CLIFT: a Cross-Layer InFormation Tool for Latency Analysis Based on Real Satellite Physical Traces

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***Abstract*—New mobile technology generations succeed in achieving high goodput, which results in diverse applications profiles exploiting various resource providers (Wifi, 4G, 5G, . . .). Badly set parameters on one of the network component may severely impact on the transmission delay and reduce the quality of experience. The cross layer impact should be investigated on to assess the origin of latency. To run cross-layer (from physical layer to application layers) simulations, two approaches are possible: (1) use physical layer models that may not be exhaustive enough to drive consistent analysis or (2) use real physical traces. Driving realistic measurements by using real physical (MAC/PHY) traces inside network simulations is a complex task.**

We propose to cope with this problem by introducing Cross Layer InFormation Tool (CLIFT), that translates real physical events from a given trace in order to be used inside a network simulator such as ns-2. Our proposal enables to accurately perform analysis of the impact of link layer reliability schemes (obtained by the use of real physical traces) on transport layer performance and on the latency. Such approach enables a better understanding of the interactions between the layers. The main objective of CLIFT is to let us study the protocols introduced at each layer of the OSI model and study their interaction. We detail the internal mechanisms and the benefits of this software with a running example on 4G satellite communications scenarios.

I. Introduction

In [1], the authors highlight that even though new mobile technology generations reduce the latency, each component of the network adds delay and may severely impact the end user experience. As an example, on top of the transmission delay of a satellite link (254 ms), the various delays that are added along the path bring the “one way delay” to 329 ms. Badly set parameters on one of the links of the end-to-end path may severely impact the transmission delay and reduce the quality of experience. In order to resolve those issues, cross layer interactions should be investigated.

The increase of wireless and satellite links in current networks introduces challenging issues. In the case of Land-Mobile Satellite (LMS) channels, the most powerful codes cannot recover lost data, due to long bit-errors bursts at the physical layer [2]. The implementation of physical layer schemes is commonly linked to specific hardware, making it ill suited to modifications after the design or deployment of the system. To overcome the extremely challenging conditions in mobile satellite environment, reliability schemes can be introduced at the link layer in order to recover data that the physical layer may not be able to rebuild. In [3], the authors conduct an extensive study on the reliability schemes that can be implemented at the link layer level: Forward Error Coding (FEC), Automatic Repeat reQuest (ARQ), Selective-Repeat Automatic Repeat reQuest (SR-ARQ) and Hybrid-Automatic Repeat reQuest type II (HARQ-II). Introducing reliability schemes at this level can prevent the transport layer from decreasing its congestion window in case of isolated errors. Moreover, the spectrum efficiency may be optimized, as introducing redundancy at the link layer may enable the usefulness of previously received data.

In the context of high latency links, these techniques might introduce critical delays and impact the transport layer protocols performance [4]. Preliminary studies have explored TCP performance over link layer ARQ protocols in wireless environment [5], [6] and in the context of 4G satellite system downlink [7]. One recent proposal [8] has developed analytical tools in order to evaluate the impact of reliability schemes at the link layer on transport layer protocols while some others [9], [10] attempt to consider link-layer data units. Nowadays, there is a clear need for a tool allowing to evaluate currently deployed protocols (CUBIC in GNU/Linux or Android and TCP Compound in Windows operating systems) over realistic MAC/PHY layer traces. Unfortunately, and to the best of our knowledge, there is no tool allowing to easily perform such study.

Even though their results are accurate and relevant, testbeds suffer from various drawbacks, such as the difficulty to run exotic simulations or the hardware limitations. In the context of satellite communications, the access to the media might be expensive without specific rights. Also, without the “super-user” rights, exotic simulations can not be launched and the protocols of different layers can not be modified much [11]. Following this idea and the need for cheap (in terms of simulation time, and computer process) and realistic evaluation tools, this document argues for methods to integrate low layers in the high-level network simulator NS-2.

Our proposal, called Cross-Layer InFormation Tool (CLIFT), links an updated and maintained network simulator, ns-2, with recent lower layers codes performing over real physical channel state traces. CLIFT is not a physical layer simulator (as opposed to [12]) but a way to take into account physical layer traces inside a network simulator. Therefore, CLIFT allows to study the impact of link layer reliability

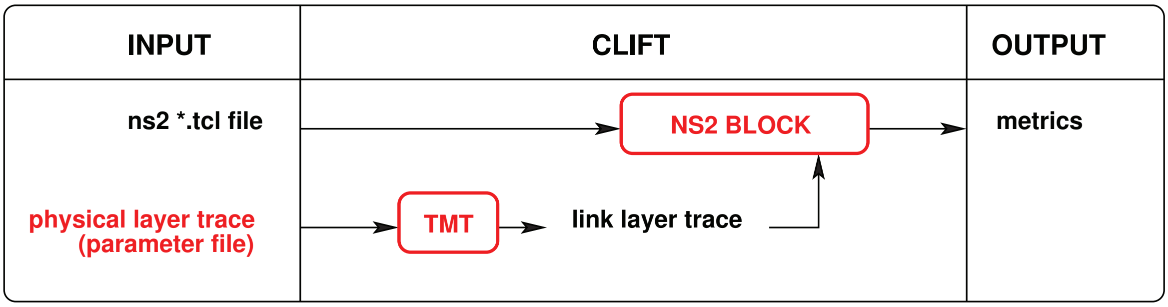


Fig. 1. Structure of CLIFT: Trace Manager Tool (TMT) (physical and link layers) and an NS2 module (upper layers)

schemes, as a function of a given physical channel, on transport protocols performance. The rationale of our approach is to replay MAC/PHY traces (CLIFT allows to read multiple existing traces format) either empirically measured or generated by a physical layer emulator or simulator.

The rest of the paper is organised as follows: in Section II, we briefly detail the structure of our tool. In Section III, we present the physical layer traces and how CLIFT can consider link layer reliability schemes. Then, we detail the problems encountered in the development of the queuing module for ns-2 in Section IV. We illustrate the potential of our tool through an example in Section V and propose a use-case example in Section VI. We conclude in Section VII.

II. Software Architecture

Before diving into the software details, we propose in this section to firstly present the overall structure of CLIFT and the linkages between each internal component. We also detail how to define a simulation and present the metrics provided by CLIFT.

A. CLIFT main internal components

CLIFT is based on two main components presented in Figure 1.

The *Trace Manager Tool (TMT)* component: for each link of the network, CLIFT loads a given physical trace and a parameter file (containing link-layer parameters, such as the reliability scheme used or the size of the link layer data units). We explain in Section III how reliability schemes at this layer can be taken into account.

The *ns-2 block* component: we developed a queuing module in ns-2 that loads these link layer traces to schedule the transmission of the transport layer packets. The ns-2 module implementation is detailed in Section IV.

B. Defining a complete simulation

A simulation is performed following the ns-2 standard procedure where the user needs to: (1) define the network structure through a standard TCL ns-2 simulation file; (2) for each link, define a parameter file and provide a physical layer trace; (3) then run ns simulation.

For each link, CLIFT adapts the measurements trace depending on the possible reliability schemes introduced and analyses the traces to compute the relevant metrics.

C. Metrics evaluation

Two kinds of metrics are returned by CLIFT:

- link layer level metrics: throughput efficiency, delay, retransmission distribution, erasure distribution;
- transport layer level metrics: used resources (percentage of the bandwidth), delay, number of RTO events, retransmission distribution, throughput, queuing delays.

All these metrics allow to perform cross-layer analysis. This will be later illustrated in Section V.

III. Physical Layer Trace

One of the main advantage of CLIFT is to bring real physical traces into network simulation. In this section, we thus focus on the physical layer trace format and present the erasure codes that can optionally be applied.

A. Physical layer trace format

CLIFT accepts, as an input, several physical traces format: both measured (as those provided in CRAWDAD (see http://crawdad.cs.dartmouth.edu) or generated by physical layer emulators [12] or simulators [13]. As an example, we propose the use of OFDM and TDM simulators from CNES. CNES is a government agency responsible for shaping and implementing France's space policy in Europe, see http://www.cnes.fr/. that take into account realistic satellite links characteristics, such as satellite orbits or recent correcting codes to generate physical layer traces [14]. Each packet sent at the physical-layer level is characterised by a transmission date and a decoding time. In Figure 2, in order to better assess the link between transmission date and decoding time, we illustrate how they are affected by interleaving at the physical layer. The transmission date is linked to the bandwidth and the length of the code at the physical layer. The decoding time is linked to the duration of the interleaving, the channel state and the transmission time. As CLIFT can load any physical layer trace compliant with this format, they can be either real measured traces or traces obtained by a physical layer simulator. Therefore, the main achievement of CLIFT is that real measured channel evolutions can be considered, while modelling such channels might lead to approximation and errors.

The decoding time is composed of the different delays caused by the reliability schemes at the physical layer level

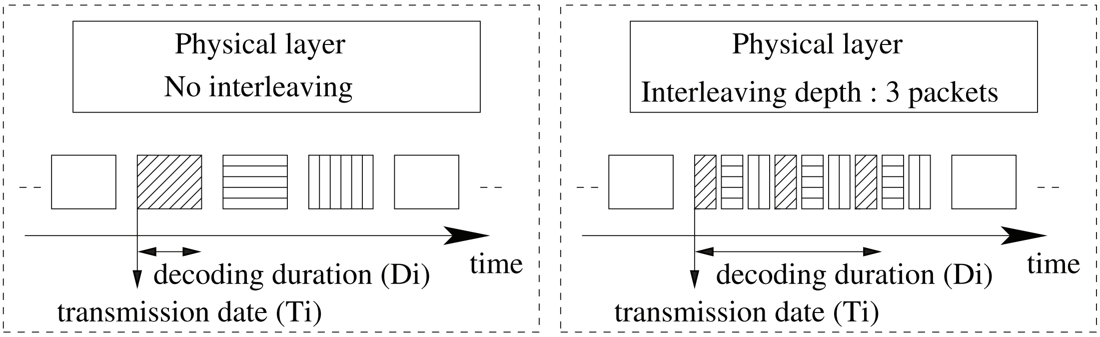


Fig. 2. Physical layer traces: transmission and decoding times

(interleaving and recovery delay). In the following, we denote by $LLDU$, one Link Layer Data Unit, t_i, the transmission date of $LLDU_i$, d_i, the decoding time of $LLDU_i$ and $d_i = 0$, the erasure event of $LLDU_i$. At $t = RTT/2 + t_i + d_i$, the physical-layer delivers $LLDU_i$ to the link layer, if there is no supplementary delay (congestion, queuing, ...).

B. Link layer Model

The traces considered by CLIFT can be MAC/PHY traces that may optionally implement reliability schemes. If we use traces that do not enable reliability mechanisms at the MAC level (*e.g.* ARQ or H-ARQ), we could also perform a pre-treatment over these traces with tools such as TMT [15], PPR [16] or DUMMYNET/NETEM[17] that allow to apply reliability mechanisms up the MAC level. Basically, these tools allow to modify the PHY traces, following a given reliability mechanism used at the MAC level, by recomputing the transmission slots. The principle is as follows : the decoding time of one erased LLDU is linked to the reliability scheme involved to estimate the time when the recovered LLDU must be sent. The supplementary time introduced by the link layer reliability scheme, denoted d'_i, is the time needed to obtain (t_R) and decode (d_R) the $LLDU$ that enables the recovery of $LLDU_i$: $d'_i = t_R + d_R - t_i$. A physical layer data unit will be delivered to the link layer at $RTT/2 + t_i + d'_i$.

We detail below commonly used reliability schemes:

- FEC: The sender sends N_D data and N_R repair LLDUs. From a FEC block composed of $N_D + N_R$ LLDUs, the link-layer can repair a maximum number of N_R LLDUs;
- SR-ARQ: The link layer retransmits the lost LLDU;
- HARQ of type II: This mechanism is a combination of FEC and SR-ARQ. After a first transmission of a FEC block, including data and repair LLDU, HARQ-II allows the sender to send additional repair LLDU when a recovery is not possible at the receiver side.

We denote HARQ (N_D,$N_D + N_R$) (or FEC (N_D,$N_D + N_R$)), where N_D is the number of data LLDU and N_R the number of repair LLDU.

As a result, one other main achievement of CLIFT is to consider the most recent link layer reliability schemes applied on realistic physical layer traces.

IV. Internal software principle

CLIFT schedules the transmission of the IP packets depending on the link layer traces (section III-B). We introduce a new queuing module in ns-2 that loads these traces and determines when a packet can be received by the upper layer (depending on the reliability schemes introduced) and sent. The queuing system in ns-2 is mainly driven by the following entities: packets (with arrival times and services times attributes) and queues (with empty and non-empty attributes).

The `enqueue()` function is called when a packet arrives in the queue. When the channel is idle, the `dequeue()` function is called to transmit the packet chosen depending on the queuing mechanism. We modify these functions according to the scheduling read in the link layer trace.

A. Add an IP packet in the queue: the `enqueue()` function

One IP packet is divided into m LLDU ($LLDU_n, ...LLDU_{n+m}$). We denote by E_i, the enqueueing date of $IPpacket_i$, T_i its the transmission date, D_i its decoding duration and R_i its reception date. We look in the link layer trace for the LLDU that matches $t_n \leqslant E_i < t_{n+1}$. Over the m LLDUs, we compute $D_i = \max_{k\in[n,n+m]}(t_k + d_k) - T_i$. When $R_i = \max_{k\in[n,n+m]}(t_k + d_k) + RTT/2$ is actually the date when $IPpacket_i$ is delivered to the receiver.

We handle the case $D_i < E_i$ since ns-2 is a event-driven simulator: for example, this event might occur when erasure codes are used, and bursts of LLDUs are forwarded to the upper layer. With a FEC code, if LLDUs are lost, they are all rebuilt at the same time with the reception of the N_R^{th} LLDU.

B. Removing an IP packet from the queue: the `dequeue()` function

As soon as an IP packet enters the queue, we introduce a timer which value is set depending on the transmission date of the LLDU packets the IP packet is broken down into. The timer is set to expire when there is an IP packet to transmit. Therefore, at each expiration of the timer, the method `dequeue()` is called and the corresponding IP packet is transmitted. We reinitiate the timer value if: (1) an IP packet is enqueued and there is no other packet in the queue; (2) an IP packet is enqueued and its transmission date is earlier than

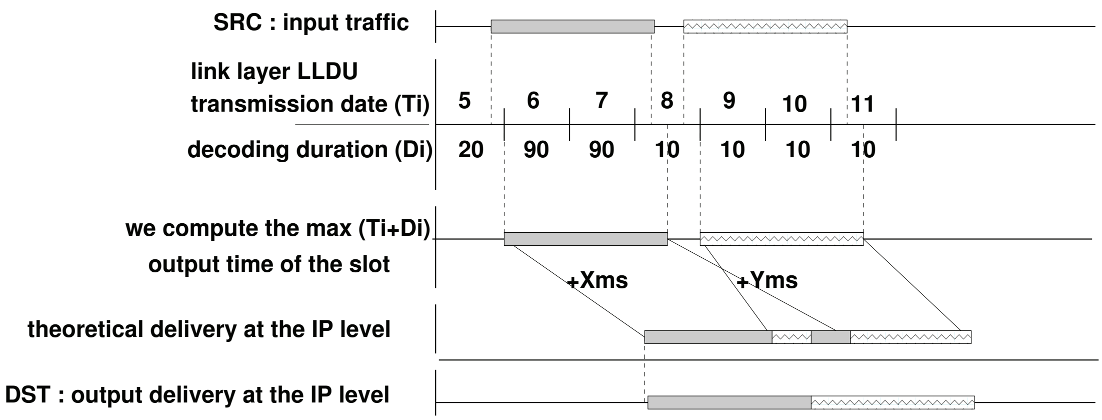


Fig. 3. Two packets sharing channel in ns-2

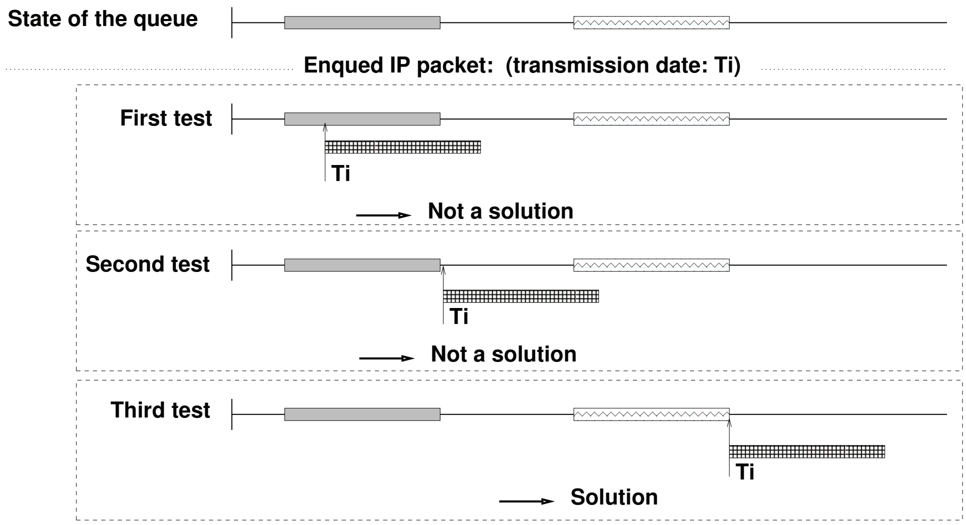


Fig. 4. Adaptation of the transmission date of the IP packet

those of the packets in the queue; (3) an IP packet has to be removed from the queue (timer expiration) and there are IP packets in the queue.

C. Packet sending and scheduling principles

Figure 3 illustrates the problem occurring when LLDU reliability schemes overlap IP packets in terms of channel occupancy. In this example, both IP packets are broken into 4 LLDUs. The algorithms introduced at physical and link layers make that parts of the second packet must be transmitted before parts of the first packet. As a result, in this example, CLIFT adapts the transmission date of both packets that the transmission does not overlap at the network layer level.

In Figure 4 we detail the different cases we had to consider since ns-2 prevents one node from sending two packets at the same time.

If one of the LLDU is erased, the whole IP packet is dropped. The date of this event is linked to the reliability scheme introduced at the link layer. Indeed, the computed transmission date becomes the drop date. We also consider that a dropped packet still uses the channel for its transmission and has to be taken into account in the scheduling detailed in Figure 4.

V. Illustration example with limited congestion window

In this section, we show an example of what CLIFT enables to assess. We do not focus on a realistic example. The results are not vastly analyzed, but an illustration of the potential of our tool.

A. Simulation definition

1) Network and objectives: We study the impact of retransmissions at the link layer on the performance of the transport protocol in a high bandwidth-delay product context. We consider a link between a satellite and a mobile receiver.

2) Physical layer characteristics: The physical layer trace corresponds to a mobile receiver moving at 60 km per hour. The simulation lasts 400 seconds. The size of the physical layer data unit is 33 bytes and the capacity 2,3 Mbps. We

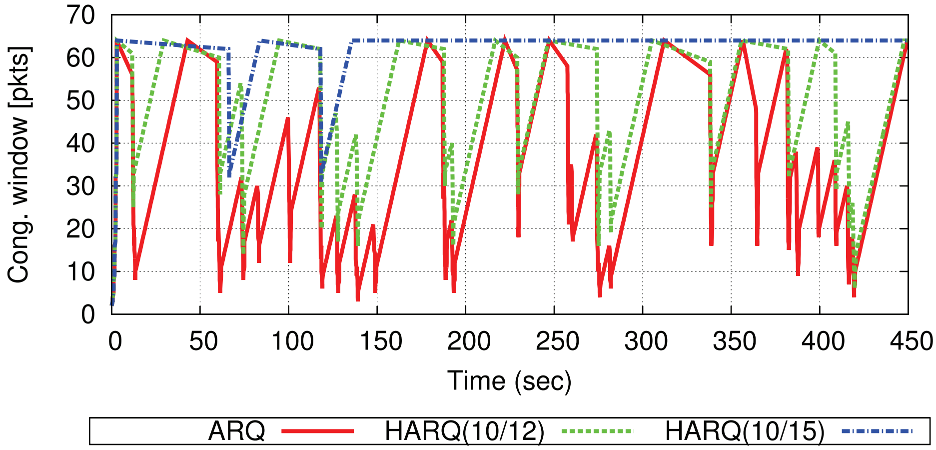


Fig. 5. Congestion window evolutions: when there is more redundancy, there are less congestion window reductions

consider an interleaving at physical layer of 35,5 ms and coding ratio of 1/3, waveform suitable for LTE uplink signals and a RTT of 500 ms. In accordance with the phenomena described in [2], the data obtained introduces realistic signal-to-noise ratio variations (and burst erasures), modulations, multiplexing or frequency. The physical layer traces have been provided by CNES.

3) Link layer characteristics: In this example we study the impact of retransmissions at the link layer level on the performance of transport protocols. Therefore within the different reliability schemes introduced (detailed in III-B), we focus on ARQ and HARQ of type II. For HARQ, we choose to use $N_D = 10$ data LLDU and $N_R = 2$ or 5 repair LLDU. The LLDU packet size is set to 33 bytes.

4) Transport layer characteristics: The transport protocol used is TCP NewReno, implemented in ns-2. The IP packet size is set to 500 bytes. On the receiver side, we introduce a SACK mechanism. We aim to show the impact of the retransmissions at the link layer on the congestion window size. In order to better visualize the impact of congestion window reduction, we limit the congestion window to 64 IP packets: this parameter prevents TCP from reaching the optimal congestion window, but, the potential of our tool to assess the impact of link layer parameters on TCP.

5) Application layer characteristics: We introduce a File Transfer Protocol (FTP) between the satellite and the mobile receiver. The source is non application limited. FTP may not be a commonly used 4G mobile application, but FTP is uses as much network resources as the rate control allows. The greedy usage pattern allows us to test the boundary performance of the transport.

B. Results and interpretation

In this section, before interpreting the results, we collect the different metrics obtained during this simulation, in terms of: (1) used resources, goodput, mean coding ratio (MCR), delay, retransmission distribution (Table I); (2) congestion window evolution and packet transmission (Figure 5).

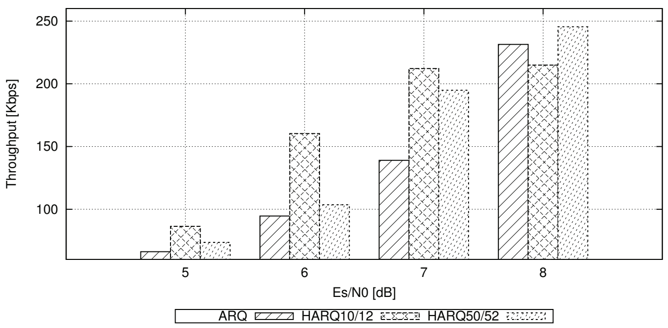
TABLE I
METRICS GIVEN BY CLIFT

Metrics		ARQ	HARQ (10/12)	HARQ (10/15)
% of the bandwidth used		13%	17%	23%
Goodput (kbps)		305	351	390
MCR ($\frac{useful\ data}{sent\ data}$)		95%	80%	65%
delay (ms)	minimum	287	287	288
	mean	288	288	289
	maximum	383	341	327
Retransmission number (link layer)	0	99%	98%	99%
	1	0,7%	1,4%	0,6%
	2	0,04%	0,03%	0,01%
	3	0,0007%	0%	0%
Retransmission number (transport layer)	0	98%	99%	99%
	1	1,5%	0,6%	0,7%
	2	0,1%	0,1%	0%

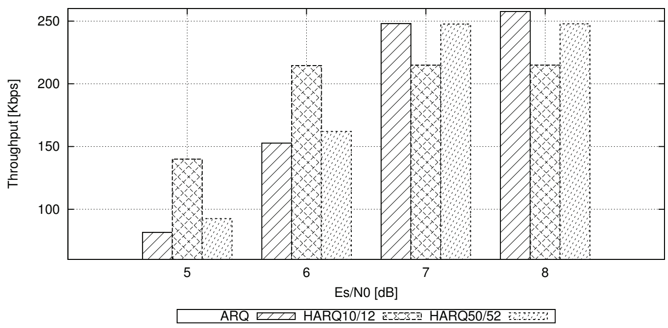
With the data gathered in Table I, we can see that HARQ (10/15) has the best performance in terms of goodput and delay. Thereby, as more repair packets are sent, more bandwidth is used for this only application. Moreover, we can notice that even if we do not optimise the value of N_D nor the ratio between N_D and N_D+N_R, HARQ of type II enables the transmission of more data than an SR-ARQ reliability scheme, but uses more capacity.

We can see that there are more retransmissions at the transport layer with a SR-ARQ mechanism at the link layer. In consequence, we also see that the congestion window is reduced more often. Indeed, this can be explained by the fact that, while this mechanism enables the recovery of data, the IP packet is received after an additional delay. As the delayed IP packet is not acknowledged, the transport protocol assumes that it has been lost. When the congestion window is large, the delayed acknowledgements introduces spurious retransmissions and might greatly deteriorate the transmission of data as there is a reduction of the size of congestion window.

Through this example, we illustrated that, on a channel with



(a) TCP New Reno



(b) Cubic

Fig. 6. Comparing Cubic and TCP NewReno when $Es/N0$ decrease: when the bit-error-rate is high, we measure the interest for introducing redundancy at the link layer

a high erasure probability, with realistic parameters and bursty aspects, an SR-ARQ mechanism can introduce an important number of spurious retransmissions and reductions of the congestion window size: as the retransmissions modify the scheduling of the IP packets, the non-acknowledgement of some IP packets greatly deteriorate the performance of TCP NewReno protocol. As a future work we aim to study and observe the impact of retransmissions at the link layer level on the performance of the most recent transport protocols implemented in ns-2.

We illustrated here that retransmissions at the link layer can greatly deteriorate the performance of a loss-based transport protocol. As an HARQ-II mechanism first sends a FEC block, it improves the performance in the simulation context. We considered a maximal congestion window of 64 packets. It would be interesting to study the impact of the bandwidth reduction due to the transmission of these repair packets. When the capacity of the link is reached, a trade-off has to be found between reducing the congestion window (with SR-ARQ) and reducing the available bandwidth (HARQ-II).

VI. Use-case: comparing Cubic and TCP NewReno over various link layer reliability schemes in the context of 4G links

In this section, we present a use-case example for which CLIFT can provide realistic results. An extended version of these results can be found in [18].

A. Simulation definition

1) Network and objectives: We compare, in ns-2, the performance of Cubic and TCP NewReno over various link layer reliability schemes in the context of 4G satellite links.

2) Physical layer characteristics: The physical layer trace corresponds to a mobile receiver moving at 60 km per hour. The simulation lasts 400 seconds. We introduce a Turbo Code 3GPP with a code word (before coding) of 33 bytes on both up and down links. The interleaving depth at the physical layer of 36ms. We present the results of this scenario with $Es/N0 \in [5; 8]$ dB, i.e. $PER \in [10^{-2}; 10^{1}]$. The capacity is 0.26 Mbps and the RTT 500 ms. In accordance with the phenomena described in [2], the data obtained introduces realistic signal-to-noise ratio variations (and burst erasures), modulations, multiplexing or frequency. The physical layer traces have been provided by CNES.

3) Link layer characteristics: As in the previous section, we focus on ARQ and HARQ of type II. For HARQ, we choose to use (1) $N_D = 10$ data LLDU and $N_R = 2$ repair LLDU or (2) $N_D = 50$ data LLDU and $N_R = 2$ repair LLDU. The LLDU packet size is set to 33 bytes.

4) Transport layer characteristics: The transport protocol used is TCP NewReno or Cubic, both implemented in ns-2. The IP packet size is set to 1500 bytes. On the receiver side, we introduce a SACK mechanism. Contrary to the previous section, the congestion window is not limited to 64 IP packets.

5) Application layer characteristics: We introduce a File Transfer Protocol (FTP) between the satellite and the mobile receiver. The source is non application limited.

B. Results and interpretation

In Figure 6, we present the average throughput measured at the mobile receiver side. When the physical layer unit error rate is high, we note that there are important benefits in terms of bandwidth that can be achieved when HARQ-II are introduced at the link layer:

- with Cubic: at $Es/N0 = 5$ dB, with ARQ, we measured an achieved throughput of 81 kbps, and with HARQ(10/12), of 140 kbps: introducing HARQ(10/12) at the link layer increases the goodput by 59 kbps. At $Es/N0 = 6$ dB, with ARQ, we measure an achieved throughput of 153 kbps, and with HARQ(10/12), of 215 kbps: introducing HARQ(10/12) increases the goodput by 62 kbps.
- with TCP NewReno: at $Es/N0 = 5$ dB, with ARQ, we measured an achieved throughput of 66 kbps, and with HARQ(10/12), of 86 kbps: introducing HARQ(10/12) at the link layer increases the goodput by 20 kbps. At $Es/N0 = 6$ dB, with ARQ, we measure an achieved throughput of 92 kbps, and with HARQ(10/12), of 162 kbps: introducing HARQ(10/12) increases the goodput by 70 kbps.

When there are less physical layer errors, we validate the assumption that when the capacity is fully exploited, transmitting redundancy packets with HARQ-II reduces the goodput, *i.e.* the available bandwidth. Indeed, when the transport layer protocol is Cubic, at $Es/N0 = 8$ dB, with ARQ, we measure an achieved throughput of 258 kbps, and with HARQ(10/12), of 215 kbps. Introducing HARQ(10/12) reduces the goodput by 43 kbps.

We propose to evaluate the behaviour observed in the previous simulations by considering the transmission of 0.1 Mb (median Internet web page size according to Google Web Metrics [19]) with different transport layer protocols, different reliability schemes and different transmission times (to consider different channel states). In Table II, we present the time needed to transmit these data using the different simulation parameters: we ran 200 iterations and present the average value. As pointed out before, the impact of the value of $Es/N0$ severely impacts on the transmission delay. We measure that the transmission is quite faster with ARQ than with HARQ when the signal-to-noise ratio is high. When the signal-to-noise ratio decreases, we quantify that there is more interest for considering HARQ schemes. Also, we can see that the performance of Cubic and TCP NewReno are approximatively the same, due to the small size of the file transmitted.

TABLE II
TIME NEEDED TO TRANSMIT 0.1 MB (IN SECONDS)

Transport layer protocol	Link Layer reliability scheme	Es/N0 5 dB	6 dB	7 dB	8 dB
TCP New Reno	ARQ	12.1	8.1	5.6	5.0
	HARQ(10/12)	8.2	5.7	5.2	5.1
	HARQ(10/15)	6.5	5.9	5.9	5.9
Cubic	ARQ	9.8	7.1	5.4	4.8
	HARQ(10/12)	7.3	5.4	5.2	5.1
	HARQ(10/15)	6.2	5.9	5.9	5.9

In this section, we conclude that when the number of error increases at the physical layer, HARQ-II enables a significant improvement of the performance of transport layer protocols: we justify this by measuring the achievable throughput when FTP applications are considered and by measuring the delay needed to transmit a fixed amount of data. Also, we measured that Cubic shows better throughput than TCP NewReno and quantify this gain for various signal-to-noise ratios and link layer configurations.

VII. CONCLUSION

We have presented a tool that enables cross-layer studies between transport and MAC/PHY layers. We have developed the Cross Layer InFormation Tool (CLIFT), a simulator based on ns-2 that takes into account physical or link layer traces to schedule the transmission of transport layer packets.

Our software can consider several networks architectures while taking into account most recent transport protocols. The originality of our tool consists in taking into account realistic sets of physical layer parameters (coding ratio, modulation, waveform). An important variety of existing tools can provide traces loaded in CLIFT, as they can be measured or simulated. In this article, we focused on 4G satellite links. However, CLIFT can take into account any physical layer traces (Wi-Fi, wired or 5G satellite links) in the context where cross-layer studies are of interests. We provide an exemple of use case with 4G satellite links, but we also used CLIFT to conduct investigations of link layer retransmissions impact on TCP in the context of Aeronautical Communications [20]. CLIFT is well suited to study and optimize the protocols introduced at various layers of the OSI model to reduce the latency measured in the network.

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