Does Relay of Corrupted Packets Increase Capacity?

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Abstract—Cross-layer protocols that are designed for wireless exhibit both errors and erasures. The nature of these error/erasure impairments and their impact on capacity is a function of the particular cross-layer scheme used. In this paper, we consider two (rather abstract) communication schemes, cross layer design (CLD) and cross layer design with side-information (CLDS). We make a comparative analysis of the channel capacities of these schemes over single and multi-hop wireless channels to identify the conditions under which the cross-layer protocols/channels can provide improved performance over traditional (pure) erasure channels. We show that cross-layer schemes like CLD lead to a capacity increase in most realistic channel scenarios (especially over a single hop) and schemes such as CLDS always lead to a capacity increase.

I. INTRODUCTION

In order to provide support for high bitrate transmission and improve other network functionalities over wireless networks, there is an increased willingness to allow inter-layer communication [1], [2]. Network strategies, which allow cross-layer information transmission, have been broadly classified as cross-layer protocols [1]-[8]. A complete redesign of the entire stack would naturally facilitate an improved performance, but due to the large-scale deployment of existing standards, such an approach is impractical. Hence, the current attempts at designing cross-layer protocols have to comply with existing architectures. However, clever manipulation of some of the already available functionalities can lead to a vast improvement. UDP-lite protocol and its extensions [4]-[7] are one such example. In this scheme the link-layer check sums are turned off (i.e., the MAC [7] layer passes corrupted packets to the transport layer), while the transport layer CRC checks are run only over the packet header instead of the entire packet. This leads to a reduced number of packet drops on account of residue errors[1] and thus a reduced number of erasures at the application layer. Bandwidth hungry video applications can benefit immensely from such modifications [4], [6], [7].

However, it should be noted that such a modification leads to the existence of errors at the application layer. It is well known that the erasure correcting capability of any code is much better than its ability to correct symmetric errors. Thus allowing the existence of corrupted packets at the application layer can lead to a reduction in throughput and channel capacity. If the number of errors in the corrupted packets is not large, then the total number of channel failures is reduced. This reduction in total number of failures can lead to an increase in channel capacity. Thus there is an inherent tradeoff between allowing and disallowing the relay of corrupted packets to the application layer. Thus the principle goal of the presented work is to analyze this tradeoff and identify the channel conditions under which the existence of corrupted packets at the application layer can be preferred over dropping them entirely.

Previous studies, [4]-[7] have assumed that the probability of bit-error in the corrupted packets is always low enough to render the performance of a cross-layer approach to be better than a conventional one. However it was shown in [7] that the choice between a cross-layer scheme such as UDP-lite/Mac-lite and the conventional stack is not always straightforward. Moreover none of the previous studies have extended the cross-layer approach of allowing the relay of corrupted packets to a multi-hop scenario. The level of corruption in a packet increases as it iteratively undergoes impairments when relayed over multiple wireless hops. Thus the above-mentioned tradeoff needs to be analyzed and studied in greater detail.

In order to keep the discussion generic and not dependent on a particular implementation (or standard), in this paper we consider three communication schemes (a) transmission over erasure channels, which represents the conventional protocols like UDP (CON) (b) transmission in presence of erasures and errors using a cross-layer design (CLD), which is representative of cross-layer schemes like UDP-lite (c) side-information enhanced transmission in presence of erasures and errors using a cross-layer design (CLDS). Detailed description of these schemes is provided in section II. Moreover, in section III we evaluate the channel capacity of each of the above schemes. A comparative analysis of the channel capacities, in order to identify the conditions under which the cross-layer protocols can provide improved performance, is also presented in this section.

Section III provides the principle analysis and primary results of this work. Section IV is a discussion section which further analyzes some of the associated sub-problems and provides a more detailed justification for some of the assumptions made in section III. In particular, 1) in Section IV.A we consider the dependence of the CON, CLD, CLDS channel capacities on the link-layer channel model for some simple channel models, 2) in Section IV.B we show how the capacity of the cross-layer scheme can get affected if a part of the network doesn't comply with the cross-layer architecture,

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[1] Errors are encountered at the link layer only when the physical layer error control fails and thus link layer errors can be termed as residue errors.

3) section IV.C studies the impact of embedding error control within the network on the capacity of the considered schemes.

Finally, we provide the summary of our conclusions and future work under consideration in section V.

II. CHANNEL CHARACTERIZATION

In this section we primarily characterize the channel of the three protocols under consideration when the transmission is over a single wireless link. In a later of the part of the paper we show that this characterization can be easily extended to a multi-hop scenario.

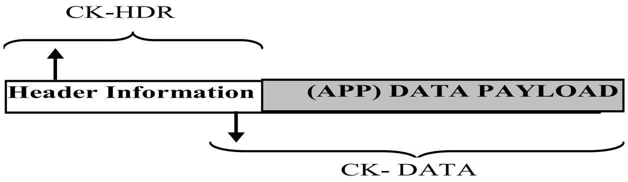

Figure 1 A single Logic Transmission Unit (LTU)

The three communication schemes considered in this paper can be explained by considering a generic Logic Transmission Unit (LTU) as shown in Figure 1. The general packet structure can be segregated into two parts:

1) The header information[2] and 2) The data payload.

In addition to traditional header information (e.g., node addresses), the LTU header contains two sets of check sums[3] CK-HDR and CK-DATA. The CK-HDR checksum is applied to and dependent on the header information only; while the CK-DATA check sum is applied to and dependent on the data payload only. Hence, under this generic LTU model:

- The conventional (non-cross layer) protocols drop a packet if either of the checksums CK-HDR, or CK-DATA is not satisfied.
- CLD, which represents protocols like UDP-lite [4]-[6], turns the CK-DATA checksum off and drops the packet only if CK-HDR is not satisfied. Therefore, a CLD channel exhibits both erasures (due to CK-HDR violations) and possible errors in some of the delivered packets. It is important to note that (without further information or additional parity bits) the CLD channel receiver does not know which delivered packets are error-free and which packets are corrupted. It only distinguishes between erasures and delivered packets.
- CLDS is a new alternative to the above schemes. Similar to CLD, a CLDS channel drops a packet only if CK-HDR is not satisfied. However, in CLDS the CK-DATA is not turned off but neither is the decision to drop a packet dependent on this checksum. Moreover CK-DATA and information about the success or failure of this check-sum is made available to the application layer as side information. Therefore, and unlike a CLD receiver, the CLDS receiver can distinguish corrupted packets from error-free packets.

Thus the channels under consideration can be characterized as given below:

- δ is the probability that at least a single bit is in error in the header and/or the data payload. Thus δ is the probability of a packet being dropped in a conventional (non-cross layer) protocol because at least one of the check sums, CK-HDR and/or CK-DATA, was not satisfied.
- λ is the probability that the packet header contains at least a single bit in error. Thus λ is the probability of packet being dropped in the cross-layer schemes because the check CK-HDR was not satisfied. (Note that this event could occur regardless if there is an error within the packet data or not.)Thus $\delta-\lambda$ represents the probability of a corrupted packet being delivered to a CLD/CLDS channel receiver.
- ε is the conditional probability of a bit in the data payload being in error given that the checksum CK-HDR is satisfied and checksum CK-DATA has failed. Given a corrupted packet at a CLD/CLDS receiver, ε represents the probability of having a random bit selected from that packet to be in error. Thus the probability of bit error is given by $(\delta-\lambda)\cdot\varepsilon$. Let p be the conditional probability that a bit in an unerased packet is in error. By definition of the above parameters we can deduce that $p=\dfrac{(\delta-\lambda)\cdot\varepsilon}{(1-\lambda)}$.
- For a cross-layer protocol with side-information (CLDS) let Z be a discrete random variable that takes on three possible outcomes: $S_z=\{0,1,?\}$. Where,
  - ***Z*** = ? if the header contains at least single bit error and CLDS drops the packet . Thus $p(Z=?)=\lambda$
  - ***Z*** = 0 if a packet contains no errors in the header but contains at least a single bit error in the data payload. Thus $p(Z=0)=(\delta-\lambda)$
  - ***Z*** = 1 if neither the header nor the data payload contain even a single erroneous bit. Thus $p(Z=1)=(1-\delta)$.

III. CAPACITY EVALUATION

The channel capacities of the above-described channels can be expressed as:

- It is well known [9] that the channel capacity of a BEC is given by $1-\delta$, thus capacity of a conventional protocol is given by

$$C_{CON}=1-\delta \qquad (1)$$

- The cross-layer channel can be represented as a cascade of a BEC channel with probability of erasure equal to λ followed by a Binary Symmetric Channel (BSC) with

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[2] In practical implementations the header and CK-HDR might be further partitioned into multiple headers and checksums. In addition, it is noteworthy that we assume that the total number of bits in the header and the total number of bits in the data payload remain exactly identical for all the three communication schemes outlined above.

[3] In this paper we assume that probability of false alarm and the probability of missed detection of the checksums is negligibly small. For most practical implementations using Cyclic Redundancy Check (CRC) based checksums this assumption is indeed very appropriate.

probability of bit error equal to p. It can be easily shown that the channel capacity of such a cascade is given by the product of the channel capacities of the individual channels:

$$C_{CLD} = (1-\lambda)\cdot(1-h_b(p)) \tag{2}$$

- The channel capacity of the cross-layer channel in presence of side information $\boldsymbol{Z}$ is as follows: when $\boldsymbol{Z}=1$ all the bits are transmitted reliably and conditional capacity is 1, when $\boldsymbol{Z}=?$ all the bits get erased and conditional capacity is 0 while when $\boldsymbol{Z}=0$ the channel reduces to BSC with cross-over probability ε and conditional capacity is $(1-h_b(\varepsilon))$. Thus the channel capacity of CLDS is given by

$$C_{CLDS} = (1-\delta)+(\delta-\lambda)\cdot(1-h_b(\varepsilon)) \tag{3}$$

A. Transmission over multiple-hops

A multi-hop wireless channel can be represented as a cascade of channels. For example, a cascade of BEC channels can represent the conventional scheme, where a distinct BEC channel in the cascade represents each link. Similar cascade of channels can be made for the cross-layer schemes too. However, in case of CLDS it should be noted that the side information Z shall depend on the cumulative errors encountered over all the hops. Thus expressions for capacities over multiple hops are given by equations (4), (5), (6).

$$C_{CON(n-hop)} = \prod_{i=1}^{n}(1-\delta_i) \tag{4}$$

$$C_{CLD(n-hop)} = \left(\prod_{i=1}^{n}(1-\lambda_i)\right)\cdot\left(1-h_b\left(\mathop{*}_{i=1}^{n} p_i\right)\right) \tag{5}$$

Note: In this paper the operator $*$ is defined such that

$$p_1 * p_2 = p_1\cdot(1-p_2)+p_2\cdot(1-p_1) \text{ and}$$

$$\mathop{*}_{i=1}^{n} p_i = (p_1 * p_2) * p_3)\cdots) * p_i)\cdots) * p_n)$$

$$C_{CLDS(n-hop)} = \left(\prod_{i=1}^{n}(1-\delta_i)\right)+\left(\prod_{i=1}^{n}(1-\lambda_i)\right)\cdot \left(1-h_b\left(\left(\frac{1-\left(\prod_{i=1}^{n}(1-\lambda_i)\right)}{\left(\prod_{i=1}^{n}(1-\delta_i)\right)-\left(\prod_{i=1}^{n}(1-\lambda_i)\right)}\right)\cdot\left(\mathop{*}_{i=1}^{n} p_i\right)\right)\right) \tag{6}$$

However for most of the remaining paper we find it sufficient to maintain the discussion in terms of $\delta,\ \lambda,\ p,\ \varepsilon$ because equations (1), (2) and (3) can be converted into equations (4), (5), and (6) respectively. This can be achieved by substituting parameters $\delta,\ \lambda,\ p,\ \varepsilon$ in equations (1), (2) and (3) by $\delta_1+\sum_{i=2}^{n}\left(\delta_i\cdot\prod_{j=1}^{n-1}\delta_j\right)$, $\lambda_1+\sum_{i=2}^{n}\left(\lambda_i\cdot\prod_{j=1}^{i-1}\lambda_j\right)$, $\left(\mathop{*}_{i=1}^{n} p_i\right)$ and $\left(\frac{1-\lambda}{\delta-\lambda}\right)\cdot p$ respectively.

B. Comparative Analysis

In order to clearly establish the channel parameters under which a particular protocol offers better performance, we present a couple of lemmas.

Lemma 1: $C_{CON} > C_{CLD} \iff h_b(p) > (p/\varepsilon)$

Lemma 1 tells us that for a given $\delta,\ \lambda,$ there exists a threshold $\varepsilon_{\min}$ such that if the level of corruption in the corrupted (but not dropped) packets is greater than this threshold then the conventional schemes shall perform better than the cross-layer scheme CLD. Thus, $\varepsilon_{\min}$ divides the parameter space into two separate regions and thus demarcates the region over which cross-layer schemes can perform better than the conventional scheme. Such a threshold can be used to improve the efficiency of a communication scheme, in scenarios where side-information from the physical layer or some steady state channel statistics (or some other method) may make it possible to acquire an estimate of the corruption level in a packet. This estimate in conjunction with $\varepsilon_{\min}$ can allow us to identify the highly corrupted packets, which might be preferred to be dropped. In Figure 2 we plot $\varepsilon_{\min}$ as a function of $1-\delta$ for different parameter values of λ.

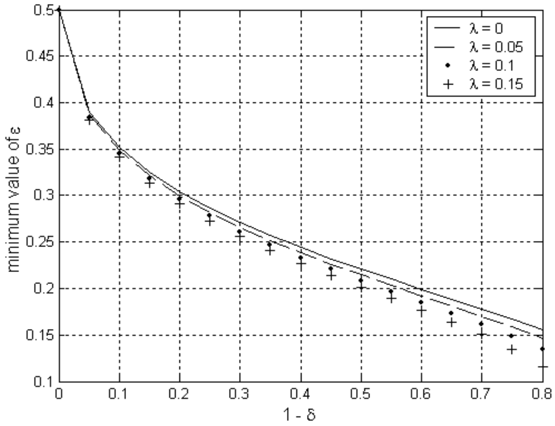

Figure 2 $\varepsilon_{\min}$ as a function of $1-\delta$

Lemma 2: *a*) $C_{CLDS} \ge C_{CON}$ with equality occurring iff $\varepsilon = 0.5$ or $\delta = \lambda$. (*b*) $C_{CLDS} \ge C_{CLD}$ with equality occurring iff $\delta = \lambda$.

Proof: a) Since $(\delta-\lambda)\cdot(1-h_b(\varepsilon)) \ge 0$. Equality occurs iff $(\delta-\lambda)\cdot(1-h_b(\varepsilon)) = 0$, i.e. iff $\delta=\lambda$ or $h_b(\varepsilon)=1$ i.e. $\varepsilon = 0.5$.

b) This result can be proved by using the following fact:
If $f^{'}(x)$ is strictly monotonically decreasing over $[a,b]$ then $\forall \alpha,\beta \in [a,b]$, $\alpha,\beta \neq 0$, $\alpha < \beta \Rightarrow \dfrac{f(\alpha)}{\alpha} > \dfrac{f(\beta)}{\beta}$. Notice that $h_b^{'}(x)$ is strictly monotonically decreasing for $\forall x \in [0,1]$. As $1-\lambda \geq 1-\delta$ it can be shown that $p \leq \varepsilon$, which implies that $\dfrac{h_b(p)}{p} \geq \dfrac{h_b(\varepsilon)}{\varepsilon}$. Thus, substituting for p we get $(1-\delta)+(\delta-\lambda)\cdot(1-h_b(\varepsilon)) \geq (1-\lambda)\cdot(1-h_b(p))$ which in conjunction with equations (2) and (3) completes the proof.

Note that equality can occur only when $p=\varepsilon$, which is possible iff $\delta=1$. Thus the capacity of the CLDS scheme is provably better than both CLD and CON.

Previous work based on "lite" protocols fails to highlight that the capacity of CLD like protocols can drop below that of CON. Though turning off the checksum at the lower layer can increase the application layer packet throughput, it also leads to loss of vital side information useful for error localization. This loss of side-information is primarily responsible for the drop in capacity of CLD relative to the CON scheme. It should be noted that this problem is indeed resolved by the CLDS scheme as the CK-DATA is not turned off in the CLDS scheme.

Figure 3 shows a comparison of the channel capacities offered by the three protocols considered above. It can be clearly seen that the cross-layer protocols can provide dramatic improvements in capacity when the corruption level in packets is low. However, it can be clearly observed as the corruption level increases (this can happen either on account of a very noisy link or on account of multiple impairments over multiple hops), the capacity of CLD can drop below that of the CON. Experiments with 802.11b WLAN [7] have shown that for a single-hop the performance of CLD is almost always better than CON, however it should be quite evident that such a conclusion cannot be generalized for all standards, or even for multi-hop transmission over 802.11b. As against this and as should have been expected the capacity of CLDS scheme at the very worst drops to a value that is equivalent to the capacity of the CON scheme[4].

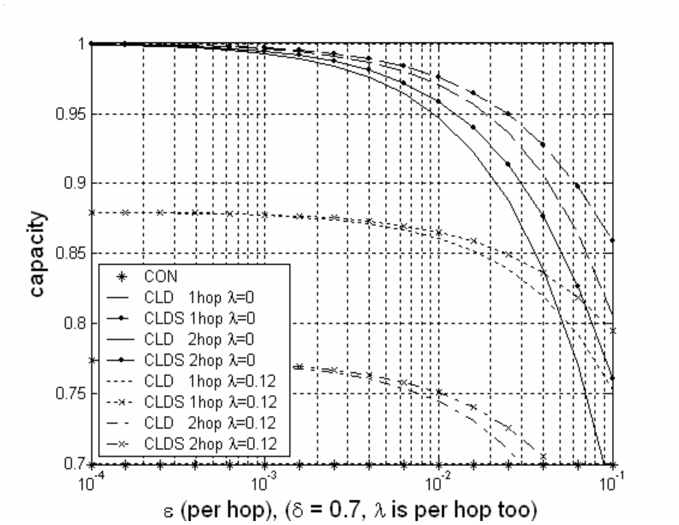

Figure 3 Comparison of channel capacity

IV. DISCUSSION

A. Dependence on the link-layer channel

In the previous section and the subsequent sections we have parameterized $\delta,\ \lambda,\ \varepsilon$, however these parameters are not actually independent of each other and are infact a function of the underlying link-layer channel. Assuming a specific link-layer channel can indeed lead to more precise conclusions and render some of the regions (combinations of $\delta,\ \lambda,\ p$) described in the previous section unachievable. Currently [7], [8] is the only study we are aware of which has extensively tried to model the link-layer channel. As [7], [8] primarily concentrate only on the 802.11b standard, we prefer parameterizing the channel as we have, since this allows us to conduct a more generalized analysis and whenever necessary $\delta,\ \lambda,\ p$ can be expressed in terms of the under-lying channel to derive more precise expressions. This section provides an example of such analysis. However, for the rest of the paper we continue to assume that $\delta,\ \lambda,\ \varepsilon$ are independent. For the remainder of the sub-section we let the h and d represent the number of header and payload bits respectively.

A.1.Link Layer Binary Symmetric Channel

If we assume the link-layer channel to be a BSC channel with cross-over probability q then we can conclude that $\delta = 1-(1-q)^{(h+d)}$, $\lambda = 1-(1-q)^{h}$ and $\varepsilon = q$. Thus, the channel capacities are given by

$$C_{CON} = (1-q)^{(h+d)} \qquad (7)$$

$$C_{CLD} = (1-q)^{h} \cdot \left(1 - h_b\left(\left(1-(1-q)^{d}\right)\cdot q\right)\right) \qquad (8)$$

$$C_{CLDS} = (1-q)^{h} \cdot \left(1 - \left(\left(1-(1-q)^{d}\right)\cdot h_b(q)\right)\right) \qquad (9)$$

Lemma 3: $\forall\, q \in (0,0.5)$, $\exists\, d_{\min} \geq 0$ s.t, $d \geq d_{\min} \Leftrightarrow C_{CLD} \geq C_{CON} \Leftrightarrow$ equality occurs iff $d = d_{\min}$.

Note: $\left(1\text{-}(1\text{-}q)^{d}\right) \geq h_b\left(\left(1\text{-}(1\text{-}q)^{d}\right)\cdot q\right) \Leftrightarrow C_{CLD} \geq C_{CON}$

The above lemma can be proved by showing that the equation $\left(1\text{-}(1\text{-}q)^{d}\right) = h_b\left(\left(1\text{-}(1\text{-}q)^{d}\right)\cdot q\right)$ can at maximum have a single non-negative solution d_{sol}. Moreover it should be observed that $\lim\limits_{d\to\infty} h_b\left(\left(1\text{-}(1\text{-}q)^{d}\right)\cdot q\right) = h_b(q)$ which is less

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[4] At this stage it is important to provide a caution that for some of the currently existing standards realizing a CLDS like protocol might require addition of a new field in the packet header.

than $\lim_{d\to\infty}\left(1-(1-q)^d\right)=1 \quad \forall\, q\in(0,0.5)$. Thus if a solution to the above equation does not exist it can be concluded that $C_{CLD}\geq C_{CON}$ while if a solution does exist than $\forall\, d>d_{sol}$, $\left(1-(1-q)^d\right)>h_b\left(\left(1-(1-q)^d\right)\cdot q\right)$. This proves the above lemma. Further details in the proof have been skipped on account of the brevity of space.

Similar to lemma 1, lemma 3 divides the parameter space into 2 halves. However, the value of $d_{\min}$ even for $q=0.4$ (value of $d_{\min}$ is strictly monotonic with q) is less than 20 bytes. Thus if the link-layer channel resembles a BSC the CLD scheme is better than CON almost always.

A.2. Link Layer 2- state Channel

The deduction made above can be generalized by considering a channel over which all the packet transmissions are not necessarily susceptible to errors. Such a behavior is very possible on time-varying channels and over wireless networks with dynamic topologies. Thus let's consider a channel over which only a fraction η number of the total transmitted packets are susceptible to errors. When packet transmissions are indeed susceptible to errors, the behavior of the link-layer channel can be assumed to be equivalent to a BSC with crossover probability of θ. For such a channel it can be shown that $\varepsilon=\theta$, $\delta=\eta-(1-\theta)^{(h+d)}$ and $\lambda=\eta-(1-\theta)^h$. Thus it can be shown that the channel capacities of the three schemes are

$$C_{CON}=1-\eta+(1-\theta)^{(h+d)} \tag{10}$$

$$C_{CLD}=\begin{pmatrix}1-\eta+\\(1-\theta)^h\end{pmatrix}\cdot\left(1-h_b\left(\frac{(1-\theta)^h\cdot\left(1-(1-\theta)^d\right)\cdot\theta}{1-\eta+(1-\theta)^h}\right)\right) \tag{11}$$

$$C_{CLD}=\begin{pmatrix}\left(1-\eta+(1-\theta)^{(h+d)}\right)+\\(1-\theta)^h\cdot\left(1-(1-\theta)^d\right)\cdot\left(1-h_b(\theta)\right)\end{pmatrix} \tag{12}$$

It should be observed that the expressions (7), (8) and (9) for the BSC case could be obtained from the above equations by setting $\eta=1$.

Figure 4 shows the comparison of the capacities of the three schemes for header and payload sizes typical to the wireless LAN for $\eta=0.4$. Thus it's again quite evident that a cross-layer approach can provide significant improvements in capacity.

At this stage it is important to highlight that the capacity of a channel with memory is dependent on the amount of available state information. If no state information is available then the capacity is the least. Thus equation (10), (11) and (12) can be considered to be lower bounds on capacity when a link-layer channel can be described by a Finite State Markov Channel [10], [11]. In fact it should be noted that the capacity of CLDS is better than CLD purely on account of having a better estimate of channel conditions (which is possible due to the side information based on CK-DATA).

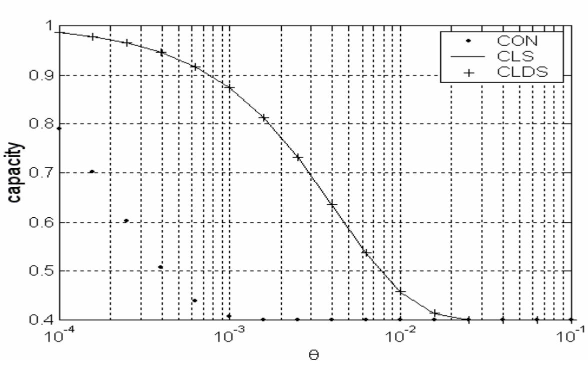

Figure 4 Capacity for h= 28 and d = 512 bytes

Furthermore, the examples considered in this section predict that it is not possible to achieve throughput improvements on account of a cross-layer channel when the number of errors in a packet is greater than 1%. This is contrary to the observations made in [7]. This apparent anomaly can also be explained by taking into consideration the role played by channel memory. The link-layer error traces used for [7] exhibited had a bursty nature and exhibited a clear temporal correlation within a packet. Thus the capacity of the channel studied in [7] is better than a memory less channel with identical error probability. We are currently analyzing the performance of CON, CLD and CLDS on link-layer channels with memory.

B. *Hybrid Architecture*

Throughout this paper we assume that the entire network path from the source to the destination is capable of supporting a cross-layer approach. However, as shown in Figure 5 that need not be the case always. If we assume that the total path consist of n-hops and hops m to s lie inside the "non cross-layer section" then the expression for capacity deduction would get modified as described below:

$$C_{CLD(n-hop)}=\left(\prod_{i=1}^{s}(1-\delta_i)\right)\cdot\left(\prod_{i=s+1}^{n}(1-\lambda_i)\right)\cdot\left(1-h_b\left(\mathop{*}_{i=s+1}^{n}p_i\right)\right) \tag{13}$$

$$C_{CLDS(n-hop)}=\left(\prod_{i=1}^{n}(1-\delta_i)\right)+\left(\prod_{i=1}^{s}(1-\delta_i)\right)\cdot\left(\prod_{i=s+1}^{n}(1-\lambda_i)\right)\cdot\left(1-h_b\left(\left(\frac{1-\left(\prod_{i=s+1}^{n}(1-\lambda_i)\right)}{\left(\prod_{i=s+1}^{n}(1-\delta_i)\right)-\left(\prod_{i=s+1}^{n}(1-\lambda_i)\right)}\right)\cdot\left(\mathop{*}_{i=s+1}^{n}p_i\right)\right)\right) \tag{14}$$

Thus it should be noted that the capacity improvement on account of a cross-layer approach can be severely diminished.

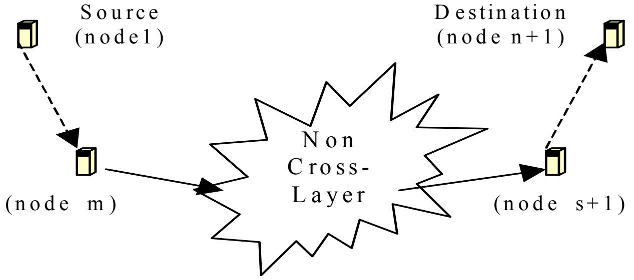

Figure 5 A Hybrid Network. In the above figure the links outside the star-cloud are cross-layer enabled but the links inside are not.

This can be avoided by addition of a field that keeps a count of the CK updates and then updating all the CK-DATA's at the last node (in this case node *m*) before the non cross-layer section begins. The end receiver can use the "*number of updates*" field in addition to CK-DATA to determine the corruption status of the payload.

C. Hop-by-Hop retransmissions

Hop-by-Hop retransmissions represent a possible way of embedding error control mechanisms within the network. Though this is the most commonly deployed method, other methods to embed error control mechanisms within the network do exist [12], [13]. Thus a network architecture, which allows embedded error control, needs separate attention and should be distinguished from end-end error control. Thus to provide a fair comparison between the cross-layer approach and the conventional approach we should permit the existence of network embedded error control in a cross-layer architecture too. The following schemes represent simple examples of embedding error control in the cross-layer architecture.

i) Hop-Hop retransmissions can be employed in a cross-layer scenario too. If the CK-HDR fails then a retransmission of the erased packet can be asked for.

ii) The schemes described in [12], [13] can be extended to work for a channel with erasure as well as errors.

iii) In the cross-layer scheme as the erasures are encountered on account of errors in the header, the headers can be made robust by embedding some FEC within each packet frame.

Thus it is quite evident that network scenarios, which permit, embedded error control merit detailed attention. On account of brevity of space we are unable to include such detailed analysis in this paper. However an interested reader can note that

a) The capacity of conventional channel employing hop-hop retransmissions is given by

$$C_{CON(retrans)} = 1 - \arg\max_{i\in[1,n]}\left(\delta_i\right) \qquad (15)$$

and the capacity of a CLD cross-layer channel employing hop-hop retransmissions as described in (i) is

$$C_{CLD(retrans)} == \left(1 - \arg\max_{i\in[1,n]}\left(\lambda_i\right)\right)\cdot\left(1 - h_b\left(\overset{n}{\underset{i=1}{*}} p_i\right)\right) \qquad (16)$$

b) Wireless LAN's usually consist of a single wireless hop. Thus for most WLANs it should be expected that the reliability offered by the considered cross-layer schemes in conjunction with FEC should be even better than a retransmission based scheme on the conventional stack.

V. CONCLUSION

The primary objective of this work was to draw attention at the utility of relaying corrupted packets and establish using reasonably simple analysis the capacity gains that can be achieved using such an approach. Thus channel conditions under which a cross layer approach can provide improvement were identified. The capacity improvements were quantified and it was established that a dramatic increase in capacity can be achieved by using a cross-layer schemes. Specifically it was shown that the CLD scheme can almost always perform better than CON over channel conditions similar to a WLAN and the CLDS scheme performs better than CON under any kind of scenario. The immediate future goal of this work is to identify good channel codes which can help realize the capacity gains offered by CLD and CLDS and to evaluate performance improvement that can be obtained by video applications in conjunction with CLD and CLDS.

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