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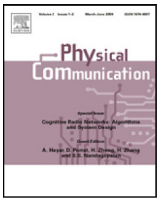

Full length article

Coexistence in fourth generation digital subscriber lines: Experiment, modeling, and simulation results

Sanda Drakulić, Martin Wolkerstorfer, Driton Statovci *

Institute of Telecommunications, TU Wien, Gußhausstraße 25/E389, A-1040 Vienna, Austria

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ABSTRACT

The deployment of fourth generation digital subscriber line (DSL) technology (“G.fast”) will be gradual and it may therefore share the cable infrastructure with legacy DSL technologies such as Very high speed DSL transceivers 2 (VDSL2). We perform experiments on coexistence of G.fast with legacy VDSL2, highlighting the practical relevance of out-of-band leakage and aliasing. Furthermore, the differences in transmission parameters (e.g., carrier width and sampling rate) and asynchronous transmission results in inter-carrier and inter-symbol interference (ICSI). Previous work on modeling ICSI in the communication field focused on modeling only a subset of these effects. Hence, we analytically derive a simplified ICSI model, which notably includes the effects of aliasing, leakage, and worst-case symbol misalignment. Our results partially based on simulations show that a) neglecting ICSI potentially leads to significant bit-rate overestimation (e.g., 18% in G.fast rates); and b) a G.fast start frequency of approximately 23 MHz may provide sufficient spectral separation with VDSL2 profile 17a transceivers.

1. Introduction

Digital subscriber line (DSL) broadband access has been evolving from exclusively copper-based to hybrid fiber-copper deployments. Although fiber-to-the-home (FTTH) is superior to hybrid fiber-copper deployments in terms of achievable bit-rates, its deployment incurs additional costs compared to the reuse of existing copper infrastructure due to the digging of trenches and fiber installation. In [1] it is shown that hybrid architectures such as fiber-to-the-distribution-point (FTTdp) save up to 80% in investment compared to FTTH. Therefore, FTTdp represents an intermediate solution to enable fiber-like speeds over the copper network and to allow operators to spread fiber investments over a longer time period. The International Telecommunication Union (ITU) has released recommendations on fourth generation DSL, specifically tailored to FTTdp deployments, called G.fast [2,3]. It targets gigabit aggregate bit-rates (downstream + upstream) over loops of few hundred meters and utilizes frequencies up to 212 MHz. However, not all service operators and customers are expected to replace existing DSL systems, such as Very high speed DSL transceivers 2 (VDSL2), with G.fast. Therefore, the coexistence of G.fast and VDSL2 is a realistic scenario in future DSL access networks.

Crosstalk cancellation (“vectoring”), is a key feature of G.fast. Current vectoring schemes assume that the crosstalk signals among different tones are orthogonal to each other. Different G.fast and VDSL2 transmission parameters such as multiplexing schemes, tone spacings, and sampling rates, produce inter-carrier and inter-symbol interference (ICSI) which couples crosstalk signals between different tones and consequently makes joint per-tone vectoring among different technologies impractical. Therefore, G.fast supports a configurable start frequency [4,5], which enables spectral separation between different systems. As shown in [4,6], starting G.fast transmission immediately above VDSL2 may result in strong ICSI for both systems, cf. also our motivating testbed experiment results in Section 2. A large spectral separation on the other hand potentially incurs a significant performance penalty, especially for longer (e.g., >100 m long) G.fast loops. Therefore, in order to optimize the selection of the G.fast start frequency and to estimate the achievable bit-rates of coexisting G.fast and VDSL2 (e.g., for spectrum balancing), a performance model which captures ICSI along with the impact of receive and transmit filtering is required.

The problem of ICSI in asynchronous DSL systems with *identical transmission parameters* has been studied in [7,8]. A frequency-domain crosstalk cancelation model between *synchronous* VDSL2 systems with different tone spacing has been presented in [9]. The authors in [10] analyze coexistence of G.fast and VDSL2 taking far-end crosstalk (FEXT) and near-end crosstalk (NEXT) into account, but neglecting the effects of ICSI. The problem of ICSI due to time and frequency offsets has also been well studied in the wireless literature. Exemplary studies on ICSI in wireless field for

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* Corresponding author.
E-mail addresses: sanda.drakulic@nt.tuwien.ac.at (S. Drakulić), martin.wolkerstorfer@nt.tuwien.ac.at (M. Wolkerstorfer), driton.statovci@nt.tuwien.ac.at (D. Statovci).

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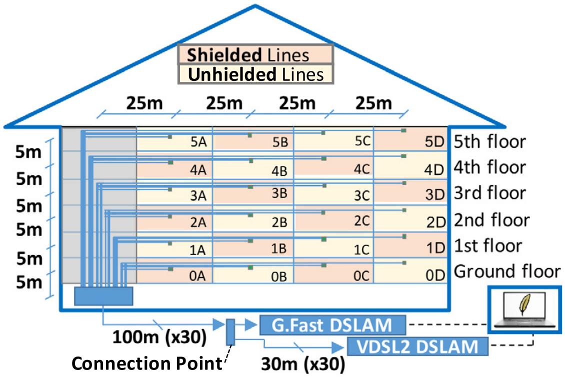
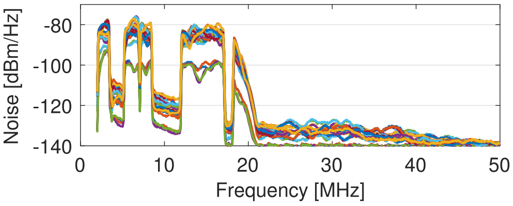
ideal and time-variant channels can be found in [11–15] while the authors in [16,17] address ICSI due to the joint effects of carrier and sampling frequency offsets. Models of ICSI produced jointly by frequency and time variations have been studied in [18–22]. However, all these ICSI models do not take differences in transmission parameters such as tone spacings and sampling rates into account, motivating the development of a simple model of coexistence in DSL.

Preliminary results related to this work have appeared in [23] and were later applied to spectrum balancing in [24]. Our main novel contributions are (a) the definition of a reworked and extended ICSI model for asynchronous discrete multitone (DMT) systems with different tone spacing and sampling rate (significantly improved and more realistic compared to that in [23]) where the model is not only restricted to DSL but it can also be used for interference analysis in other multi-carrier networks[1] ; (b) we include detailed derivations of crosstalk gains under ICSI, the influence of realistic receive and transmit filters, and the verification by time-domain simulations; and (c) an extensive simulation study on the exemplary application of the model in the selection of the G.fast start frequency and VDSL2 filtering for G.fast/VDSL2 (profile 17a) coexistence.[2]

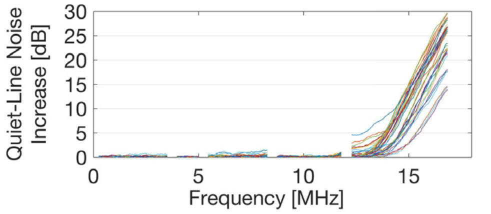
The paper is organized as follows. In Section 2 we present motivating experiment results on VDSL2/G.fast coexistence, showing the potential out-of-band leakage as well as aliasing observed using off-the-shelf DSL equipment. In Section 3 we review DMT system models with and without ICSI from literature. Afterwards we turn to the derivation and analysis of a novel ICSI model for asynchronous multicarrier systems capturing also transmission differences and the influence of filtering. Additionally, we derived an upper bound on ICSI gains. Furthermore, Section 3.3 includes the verification of the proposed ICSI model by time-domain simulations. A specific application of the developed ICSI model to the problem of selecting the G.fast start-frequency for coexistence with VDSL2 is studied in Section 4 while conclusions of our work are drawn in Section 5.



(a) Schematic of the testbed setup.

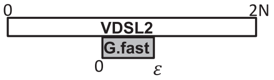


(b) Measured NEXT from 22 VDSL2 disturbers.

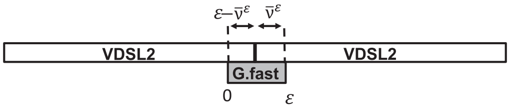


(c) VDSL2 QLN increase caused by *spectrally separated* G.fast disturbers (i.e., "aliasing").

Fig. 1. Testbed setup (a), results on measured near-end crosstalk (NEXT) from 22 VDSL2 disturbers (b), and perceived VDSL2 crosstalk quiet-line noise (QLN) from 13 spectrally separated G.fast disturbers due to aliasing reported on three different VDSL2 modem types (c).



(a) Full alignment.



(b) Partial alignment.

Fig. 2. Possible time alignments between VDSL2 and G.fast for a G.fast DFT block size of ε samples and symbol offset $\bar{\nu}^{\varepsilon}$.

2. Motivation: VDSL2/G.fast coexistence

In order to motivate this work on modeling the coexistence of different DSL technologies, we conducted experiments on a testbed using commercial DSL equipment (VDSL2 and G.fast DSL access multiplexers/DSLAMs; G.fast modems as well as three different types of VDSL2 modems). The cabling is realized by laying (shielded or unshielded) drop cables of 30-130 m length in isolated ducts (cf. the schematic illustration in Fig. 1(a)), using actual phone sockets on the line-termination side (denoted by "0A" — "5D" in Fig. 1(a)) and (30-pair) quad installation cables/patch panels on the network-termination side. NEXT from VDSL2 was measured at the connection point (i.e., close to the disturbers' DSLAM) using a spectrum analyzer (connected through a North Hills 50 Ω/124 Ω Balun; terminating the unused end of the measured line) under the disturbance of 22 non-vectored VDSL2 lines (bandplan 998/ADE17-M2x). This measurement was also qualitatively confirmed (results omitted) through readings of the actual G.fast quiet-line noise (QLN) from a G.fast victim line using its management interface [25]. Furthermore, we read the upstream and downstream QLN perceived by a VDSL2 line under disturbance from 13 G.fast lines. These disturbers include the line connected through the same quad as the victim line as well as all remaining "unshielded" drop lines, and we configured G.fast profile 106a and switched off tones below 17.6 MHz as well as tones in the FM radio band (confirmed through spectrum analyzer measurements).[3] This implies tight spectral separation between the two DSL technologies. The latter

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[1] DSL channels are usually static (i.e., *time-invariant*); therefore, the developed model only holds for time-invariant channels.

[2] Note that the selection of profile 17a is only exemplary and based on its pronounced relevance in practice. Similar studies could be performed using our model for other bandplans, such as the wider VDSL2 profile 35b.

[3] Note that due to the total power constraint of G.fast the notching of further frequency bands results in a reallocation of transmit power to lower frequencies (subject to the power spectral density mask) and therefore increases the observed disturbance from G.fast lines.