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Physical Layer Disturbances and Network Layer Packet Loss relation in an OFDM Based System

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Abstract—**Increased requirements 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 are significant examples of enablers for increasing demands on OFDM based links, e.g. VDSL2. Investigating cross-layer dependencies between all layers in the OSI reference model is important. In this paper we present an analytical model and experimental results for the relation between Electrical Impulse Noise (EIN) on a VDSL2 link and network layer packet loss. We show that this relation is non-linear dependent on the link utilisation.**

I. Introduction

The user employment of Internet based services puts new demands on existing access technologies. 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. Increasing demands on the access network together with the upcoming Fixed and Mobile Converged (FMC) networks will be applied on Very-high-bit-rate digital subscriber line, version 2 (VDSL2) links and the newly developed ITU Telecommunication Standardization Sector (ITU-T) recommendation G.9701 (G.fast) [4] in combination with Fibre Access Network (FTTx) [12], [10], [5].

Disturbances in the access network have direct impact on the perceived Quality of Experience (QoE).;In Digital Subscriber Line (DSL) systems, impulse noise is one of the most severe types of external disturbance. An EIN pulse covering the full VDSL2 spectrum hits all tones and thus damages at least one Orthogonal frequency-division multiplexing (OFDM) frame, depending on the length and power of the EIN and where in the ongoing transmission of OFDM frames it hits.

From the study of the internal functions of a VDSL2 system in [1] two hypotheses were formulated:

- Network layer packet loss due to EIN events is dependent not only on EIN bursts levels and duration but, importantly, also on the user data utilisation of the link.
- There exists an utilisation threshold over which every noise burst introduces a network layer packet loss.

These hypotheses were validated with a theoretical derivation of the packet loss probability conditioned on an EIN pulse, followed by experiments using a VDSL2 system, where EIN pulses were injected into the transmission cable.

The objective of the derivation in Section IV to establish a starting point for further elaborations, aimed at the more realistic and by far more complex case, if possible. The experiments described in Section V is performed with the same assumptions.

Section II describes other approaches to this issue. Section III gives an overview of the essential parameters of a DSL system. In Section V the lab set-up and experiment is described. The results are summarised in Section VI and discussed in Section VII, where also future works are indicated.

II. Related Work

Previous research in the area has focused on the understanding of the relations between the network layer up to the application layer. This is perfectly relevant considering the Open Systems Interconnection (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. Kuipers *et al.*[9], are directed towards video distribution whereas Kim *et al.*[8] state that packet loss is the Quality of Service (QoS) parameter on the network layer that has the highest relative importance degree (41.7%) regarding TV over Internet (IPTV).

Work has been done to understand the cross-layer relations between the physical and network layers. Goran *et al.*[7] investigated the impact of physical layer quality disorders on both QoS and QoE in an Asymmetric Digital Subscriber Line, version 2+ (ADSL2+) system. It was concluded that the number of Errored Second (ES) and Severely Errored Second (SES) are directly correlated to the IPTV stream's QoE. Škaljo *et al.*[11] estimated the impact impairments on the physical link have on IPTV quality. They found that not all Code Violations (CVs)[1] cause decreased QoE due to disturbances hitting network layer packets carrying other services. Souza *et al.*[6] 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.

III. Physical and network layer QoS parameters

A DSL communication system is based on OFDM modulation. At the initialisation of a DSL connection, parameters

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

like signal power and transmission rate are adopted to the channel characteristics. A Signal to Noise Ratio (SNR) margin of typically 6-9 dB is subtracted from the available SNR per tone, and the remaining level is used for dimensioning the modulation level with a maximum of 15 bit/tone, i.e. bit loading. After a completed initialisation 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 limited by the SNR margin.

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. Impulse noise, typically generated in or close to the home environment, is a severe impairment.

From the Digital Subscriber Line Access Multiplexer (DSLAM), the central office equipment of a DSL connection, physical layer parameters can be extracted. Error conditions are indicated by the number of bit swapping occasions, ESs, SESs and CVs.

Obvious network layer QoS parameters are packet loss, latency, Packet Delay Variation (PDV) (also called 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 Packet Transfer Mode (PTM) frames. Here a 64/65B coding is done, and it is in this block that 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 OverHead (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, 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. After the Inverse Discrete Fourier Transform (IDFT), the Cyclic Extension (CE) is added to prevent Inter Symbol Interference (ISI) due to the impulse response on the channel before the samples are Digital to Analog (D/A)-converted and transmitted over the copper line. Thus, the OFDM framing can be viewed as independent of the Ethernet and PTM framing.

The packet stream in the initial derivation is based on equally spaced Internet Protocol version 4 (IPv4) packets with 1400 bytes payload to achieve a certain data rate. The IPv4 packets correspond to Ethernet packets of length $L_e = 1438$ bytes. In the derivations, we denote by R_C the configured data rate and by R_S the considered service data rate. In an OFDM system, the tone spacing determines 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. 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 is 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 overhead. In our case, an adjusted number of bytes per transmitted Ethernet frame is $L_E \approx 1474$.

The minimum number of OFDM frames output by the PMD 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 expressed as 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. The ITU-T Study Group 15
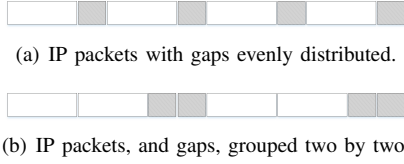
(a) IP packets with gaps evenly distributed.

(b) IP packets, and gaps, grouped two by two.

Figure 1. Packets and gaps for the two derivations.

Figure 2. Schematic view of the lab set-up for impulse noise experiments.

have carried out measurements on impulse noise in home networks [2], [3]. 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

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

A second derivation, adapted to the fact that experimental data suggested that the generated Internet Protocol (IP) packets actually were grouped in pairs, see Figure 1, was done. In the second derivation $L_P = 2 \times \frac{R_C}{R_S} L_E$ and $L_G = L_P - 2 \times (L_E(1 - C_E))$. Thus, there is a higher probability to hit a gap.

For both derivations, it is 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.
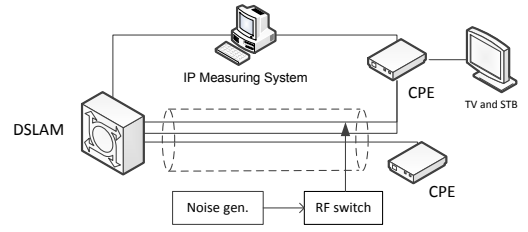
V. LAB TESTBED AND MEASUREMENTS

The laboratory environment consists of DSLAMs for ADSL2+ and VDSL2, multiple pair landline cables, Customer Premises Equipments (CPEs)[2] and home networks (Figure 2). Controlled disturbances can be injected in the DSL links via a coupler.

In the experiments, Ethernet frames with an IPv4 payload of 1400 bytes were transmitted over a VDSL2 link, configured for maximum bit rate of 60 Mbps. Different bit rate was used for each test run. During each test run, 250 bursts were injected, spaced by 20 seconds. The EIN duration was $T_B = 100\mu s$. The test set-up used a total cable length of 950 m, and the impulses were injected near the CPE. Every three seconds, the cumulated 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. Finally, the raw data was scanned, finding CVs and packet loss events within plus/minus 3 seconds from the time an impulse was injected.

To comply with the restrictions of the analytical derivation the experiment was performed without active Impulse Noise Protection (INP), physical layer retransmission or Trellis coding.

VI. RESULTS

EIN levels stronger than the SNR margin will destroy complete frames and generate CVs. The strength of the experiment's EIN pulses are much higher than the received signal. Even when the EIN overlaps only a small part of an OFDM frame, the EIN will be evenly distributed over the frame in the frequency domain. Thus, there will always be a fault in at least one OFDM frame per EIN pulse. Figure 3 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 Figure 4, the ratio of measured packet loss per CV is plotted with 95% confidence intervals together with the two packet loss ratio derivations. Both model and experimental data show the non-linear relation.

An interesting parameter for the system is the break point in service data rate for which a burst always will affect the service in form of packet loss. This can be derived by viewing
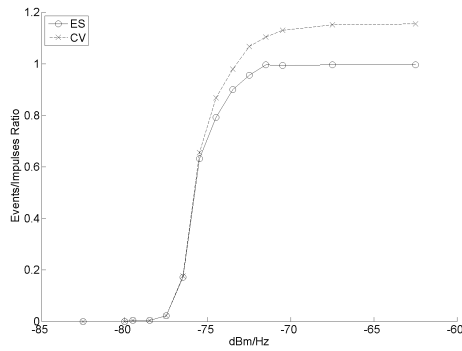
[2]Often called modems.

Figure 3. The number of ESs and CVs as a function of noise impulse power level for a duration of 100 μs.
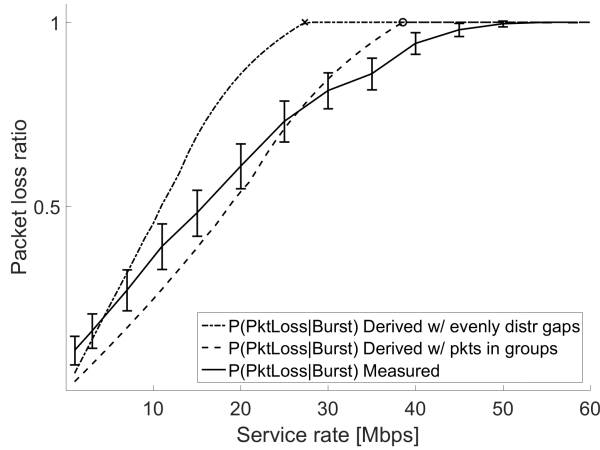

Figure 4. Estimation and measurements for packet loss probability from a burst. Two versions of the derived model compared with experimental data. The packets-in-pair derivation has the best fit.

the case when the Ethernet frame gap is shorter than the EIN pulse, 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 this break point is marked in Figure 4 with a circular and a cross mark for the two assumptions.

VII. CONCLUSION AND FUTURE WORK

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, there is a non-linear dependency between packet loss due to an EIN pulse and how much the packet stream of interest utilises the available link capacity. The effect of an EIN pulse 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 EIN pulse will have an impact on every network layer packet is significantly lower than the channel's configured maximum data rate.

Our results point out the importance of understanding of cross layer interaction. This is probably one key factor for a successful FMC network, especially when considering performance management for service assurance. The presented probability estimation model can easily be adopted to other OFDM based access systems.

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 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.

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