

# CLIX: NETWORK CODING AND CROSS LAYER INFORMATION EXCHANGE OF WIRELESS VIDEO

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## ABSTRACT

Network Coding (NC) can be efficiently combined with the “physical layer broadcast” property of wireless mediums to facilitate mutual exchange of independent information [6]. At the same time, experimental/theoretical analysis of wireless networks has shown the efficacy of cross-layer protocols that relay corrupted packets in bandwidth hungry video applications (e.g. [7]-[8]). The integration of NC-based information exchange and cross-layer (CL) protocols for wireless video is the primary theme of this work. A particular issue addressed in this paper is the impact of errors in a packet, on the performance of a network code. Thus, we identify the operating conditions under which NC, despite the presence of residue errors, is beneficial. Based on theoretical analysis and experiments using 802.11b wireless traces it is established that the combination of NC with relay of corrupted packets can perform better than (i) conventional schemes that drop all corrupted packets (ii) a scheme that deploys network coding only (iii) a scheme that only deploys a CL strategy that recovers information from corrupted packets. The proposed Cross-Layer Information-eXchange (CLIX) scheme significantly improves the performance of an H.264 based video codec for wireless networks.

## 1. INTRODUCTION & BACKGROUND

The capacity of wireless networks can be limited due to Medium Access Congestion [1]. Network Coding (NC) [2], [3], [4] in combination of physical layer broadcasting ([5] and references within, [6]) can be used to efficiently reduce the impact of congestion. In addition to Medium Access Congestion, the throughput of wireless networks can also be further reduced due to excessive packet drops due to bit corruptions. A successful strategy to counter such excessive packet drops is achieved by deploying cross-layer (CL) protocols<sup>1</sup> that permit the transport of corrupted packets (e.g. [7]-[8]). Video applications are extremely bandwidth hungry and hence stand to benefit significantly if the advantages of NC can be harnessed in the presence of corrupted packets. Therefore, in this paper we evaluate the feasibility of such a combination and in particular its utility for wireless video. More specifically, we consider the *Mutual Information Exchange* (MIE) problem introduced by Wu et. al. in [6] and exhibit the utility of combining NC with CL to facilitate efficient Cross-layer Information eXchange (CLIX).

In the context of this paper the MIE problem can be motivated as follows. Consider a wireless-network as shown in Figure 1. The

<sup>1</sup> In this paper the notion of *cross-layer protocol* refers to protocols (at link-level or above) that do not drop all packets that contain *residue errors* (i.e. errors not corrected at the physical layer).

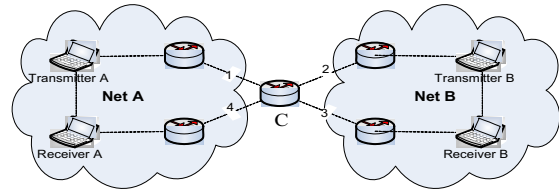


Figure 1 A wireless bridge connecting two otherwise disconnected network components

network consists of two components *Network A* and *Network B* with a “bridge” *C* connecting them. *Transmitter A* (*Transmitter B*) wants to send some information to *Receiver B* (*Receiver A*). The nodes inside a particular “component” are connected such that intra-component communication can be assumed to be (essentially) error free. The “bottleneck” in communication is the *exchange* of information that has to take place at bridge/router *C*. In a conventional network, each packet from *Transmitter A* (*Transmitter B*) to *Receiver B* (*Receiver A*) would have to be transmitted once each over links 1 and 3 (links 2 and 4). Consider that the *edge* router connected to link 1 (link2) wants to transmit packet *X* (*Y*) from *Transmitter A* (*B*) to *Network B* (*A*) for *Receiver B* (*A*). A transmission can be saved by taking advantage of the broadcast nature of the wireless links. So once packet *X* and *Y* are received at the intermediate router *C*, instead of transmitting *X* and *Y* individually in a serial manner, the router *C* performs network coding by simply XOR-ing the packets and broadcasting  $Z = X \oplus Y$  over the links 3 and 4 simultaneously. *Receiver A* (*B*) can easily obtain a copy of packet *X* (*Y*) on the basis of intra-component communication. Thus *Receiver A* (*B*) can also obtain a copy of packet *Y* (*X*) on the basis of a simple XOR operation  $Y = X \oplus Z$  ( $X = Y \oplus Z$ ).

In this paper we extend the work proposed in [6] by considering a scenario where router *C* is placed such that the packet transmissions over links 1, 2, 3, and 4 are susceptible to bit corruptions. (Such a scenario can indeed occur in regions where a network is sparse and has to communicate over long distances or poor quality channels to remain connected.) If a significant portion of packets on either of the links are dropped due to bit-corruptions, the exchange of information (despite the presence of NC at an intermediate node) won’t be efficient. Thus in such a scenario it would be essential to employ a CL protocol that allows the relay of corrupted packets and thus reduces the susceptibility to bit errors. However, XOR-ing of packets in presence of bit corruptions can lead to error propagation and a potential reduction in the efficacy of both the *Network Code* as well as the CL protocol. Furthermore it should be noted that (i) A NC scheme can benefit by employing a CL protocol if and only if, the decrease in capacity due to error propagation is lesser than the increase in capacity due to an

improved packet throughput. (ii) A CL protocol can benefit from employing a NC scheme if and only if, the decrease in capacity due to error propagation is lesser than the increase in *packet flow*.

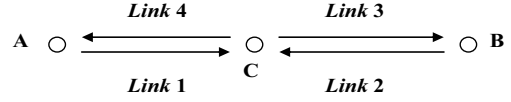
Thus in this paper to evaluate the utility and feasibility of CLIX, we conduct a rigorous comparative evaluation of all the 4 possible combinations that emerge from (i) employing traditional or CL protocols on links 1,2,3,4 and (ii) employing an NC (i.e. XOR-ing) or pure *Forwarding* functionality at router *C*. We lend additional credence to the evaluation by utilizing actual 802.11b wireless traces to emulate links 1, 2, 3, and 4. The analysis presented in this work can be broken down into the following steps: In section 2, based on some key parameters we deduce an abstract model to represent the communication over each link. The throughput capacity of each of the four schemes is deduced for such a model. Values of these key parameters, derived on the basis of actual 802.11b traces, are used to predict that CLIX should perform better than any other combination on an actual 802.11b wireless channel. Trace based simulations presented in section 3 validate this prediction. In section 3 we conduct Forward Error Correction (FEC) analysis for multiple sets of actual 802.11b wireless traces. It is observed that for a variety of coding rates and realistic channel conditions, the goodput of CLIX is superior to that of other schemes. In addition, in section 3 with the help of H.264 based video simulations we exhibit the efficacy of CLIX in improving wireless video quality. The key conclusions of this work are summarized in section 4.

## 2. THROUGHPUT CAPACITY

Since the intra-network communication in *Network A* and *Network B* is unconstrained, the entire network can be abstracted by single nodes. Thus the communication topology in Figure 1 is identical to that in Figure 2. Thus from this section onwards we utilize the topology given in Figure 2 for our analysis. At this stage, before we proceed further with the analysis, there are some important assumptions that need to be elaborated upon:

1) **Meta-data Overhead:** As XOR-ing of packets at an intermediate node or bit corruptions over the first hop alters the content of the packet, the header and the payload checksums have to be updated at the intermediate node. Additional meta-data also has to be inserted in the header at an intermediate node, a) to allow the eventual receivers to identify the packets that were XORed at the intermediate node and b) to also identify, even when the transmission over the final hop is corruption free, packets which were corrupted on an initial hop. In this paper, we assume that the overhead due to this meta-data is negligible and due to brevity do not explicitly study the impact of such an assumption.

2) **Slotted Communication:** For ease of analysis we assume a slotted communication. In addition we assume that the communication proceeds in terms of “*Exchange*” of individual packets. Thus each *Exchange* involves the transmission of 1 packet each from A to B and B to A. In an *Exchange*, packets are initially transmitted over link 1, 2 and then over links 3, 4. Thus a scheme employing NC uses three transmission slots in each *Exchange*, while a non-NC scheme uses 4 slots. If for some reason a packet involved in an *Exchange* cannot be successfully transmitted within the slots allocated for the *Exchange*, the packet is considered dropped.



**Figure 2 Mutual Exchange Between Two Nodes**

Given the brevity of space, the above assumptions allow us to focus on issues core to the proposed work, without significantly compromising the validity of the analysis and conclusions.

In this section, in order to get an estimate of the performance gain of utilizing CLIX, we assume that the communication over links 1, 2, 3 and 4 is governed by an abstract channel. Similar to the discussion in [8], for communication over each of the links we can consider a channel determined by 3 parameters, namely,

- 1)  $\delta$  which denotes the probability that at least a single bit is in error in the header and/or in the data payload.
- 2)  $\lambda$  is the probability that the packet header contains at least a single bit in error.
- 3)  $\varepsilon$  is the conditional probability of error in a packet conditioned on the event that a packet is corrupted and on the event that the header of the corrupted packet is error free.

The CL protocol we consider in this paper, drops the packet if and only if the header is corrupted. Note that a traditional (Trad) protocol drops a packet when either the data or payload has an error. Thus  $\delta(\lambda)$  denotes the probability of a packet getting dropped when a link employs a Trad (CL) protocol. We use  $C_A$  ( $C_B$ ) to denote the throughput capacity from *B* to *A* (*A* to *B*).

The throughput capacity is determined by two factors, the number of slots that are required to exchange packets and also by the actual information rate in the received packets. The information rate can be reduced due to presence of bit errors or due to packet drops. Thus on the basis of the arguments presented in [8] it can be shown that the throughput capacity of schemes Trad and CL, which do not employ any NC is given by equation (1) and (2):

$$C_{A\_trad} = \left(\frac{1}{4}\right) \cdot (1 - \delta_A), \quad C_{B\_trad} = \left(\frac{1}{4}\right) \cdot (1 - \delta_B) \quad (1)$$

$$\left. \begin{aligned} C_{A\_CL} &= \left(\frac{1}{4}\right) \cdot \left( (1 - \delta_A) + (\delta_A - \lambda_A)(1 - h_b(\varepsilon_A)) \right) \\ C_{B\_CL} &= \left(\frac{1}{4}\right) \cdot \left( (1 - \delta_B) + (\delta_B - \lambda_B)(1 - h_b(\varepsilon_B)) \right) \end{aligned} \right\} \quad (2)$$

where,

- (i)  $\delta_A = 1 - (1 - \delta_2)(1 - \delta_4)$ ,  $\delta_B = 1 - (1 - \delta_1)(1 - \delta_3)$  denote the end-to-end packet drop probability in Trad.
- (ii)  $\lambda_A = 1 - (1 - \lambda_2)(1 - \lambda_4)$ ,  $\lambda_B = 1 - (1 - \lambda_1)(1 - \lambda_3)$  denotes the end-to-end packet drop probability in CL.
- (iii)  $\varepsilon_A = (\varepsilon_2 * \varepsilon_4)$ ,  $\varepsilon_B = (\varepsilon_1 * \varepsilon_3)^2$  denotes the conditional probability of error in the corrupted un-erased packets received in CL communication at *Receiver A* and *B* respectively.

When NC is employed in conjunction with Trad, the packet drop process is identical to that of Trad; however the exchange occupies less number of slots. Thus throughput capacity for NC (similar to the discussion in [6]) is given by

$$C_{A\_NC} = \left(\frac{1}{3}\right) \cdot (1 - \delta_A), \quad C_{B\_NC} = \left(\frac{1}{3}\right) \cdot (1 - \delta_B) \quad (3)$$

<sup>2</sup> **Note:** Operator “\*” is s.t.  $p_1 * p_2 = p_1 \cdot (1 - p_2) + p_2 \cdot (1 - p_1)$

Similarly, the throughput capacity of CLIX is given by

$$\left. \begin{aligned} C_{A\_CLIX} &= \left( \frac{1}{3} \right) \cdot \left( (1 - \delta_{A\_CLIX}) + (\delta_{A\_CLIX} - \lambda_{A\_CLIX}) (1 - h_b(\varepsilon_{A\_CLIX})) \right) \\ C_{B\_CLIX} &= \left( \frac{1}{3} \right) \cdot \left( (1 - \delta_{B\_CLIX}) + (\delta_{B\_CLIX} - \lambda_{B\_CLIX}) (1 - h_b(\varepsilon_{B\_CLIX})) \right) \end{aligned} \right\} \quad (4)$$

where,

- (i)  $1 - \delta_{A\_CLIX}$  and  $1 - \delta_{B\_CLIX}$  represent the probability of receiving a packet uncorrupted and un-erased at *Receiver A* and *B* respectively.
- (ii)  $(\delta_{A\_CLIX} - \lambda_{A\_CLIX})$  and  $(\delta_{B\_CLIX} - \lambda_{B\_CLIX})$  represent the probability that a packet is received un-erased but corrupted.
- (iii)  $\varepsilon_{A\_CLIX}$  and  $\varepsilon_{B\_CLIX}$  represent the conditional probability of error in corrupted-unerased packets.

Note that:

1) A CLIX packet is received error free (e.g., by receiver *B*), if and only if, the transmission on both hops (e.g., links 1 and 3 in Figure 2) is corruption free **and** a packet is not XOR-ed with a corrupted packet (which happens either under error-free transmission over link 2 or a packet is dropped due to an error in the header over link 2, and hence no XOR-ing takes place). Thus we can deduce,

$$\left. \begin{aligned} \delta_{A\_CLIX} &= 1 - (1 - \delta_2)(1 - \delta_4)(1 - \delta_1 + \lambda_1) \\ \delta_{B\_CLIX} &= 1 - (1 - \delta_1)(1 - \delta_3)(1 - \delta_2 + \lambda_2) \end{aligned} \right\} \quad (5)$$

2) A packet is erased if and only if it encounters header corruption on either of the hops, thus  $\lambda_{A\_CLIX} = \lambda_A$ ,  $\lambda_{B\_CLIX} = \lambda_B$ .

3) There are seven possibilities that can lead to a packet being corrupted, but not being erased. (Four of these possibilities include a corruption due to XOR-ing with a corrupted packet.) The average probability of error over all such possibilities allows us to calculate  $\varepsilon_{A\_CLIX}$  and  $\varepsilon_{B\_CLIX}$ . Due to brevity, it is not feasible to step through each of these possibilities, but it can be easily shown that

$$\varepsilon_{A\_CLIX} = \left. \begin{aligned} &(1 - \delta_1 + \lambda_1) \cdot \left\{ \begin{aligned} &(1 - \delta_2)(\delta_4 - \lambda_4)\varepsilon_4 \\ &+ (1 - \delta_4)(\delta_2 - \lambda_2)\varepsilon_2 \\ &+ (\delta_2 - \lambda_2)(\delta_4 - \lambda_4)(\varepsilon_2 * \varepsilon_4) \end{aligned} \right\} + \\ &(\delta_1 - \lambda_1) \cdot \left\{ \begin{aligned} &(1 - \delta_2)(1 - \delta_4)\varepsilon_1 + \\ &(1 - \delta_4)(\delta_2 - \lambda_2)(\varepsilon_1 * \varepsilon_2) + \\ &(1 - \delta_2)(\delta_4 - \lambda_4)(\varepsilon_1 * \varepsilon_4) + \\ &(\delta_2 - \lambda_2)(\delta_4 - \lambda_4)((\varepsilon_1 * \varepsilon_2) * \varepsilon_4) \end{aligned} \right\} \end{aligned} \right\} \quad (6)$$

A similar expression can be deduced for  $\varepsilon_{B\_CLIX}$ .

#### Capacity For Parameter Values That Represent 802.11b:

There indeed exists some combination of values for the above considered parameters, such that the performance of CLIX does not provide any advantage over NC or CL and similarly there exist values for which CLIX can provide benefits. However, an important question to be raised is, "Which of these combinations are more likely to be observed on actual wireless channels?" For this purpose, we evaluate the values of  $\delta, \lambda, \varepsilon$ , on the basis of actual 802.11b error traces. The methodology for our trace collection is identical to [7], [9]. We collected traces, with a total MAC-frame size of 1024 bytes which included a combined header size of 60 bytes. The traces were collected at a PHY data rate of

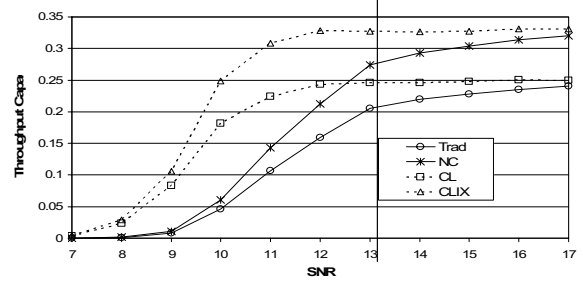


Figure 3 Capacity for parameter values based on 802.11b

11Mbps. In [9] we show that a Signal to Noise Ratio (SNR) can be associated with each received packet and thus the parameters  $\delta, \lambda, \varepsilon$  can also be evaluated as a function of SNR. For additional details of the trace collection methodology please refer to [7], [9]. In this sub-section, for ease of analysis we assumed links 1, 2, 3, and 4 to be governed by identical values of SNR and hence of identical  $\delta, \lambda, \varepsilon$ . Thus  $C = C_A = C_B$  and can be expressed as a function of SNR. Figure 3 shows the result of such an evaluation. It can be seen that CLIX provides a better throughput capacity than any other scheme for all SNR values. A marker has been put on Figure 2 to roughly demarcate (a) the SNR region where the CL aspect of CLIX allows it to perform better than NC from (b) the SNR region where the NC part of CLIX allows it to perform better than CL

### 3. 802.11B TRACE BASED SIMULATIONS

The actual 802.11b channel exhibits temporal correlation in the error process, both at the packet level and at the bit-level. Thus in the previous section, though the values of  $\delta, \lambda, \varepsilon$  were derived on the basis of actual traces, they may not capture the behavior of the 802.11b channel. Thus it is important to simulate the behavior of the considered schemes on actual sample traces. For this

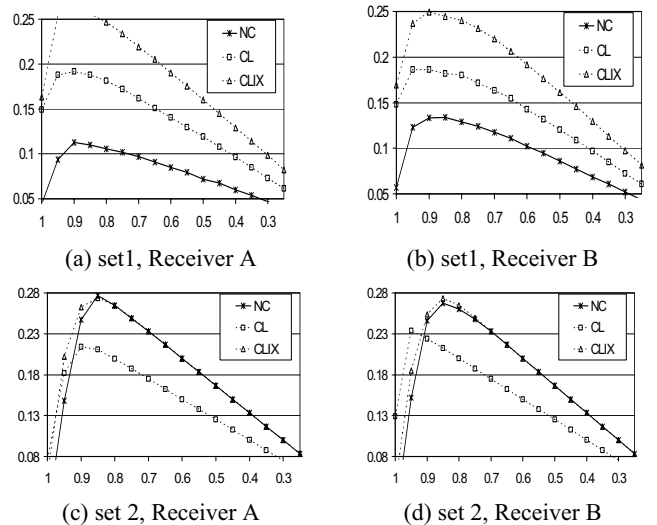


Figure 4 Goodput as a function of coding rate. In each of the above sub-figures, y-axis represents goodput, while x-axis represents channel coding rate. The goodput has been calculated as the number of message packets received, per slot, after FEC decoding. Thus the best possible goodput for NC and CLIX is 0.33, while the best possible goodput for CL is 0.25.

purpose we consider 2 sets of error traces. Each set consists of 4 traces, one to emulate each link. Each trace consists of 40,000 packets. The error traces in two sets, *Set 1* and *Set 2*, are such that *Set 1* represents a scenario where the communication over each link is highly susceptible to packet corruption, while *Set 2* represents a scenario where packet corruptions are relatively rare. More specifically, the average SNR for each trace in *Set 1* was lesser than 14dB, while the SNR for each trace in *Set 2* was in the range of 18-30dB. As mentioned in the previous section, each MAC-frame in the error trace is of size 1024 bytes and consists of a combined header size of 60 bytes. A CL scheme drops the packet whenever there is an error in the first 60 bytes of the frame, while a non-CL scheme drops the packet whenever there is an error in any of the 1024 bytes in the frame.

#### **FEC Analysis:**

We considered the performance of Reed Solomon (RS) based FEC schemes, employed in conjunction with NC, CL and CLIX, for *Set 1* and *2*. The FEC block-length was chosen in a manner to ensure that an FEC block gets exchanged in 240 transmission slots. Thus packet block-length for CL was chosen to be 60, while the block-length for NC and CLIX was chosen to be 80. Each FEC block, consisted of 964 codewords interleaved over the packets, such that each packet contributed a symbol in  $GF(255)$  for each codeword. Figure 4 shows the FEC performance for each scheme in terms of *goodput*. Note that the bad (good) channel conditions associated with *Set 1* (*Set 2*) are exhibited by the fact that the *goodput* of CL (NC) is better than NC (CL). For both scenarios, the performance of CLIX is better than CL. The comparison of NC and CLIX, shows that when packet corruptions are rare, CLIX and NC perform identically, however when the conditions deteriorate, the performance of CLIX is significantly better.

#### **Video Analysis:**

In this sub-section, we evaluate, whether the improvement in *goodput* can be translated into improvement in video quality. The results in this section are based on utilizing H.264 version 10.2 reference software. The picture frame size is maintained at 352x288 for all test sequences. The test-sequences are repeated multiple times to provide a playout sequence of 900 frames i.e. 30sec at 30fps. The GOP (IBBPB...) size is 30 frames. All standard error concealment features have been turned on, a video packet size of 1024 bytes is used and specific source bit-rates are obtained using standard rate-control.

**Table 1 Video Quality offered by NC, CL, CLIX to Receiver A<sup>1</sup>**

Set	Scheme	video	Source Bit Rate	Coding Rate	Frames Recovered	PSNR(dB)
1	CL	foreman	1.2Mbps	0.7	82%	26.2
1	NC	foreman	1.6Mbps	0.7	12%	13.1
1	CLIX	foreman	1.6Mbps	0.7	93%	29.2
1	CL	akiyo	1.2Mbps	0.7	81%	35.8
1	NC	akiyo	1.6Mbps	0.7	13%	15.3
1	CLIX	akiyo	1.6Mbps	0.7	93%	37.6
2	CL	foreman	1.2Mbps	0.7	100%	41
2	NC/CLIX	foreman	1.6Mbps	0.7	100%	42.1
1	NC	foreman	1.2Mbps	0.525	14%	13.8
1	CLIX	foreman	1.2Mbps	0.525	97%	30.1
1	NC	akiyo	1.2Mbps	0.525	18%	17.8
1	CLIX	akiyo	1.2Mbps	0.525	98%	40.6

<sup>1</sup>Despite all the error-concealment features being turned on, some picture frames are not recovered at all, thus leading to severe motion discontinuity.

In NC and CLIX, the additional bandwidth can be used for either increasing the source bitrate or to increase the parity. Hence the experiments in this section can be broken into two parts: (a) where the channel coding rate for CL, NC, and CLIX is identical and (b) where the source coding rate for CL, NC, CLIX is identical. As done in the previous subsection, the FEC block-length for CL is maintained at 60 packets, while that for NC and CLIX is maintained at 80 packets. First 8 rows of Table 1 provide the results for part (a) while the last 4 rows provide the results for part (b). Due to brevity, we present only a part of the results, and only for *Receiver A*.

For part (a), the channel coding rate is maintained at 0.7, thus the source bitrate used for NC and CLIX is 4/3 times that used for CL. In Table I, results associated with *Set 1* exhibit that, when the channel conditions are bad, the video quality offered by CL and CLIX can be significantly better than that of NC. In addition, it can be incurred that CLIX can provide substantial improvement over CL too, especially in terms of motion continuity. Observations associated with *Set 2* highlight the efficiency with which CLIX combines the advantages of NC and CL.

In poor channel conditions the additional bandwidth available to NC and CLIX is better used by providing additional redundancy. Thus for part (b), the source bit-rate was maintained constant at 1.2 Mbps for all three schemes, while a channel coding rate of 0.525 was used for NC and CLIX. The additional redundancy proves to be useful as shown in Table I. Nevertheless, the performance of CLIX is still substantially better than NC and CL.

## 4. CONCLUSIONS

In this paper, we evaluated the feasibility of employing NC in presence of severe bit corruptions in the packet. It is observed, even for the actual 802.11b wireless channel, that advantages of NC and CL can be efficiently combined. Theoretical and experimental deductions exhibited that CLIX provides an improvement in throughput capacity, FEC *goodput* and video quality.

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