFi), in this paper, we studied whether NC can also help the delivery of MDC media, and in particular, if MDC combined with NC performs better than MRC combined with NC. Intuitively, this should be the case, as with no inter-layer dependency in MDC, receiving any K layers can lead to better quality of video compared to receiving less than K layers. Rather surprisingly, our simulation study shows that, even though MDC generally outperforms MRC without network coding, most of the benefit of MDC over MRC is lost after applying network coding to both schemes.

Note that, in this paper, our evaluation metric was the average number of decoded layers rather than the PSNR metric, which is traditionally used for video delivery schemes. However, since the two schemes deliver similar number of layers when combined with NC and MDC generally performs very poorly in terms of coding efficiency compared to MRC, the PSNR relationship can easily be



(a) MDC-C4 vs. MDC-NC (b) MDC-C5 vs. MDC-NC (c) MDC-C5 vs. MDC-C4

Figure 5: The benefit of applying NC to MDC in case of 2 clients in Glomosim.



(a) 2 clients (b) 4 clients (c) 6 clients

Figure 6: CDFs of gain of MDC-C4 and MDC-C5 over MDC-NC for 2, 4 and 6 clients.

deduced by our results, i.e., for the same capacity, MRC with NC will typically deliver higher PSNR than MDC with NC.

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