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Published in:
22nd International Conference on Software, Telecommunications and Computer Networks (SoftCOM), 2014

DOI:
10.1109/SOFTCOM.2014.7039075

2014

Citation for published version (APA):
Andersson, J. A., Höst, S., Cederholm, D., & Kihl, M. (2014). Analytic Model for Cross-Layer Dependencies in VDSL2 access networks. In *22nd International Conference on Software, Telecommunications and Computer Networks (SoftCOM), 2014* (pp. 269--273). IEEE - Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/SOFTCOM.2014.7039075

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- Accepted paper, for presentation at SoftCOM 2014, Sept 17-19, Split, Croatia
- Addendum dec 2016, not peer-reviewed

Analytic Model for Cross-Layer Dependencies in VDSL2 access networks

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***Abstract*—Recent changes in user employment of Internet based services, new deployment technologies for mobile networks as well as an ongoing realisation of fixed and mobile converged networks e.g. the EU FP7 project COMBO, are significant examples of enablers for increasing demands on DSL links, especially VDLS2. Investigating cross-layer dependencies between all layers in the OSI reference model becomes increasingly important. In this paper we present an analytical model and experimental results for the relation between impulse noise on a VDSL2 link and the effect this have on the network layer packet loss. We show how the packet loss rate is dependent not only on the disturbance signal level and periodicity but also on the link utilisation.**

I. INTRODUCTION

The user employment of Internet based services has changed radically over the last couple of years, which puts new demands on the existing access technologies. The increasing demands concern both more extensive use of capacity demanding services like streaming video, as well as new technologies when small cells starts to go into the home network. The next generation mobile access networks will call for exertion of currently available access networks, including copper based networks technologies, for mobile backhaul (or even fronthaul). In these environments one link will service many users that, though mobile, have the same quality demands on services, such as video, as if it was streamed over fixed access. These increasing demands on the access network together with the upcoming fixed and mobile converged (FMC) networks will be applied on VDSL2 links and the newly developed ITU-T standard G.9701 (G.fast) [1] in combination with fibre access networks (FTTx) [14], [12], [7]. This is indeed a new challenge for the DSL technology.

Disturbances in the access network have direct impact on the perceived Quality of Experience (QoE); A physical layer bit error could result in a lost packet on the network layer, which in turn will influence the application's buffering of video chunks, or in the case of UDP based transport be directly visible as pixelations or freezing of the TV picture. Impulse noise is one of the most severe types of external disturbance in a DSL system. An impulse covering the full VDSL2 spectrum hits all tones and thus damages at least one OFDM frame, depending on the length and power of the noise impulse and where in the ongoing transmission of OFDM frames it hits.

To be able to realise new technologies and services e.g mobile backhauling over DSL access networks a deeper understanding and relation of measured Quality of Service (QoS) parameters on different layers in the OSI reference model is essential.

From the study of the internal functions of a VDSL2 system in [2] two hypotheses were formulated:

- Packet loss on the network layer is dependent not only on noise bursts levels and duration but importantly also of the user data utilisation of the link
- There exist a utilisation threshold over which every noise burst introduces a network layer packet loss.

To validate these hypotheses first a theoretical derivation of the packet loss probability conditioned on an impulse was performed, followed by experiments using a VDSL2 system, where impulse noise has been injected into the transmission cables.

The theoretical derivation in Section IV is for a basic scenario without Forward Error Correction and Physical Layer Retransmit. The objective is to establish a starting point for further elaborations aimed at the, in practice, more realistic and by far more complex case, if possible. The experiment described in Section V is performed with the same assumptions. In reality an operator will of course deploy the coding and error correction functionality called for, but the current investigation gives a primary understanding of the relation between impairments on the physical layer and the network layer. From before, see Section II, it is known that there is a relation between specific physical layer parameters and QoE for the end user, but not how this relation is manifested. The studied disturbances in this contribution are based on impulse noise.

Section II describes other approaches to this issue. In Section III an overview of the essential parameters of a DSL system is given. To understand the IP packet loss ratio Section IV derives an estimation based on the probability that an noise impulse will hit an OFDM frame containing Ethernet frames and in Section V the lab set-up and experiment is described. The results are summarised and discussed in Section VI, where also future works are indicated.

II. RELATED WORK

Much of previous research in this area has been focused on the understanding of the relations between the network layer up to the application layer. This is perfectly relevant considering the OSI reference model; the impact on higher layer delivery quality from the network layer should be independent of lower layer technology. Many of the studies, e.g. [11], are directed towards video distribution where as Kim *et al* in [10] state that packet loss is the QoS parameter on the network layer that has the highest relative importance degree (41.7%) regarding IPTV.

There is work done in understanding the cross-layer relations between the physical and network layers. Recently Goran *et al* investigated the impact of physical layer quality disorders on both QoS and QoE in an ADSL2+ system in [9]. It was concluded that the number of Error Seconds (ES) and Severely Error Seconds (SES) are directly correlated to the IPTV stream QoE. Škaljo *et al* estimated in [13] the impact impairments on the physical link have on IPTV quality. Five physical layer parameters of an ADSL2+ system were considered, among them ES. They found that not all Code Violations (CV)[1] cause decreased QoE due to disturbances hitting layer 3 packets carrying other services. In [8] Souza *et al* described how non-stationary noise impacts a DSL system. Here it was determined that the packet loss rate, packet loss count, bandwidth and transfer delay are not suitable for a detailed analysis of impulse noise impact. Begen investigated physical-layer impairments and error-mitigation techniques for DSL environments in [5]. The objective was to evaluate Forward Error Correction (FEC) as an error-control for IPTV over DSL. The necessity for DSL error control was further discussed in [6] by Begen *et al.*

III. NETWORK PARAMETERS

The DSL communication system is based on an OFDM modulation where the tone separation is typically[2] $\Delta F = 4.3125$ kHz. At the initialisation of a DSL connection the parameters are adopted to the channel behaviour in terms of bit loading, i.e. power and transmission rate. After a completed initialisation in the active state it is assumed that the channel parameters are slowly varying, following e.g. the noise level changes over the day. The adaptation to changes in the channel is therefore limited to an SNR margin of typically 6-9 dB. The SNR margin is subtracted from the available SNR per tone, and remaining level is used for dimensioning the modulation level with a maximum of 15 bit/tone.

Even though the channel does not change in the same manner as a typical radio channel, these precautions are sometimes not enough. The dominating disturbance in a DSL system is due to inductive crosstalk from other users, via electrical couplings in the cable bundle. Next to this, impulse noise, typically generated in or close to the home environment, is a severe impairment for copper based access.

In the central office equipment of the DSL connection (DSLAM) typical physical layer parameters can be read via SNMP. Among those the error conditions are indicated by the number of bit swapping occasions, ESs, SESs and CVs during a time period. Similarly, considering the path from the content server to the end user, obvious QoS parameters on the network layer are packet loss, latency, packet delay variations (PDV or jitter), inter packet arrival time and packet rate.

IV. ESTIMATION OF PACKET LOSS PROBABILITY

When an Ethernet frame is entered into the DSL system it is passed through three main blocks in the conversion to signals for the transmission. The first block is the Transport Protocol Specific Transmission Convergence (TPS-TC) block where it is re-framed into PTM frames. Here a 64/65B coding is done, and it is in this block that the idle bits are added. The TPS-TC block delivers a byte stream containing among others the Ethernet frame data and the idle bits to the Physical Media Specific Transport Conversion (PMS-TC) block where scrambling, optional error control in form of Reed-Solomon coding, trellis coding and interleaving is added. The byte stream is divided into so called OH frames over which a one byte CRC is calculated. It is this CRC that indicates the CVs that are measured in the experiments. In addition to the CRC byte, other overhead data is added to the byte stream. The last block is the Physical Media Dependent (PMD) block where the now purely binary stream is blocked according to the bit loading and modulated to signals through the OFDM system. It is now viewed as complex samples in the frequency domain. After the IFFT the cyclic extension (CE) is added to prevent ISI due to the impulse response on the channel before the samples are D/A-converted and transmitted over the twisted pair copper line. Thus, the OFDM framing can be viewed as independent of the Ethernet and PTM framing.

The packet stream in the derivation is based on IPv4 packets with payload 1400 bytes equally distributed over time to achieve a certain data rate. These IPv4 packets corresponds to Ethernet packets of length $L_e = 1438$ bytes. In the derivations we denote by R_C and R_S the configured data rate and the considered service data rate, respectively. In an OFDM system the tone spacing determine the symbol rate since this is also the frame rate on the physical layer. With a tone spacing of 4.3125 kHz the OFDM frame length equals $\frac{1}{4.3125} = 232\mu s$. Adding the CE extends the OFDM frame to $250\mu s$. Hence, in DSL the transmission rate of the OFDM frames is $F_S = 4$ kHz. Then each of the OFDM frames carry $L_O = \frac{R_C}{8F_S}$ bytes.

When re-framing Ethernet frames into PTM frames, two or four CRC bytes, N_{FCS}, are appended to the PTM frame. Additionally two overhead bytes, SC, are added, one in the beginning and one at the end of each PTM frame. The PTM frames are then split in blocks of 64 bytes. Each of these blocks are framed by one byte, meaning the number of bytes corresponding to an Ethernet frame of L_e bytes is

$$L_E = L_e + N_{FCS} + SC + \left\lceil \frac{L_e + N_{FCS} + SC}{64} \right\rceil$$

where the last term corresponds to PMS-TC framing OH. In our case an adjusted number of bytes per transmitted Ethernet frame becomes $L_E \approx 1474$.

The minimum number of OFDM frames output by the PDM

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[1] A Code Violation (CV) occurs when the Cyclic Redundancy Check (CRC) decoder indicates an error.

[2] ADSL, ADSL2+ and VDSL2 all have tone spacing of 4.3125 kHz, except for the 30 MHz band-plan in VDSL2 that has the double.

block containing any of the Ethernet/PTM bytes is

$$N_{\min} = \left\lceil \frac{L_E}{L_O} \right\rceil$$

Alternatively, an Ethernet frame can occupy $N_{\min} + 1$ OFDM frames and the probabilities for these two events are

$$P_{EO}(N_{\min}) = \frac{N_{\min} L_O - L_E}{L_O}$$

$$P_{EO}(N_{\min} + 1) = 1 - P_{EO}(N_{\min})$$

Hence, expected number of OFDM frames occupied by an Ethernet frame is $E[N] = \frac{L_E + L_O}{L_O}$.

Similarly, it is important to measure the gap between two consecutive Ethernet frames in terms of number of OFDM frames. Since we are considering a sequence of evenly spaced Ethernet packets, it is possible to derive the number of bytes in one period, i.e. from the start of an Ethernet packet to the start of the next, as $L_P = \frac{R_C}{R_S} L_E$, and the total number of bytes in a gap is $L_G = L_P - L_E$. The maximum number of OFDM frames in a gap that does not have any content from the Ethernet/PTM frames is

$$G_{\max} = \left\lfloor \frac{L_G}{L_O} \right\rfloor$$

and alternatively the gap can contain $G_{\max} - 1$ idle OFDM frames. The corresponding probabilities are

$$P_{GO}(G_{\max}) = \frac{L_G - G_{\max} L_O}{L_O}$$

$$P_{GO}(G_{\max} - 1) = 1 - P_{GO}(G_{\max})$$

The expected value of a gap is, as long as $L_G \geq L_O$, $E[G] = \frac{L_G - L_O}{L_O}$.

Finally, to derive the probability for packet loss from an impulse disturbance, the span of the impulse must also be translated into OFDM frames. In [3], [4] measurements on impulse noise in the home network has been carried out. There is a wide spread in the time duration of the impulses, but an average value of about $100\mu s$ turns out to be reasonable for tests. Since the cyclic extension of the OFDM frame will be discarded in the receiver, it is not a problem if an impulse hits this part. Therefore, the effective burst duration will be $\tilde{T}_B = T_B - T_{CE}$, where T_B is the burst duration and T_{CE} the duration of the cyclic extension. The minimum number of OFDM frames affected by an impulse of time T_B is

$$B_{\min} = \lceil \tilde{T}_B F_S \rceil$$

It should be noted that the expression for $\tilde{T}_B$ can be negative, which means that the burst time is shorter than the cyclic extension. This will give that $B_{\min}$ equals zero. The probabilities for the number of OFDM frames affected by an impulse is

$$P_{BO}(B_{\min}) = B_{\min} - \tilde{T}_B F_S$$

$$P_{BO}(B_{\min} + 1) = 1 - P_{BO}(B_{\min})$$

The corresponding expected value is $E[B] = 1 + \tilde{T}_B F_S$.

Now, as everything is synchronised with the OFDM frames, the probability for packet loss due to a burst can be derived. Under the condition that an Ethernet frame corresponds to N OFDM frames and the corresponding gap G OFDM frames, and that the burst corresponds to B OFDM frames, the packet loss probability is

$$P(PL|N, G, B) = \frac{N + B - 1}{N + G}, \quad L_G \geq L_O$$

That gives the unconditional probability as[3]

$$P(PL) = \sum_{i,j,k=0}^{1} P_{EO}(N_{\min}) P_{GO}(G_{\max}) P_{BO}(B_{\min}) \cdot P(PL|N_{\min} + i, G_{\max} - j, B_{\min} + k)$$

V. Lab Testbed and Measurements

The laboratory environment consists of a Digital Subscriber Line Access Multiplexer (DSLAM) for ADSL2+ and VDSL2, multiple pair landline cables as well as modems (CPEs) and home networks (Figure 1). Controlled disturbances can be injected in the DSL cables via a coupler that matches to the different impedances in the telephony cable and the noise generator.

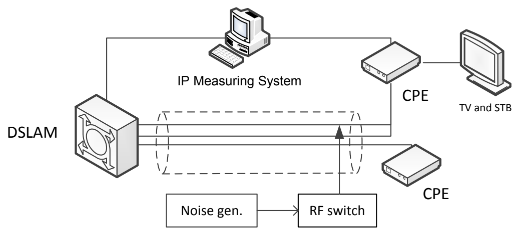

Figure 1. Schematic view of the lab set-up for impulse noise experiments.

To model the disturbances a noise generator with close to white noise in the frequency range 10 kHz to 80 MHz is used. A noise burst will therefore hit all tones in the DSL communication, thus effectively averting bit swapping. The noise generator has a fast switch connected to its output and can thus generate impulse noise of chosen length. The position of the injection on the cable plays a role since the downstream signal is much more attenuated on the CPE side than in the central office.

In the experiments Ethernet frames with IP payload of 1400 bytes were transmitted over a VDSL2 link, configured for maximum bit rate of 60 Mbps. The packets were transmitted equally spaced with various total bit rate for the different test runs. For each test run 250 bursts were injected, spaced by 20 seconds, giving a duration of 5 000 seconds. The noise impulses duration was $T_B = 100\mu s$. In the test set-up a total cable length of 950 m was used and the impulses were injected near the CPE. Every three seconds the accumulated number of ESs and CVs were read. The number of packets lost during one second was sampled periodically. Each reading was time stamped with NTP synchronized clocks. The raw data was then

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[3] It is here assumed that the Ethernet frame length and the gap length are independent. This is not entirely true but it simplifies the calculations considerably and the error is negligible.

Table I
RESULT FROM TEST RUNS. COLUMN 2 SHOWS THE NUMBER OF CVS GIVEN AN IN EVENT AND COLUMN 3 SHOWS THE NUMBER OF PACKET LOSS EVENTS GIVEN A CV GIVEN AN IN EVENT.

Rate (Mbps)	# CV	# Pkt Loss	Pkt Loss/CV
1	249	27	0.1084
3	242	39	0.1612
7	250	68	0.2720
11	243	95	0.3909
15	249	120	0.4819
20	248	151	0.6089
25	249	182	0.7309
30	248	202	0.8145
35	250	215	0.8600
40	244	230	0.9426
45	246	241	0.9797
50	250	250	1.0000
55	247	247	1.0000
58	247	247	1.0000

scanned finding CVs and packet loss events within plus/minus 3 seconds from the time an impulse was injected. The test results are given in Table I.

To comply with the restrictions of the analytical derivation above the experiment was performed without active Impulse Noise Protection (INP) and neither physical layer retransmission nor Trellis coding.

VI. RESULTS AND DISCUSSION

Table I show that a CV occurs for almost all noise impulses, independent of the service rate. An impulse will always hit an OFDM frame which will generate a CV, independent of the frame carrying user data or idle bits. Thus, probability of packet loss is a function of the service rate. When the service rate is low compared to the configured rate there will be many OFDM frames carrying only idle bits. If an impulse hits such a frame a CV will be the result but it will not affect user data.

In the experiment leading to Table I the strength of the noise impulses are much higher than the received signal in the downstream direction. Even when the impulse overlaps only a small part of the OFDM frame in time, this noise energy will be evenly distributed over the frame in the frequency domain after the FFT in the receiver. If the resulting noise level is stronger than the SNR margin this should give an extensive error over the complete frame. Hence, in our case there will essentially always be a fault in at least one OFDM frame. However, this is dependent of the energy of the impulse noise. Figure 2 shows the average number of ESs and CVs as a function of the power level of the impulse noise. There is a quite distinct threshold where the energy of the noise will fill up the SNR margin in the VDSL2 bit loading.

In the laboratory set-up described above for a VDSL2 connection using the 17a band plan, the measurements in Table I is plotted in Figure 3 together with the 95% confidence intervals. In the figure the estimated probability of packet loss for the same settings is also plotted. It is seen here that the curves coincide reasonably well. In the derivations it is assumed that all Ethernet frames are handled by the system without changing the inter packet gap, i.e. the distribution of arrivals to the TPS-TC and PMS-TC blocks is deterministic. In reality this is not necessarily true; the measured data suggest that some functionality in the VDSL2 system changes the inter packet gap slightly.

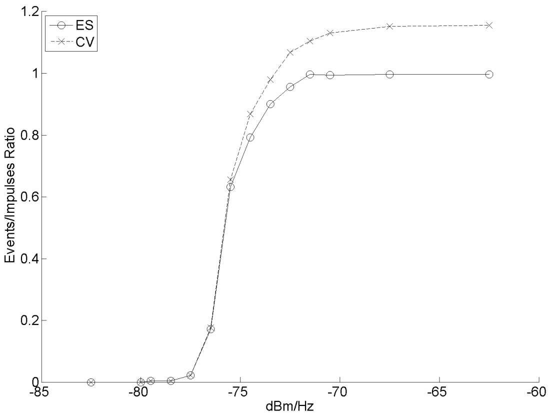

Figure 2. The number of ESs and CVs as a function of noise impulse power level for a duration of 100 μs.

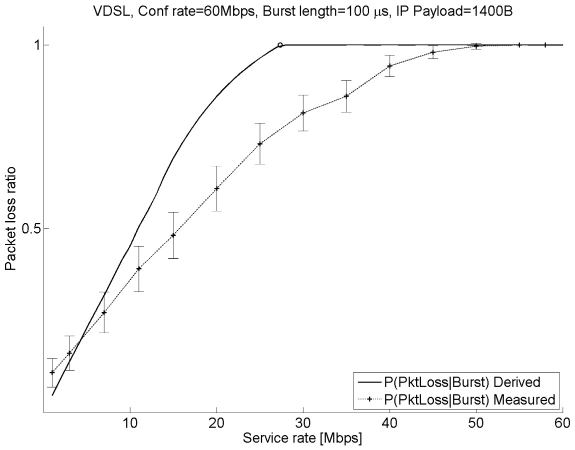

Figure 3. Estimation and measurements for packet loss probability from a burst.

An interesting parameter for the system is the break point in service data rate for which a bursts always will affect the service in form of packet loss. For the theoretically estimated plot, this can be derived by viewing the case when the gap length is shorter than the gap, giving the following bound for when $P(PL) = 1$,

$$R_S > \frac{L_E}{L_O\lceil\frac{L_B}{L_O}\rceil + L_E - L_{CE}} R_C \tag{1}$$

For $R_C = 60$ Mbps it gives the service rate $R_S > 27.4$ Mbps, which is marked in Figure 3 as a circular mark. In Figure 4 this break point service data rate is plotted as a function of the configured data rate. As can be seen the break point is roughly half of the configured data rate. This might be the reason for the well spread rule of thumb that a CV will invoke a packet loss. This miss-understanding probably comes from the deployment of IPTV over ADSL2+, where the rule of thumb is true in many cases, but it does not apply to VDSL2.

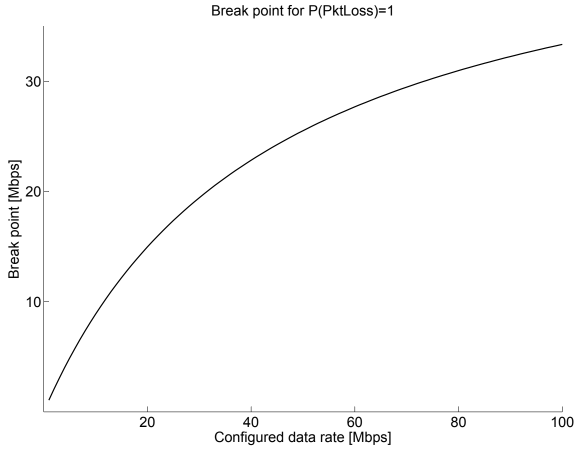

Figure 4. Estimation of the break point for which a burst will always give a packet loss in the IP stream.

The effect of noise impulses on packet loss of an IP stream does not depend only on how the noise impulse affects OFDM frames but also to what extent OFDM frames carrying user data are hit. Thus, there is no direct mapping between ES or CV on the physical layer and QoE for the service. Because of how the DSLAM inserts idle bytes to fill up the OFDM frames and to what extent other network layer packets carrying other services are present, packet loss depends on how much the packet stream of interest utilises the available link capacity. The effect of an impulse is therefore also a function of the link's configured maximum data rate and the regarded service data rate. The service data rate when each burst will have an impact on each network layer packet is significantly lower than the channel's configured maximum data rate when no IN protection is deployed. The presented probability estimation model can easily be adopted to other OFDM based access systems, such as G.fast, Wi-Fi and LTE.

Monitoring DSL performance parameters gives a good estimate of the user's perceived quality in the single user case where the link is utilised close to maximum. Our results show that this is not enough for newer technologies like VDSL2 and G.fast.

In the near future it is expected that available copper based access networks will be used in a multi-user environment, both for mobile backhaul and for packet based fronthaul, e.g. CPRI, for small cell deployment. The effect of disturbances in this situation is more complex than in use case with a single user. Thus, future work will explore these multi-user scenarios. It will also include extended experiments in more realistic physical layer configurations including FEC and physical layer retransmit.

VII. ACKNOWLEDGEMENTS

The work leading to these results has received funding from the European Union's Seventh Frame work Programme (FP7/2007-2013) under grant agreement no 317762. The authors also acknowledge the CELTIC+ project HFCC and the EIT ICT Labs.

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Addendum to Analytic Model for Cross-Layer Dependencies in VDSL2 Access Networks

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2016-12-05

Abstract

In this Addendum we present a possible explanation to why data derived from our analytical model does not correlate more than reasonably well to experimental data.

1 Introduction

In [1], also included in [2], an analytical model for packet loss due to impulse noise induced in a VDSL2 link is presented. The model was compared to and showed resonable corrolation with experimental data. From reference measurement, it has been noticed that packet seem to be grouped together at the receiver side. That is, the inter packet gap introduced at the packet generator, has in the DSL system or elsewhere in the laboration setup been changed. Modifying derivation of the model to reflect the grouping shows that this is the case.

2 The Second Derivation

The derivation of the model is changed in Figure 1 so that each two ip packets entering the DSL system are grouped together without any gap between them. Following each group of two packets, a gap of twice the original gap length is added, see Figure 2.

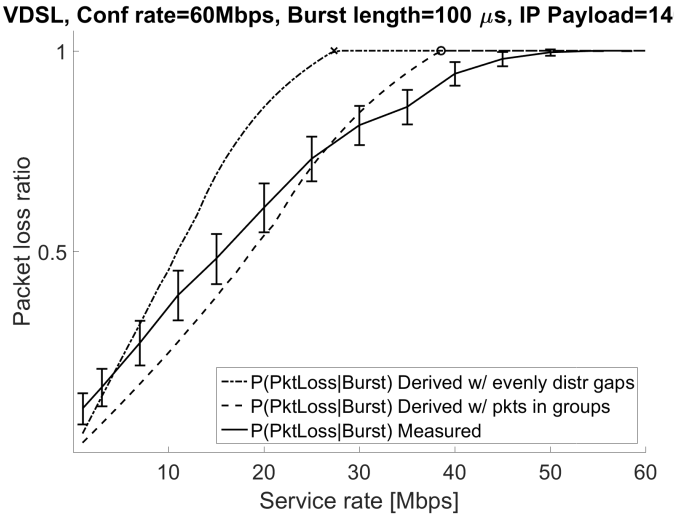
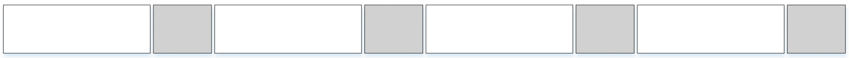
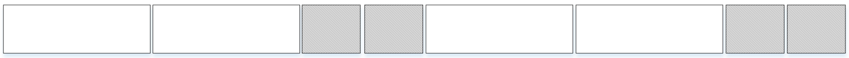


Figure 1: Two versions of the derived model compared with experimental data.

The new derivation clearly correlates much better to the measurements. Thus, it can be stated that an evenly distributed interpacket gap, as shown in Figure 2(a), is not true in the experiment setup. Somewhere, in the path from the packet generating application to the land line, grouping of ip packets will take place, a grouping that de facto makes the gap used in the derivation of the model



(a) IP packets with gaps evenly distributed.



(b) IP packets grouped two by two, thereby also grouping the gaps.

Figure 2: Packets and gaps for the two derivations.

bigger, see Figure 2(b), and thus, the probability of an noise impulse hitting a gap instead of a DSL frame containing real data is increased.

Why this effect occurs is yet to be examined. It could originate from the LINUX kernel of the packet generator, but also from intermediate switches, and finally in the DSLAM itself.

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