Multi-Gigabit Wireline Systems over Copper: An Interference Cancellation Perspective

S. M. Zafaruddin, Member, IEEE and Amir Leshem, Senior Member, IEEE

Abstract—Interference cancellation is the main driving technology in enhancing the transmission rates over telephone lines above 100 Mbps. Still, crosstalk interference in multi-pair digital subscriber line (DSL) systems at higher frequencies has not been dealt with sufficiently. The upcoming G.(mg)fast DSL system envisions the use of extremely high bandwidth and full-duplex transmissions generating significantly higher crosstalk and self-interference signals. More powerful interference cancellation techniques are required to enable multi-gigabit per second data rate transmission over copper lines. In this article, we analyze the performance of interference cancellation techniques, with a focus on novel research approaches and design considerations for efficient interference mitigation for multi-gigabit transmission over standard copper lines. We also detail novel approaches for interference cancellation in the upcoming technologies.

I. INTRODUCTION

Evolution of data transmission technologies over copper lines has been very rapid. Recent extensions achieve bit rates of several gigabits per second [1]–[4]. This growth is possible by exploiting higher transmission bandwidth over the same telephone lines [5]. However, an increase in the bandwidth increases the crosstalk among closely packed telephone lines in a binder caused by the electromagnetic coupling. Furthermore, the upcoming copper line technology might include full-duplex transmission creating problems of self-interference [6], [7]. In addition, subscribers can experience interference external to the binder. Novel interference cancellation techniques are required to realize a multi-gigabit rate transmission over copper lines. In this article, we analyze the performance of interference cancellation techniques, with a focus on novel research approaches for efficient interference mitigation for next generation digital subscriber line (DSL) systems.

The coordinated processing of the signals over all lines referred to as vectoring [8], is a viable technique to deal with crosstalk in the DSL systems. This joint processing can be applied on the signals transmitted from the central point to the end users in the downstream and on the signal received at the central point from the users in the upstream transmissions. Since DSL channels are well conditioned at lower frequencies, linear vectored processing is near optimal for crosstalk cancellation in the very high-speed digital subscriber line (VDSL) system [9], and it is recommended for the 106-MHz G.fast system [1]. With further increase in frequency as in the 212-MHz G.fast system, and in the upcoming 424-MHz and 848-MHz G.(mg)fast systems, crosstalk is significantly higher than the direct path thereby the channel matrices are no longer diagonal dominant. In the 212-MHz G.fast system, linear cancellation schemes are shown to be near-optimal [10]. Recently, lattice reduction based techniques are employed for the the 212-MHz G.fast system that incurs an extra run-time complexity [11]. It is interesting to evaluate the performance of linear and non-linear processing for G.(mg)fast systems. It is well known that the nonlinear schemes are computationally more complex than the linear techniques. This opens an exciting opportunity to develop computationally efficient crosstalk cancellation schemes for the next generation multi-pair DSL systems.

The upcoming G.(mg)fast systems promise to achieve multi-gigabit data rates using full-duplex (FD) transmissions, and by exploiting higher bandwidth than the previous standards [5]–[7]. This is in contrast to the VDSL system based on the frequency division duplexing (FDD) and to the G.fast system based on the time division duplexing (TDD). Although FD transmissions can double the throughput, self-interference or the echo signal can be detrimen-
TABLE I: Evolution of transmission over telephone lines technology with system parameters. Aggregate data rate is for each user upstream and downstream combined for FDD and TDD systems, and either upstream or downstream in the FD system. FD: full-duplex; FDD: frequency division duplexing; TDD: time division duplexing.

Tone Spacing
ITU-T

Symbol Rate
Agg. Data Rate

No. of Tones

Technology
Duplexing
Bandwidth
Tone Spacing
G.9700 (2014)

G.993.2 (2006)

G.9700 (2014)

G.9700 (2014)

G.9711 (Sept-2020)

G.9711

Technology
Duplexing
Bandwidth
Tone Spacing
Symbol Rate
No. of Tones
Agg. Data Rate
ITU-T

VDSL2
FDD
17 MHz
4.3125 KHz
4 KHz
4096
100 Mbps
G.993.2 (2006)

G.fast 106
TDD
106 MHz
51.375 KHz
48 KHz
2048
1 Gbps
G.9700 (2014)

G.fast 212
TDD
212 MHz
51.375 KHz
48 KHz
2048
2 Gbps
G.9700 (2017)

G. (mg)fast 424
FD
424 MHz
51.375 KHz
48 KHz
8192
5 Gbps
G.9711 (Sept-2020)

G. (mg)fast 848
FD
848 MHz
102.750 KHz
96 KHz
8192
10 Gbps
G.9711

The lack of signal-coordination of the interference external to binder i.e., from other existing broadband services and through the usage of various electrical appliances in the vicinity of a CPE limits the possibility of its cancellation. The usual practice to deal with the impulse noise is the use of error-correcting codes together and physical layer retransmission. The use of noise reference modules has shown promise for impulse noise mitigation in VDSL system [13].

This article analyzes the performance of multi-gigabit rate DSL systems. In this paper our focus is on comparative study of FEXT cancellation (vectoring) techniques, which are the main building block in VDSL and G.fast and will continue to be significant in G.(mg)fast.

II. OVERVIEW OF DSL TECHNOLOGIES

Discrete multi-tone (DMT) is the de facto multi-carrier modulation for frequency selective DSL channels. Of course, there is a change in the parameters for different technologies. The main system parameter is the sub-carrier spacing which is chosen to limit the number of tones to 4096 to accomplish per-tone processing. For the VDSL system with 17 MHz bandwidth, the sub-carrier spacing is 4.3125 KHz. The sub-carrier spacing in the G.fast is 51.75 KHz which accounts for 2048 tones and 4096 tones in the 106 MHz and 212 MHz G.fast systems, respectively. The 424 MHz G.(mg)fast system employs 8192 tones with a subcarrier spacing of 51.75 KHz. In order to limit the number of tones, we anticipate that the sub-carrier spacing of the G.(mg)fast- 848 MHz system should be double compared the G.fast system.

Duplexing techniques are another distinguishing feature among different DSL technologies. These techniques separate the upstream and downstream to avoid the NEXT and echo signals in the DSL systems. The VDSL standard separates the upstream and downstream in the frequency domain, known as the FDD. The latest G.fast standard employs a TDD where the upstream and downstream are transmitted at different times. The next generation G.(mg)fast targets a more ambitious full duplex transmission to double the throughput with a provision of efficient echo and NEXT cancellation. Table 1 presents important parameters of the various technologies.
III. NOISE AND INTERFERENCE ENVIRONMENT

Thermal noise caused by the random movement of electrons is inherently present in all communication systems. This presents a noise floor which is generally considered with a power spectral density (PSD) of $-174$ dBm/Hz at the room temperature. The PSD of background noise is around $-140$ dBm/Hz for the VDSL frequencies which decreases to $-150$ dBm/Hz for the G.fast system. The noise floor for the G.(mg)fast systems needs to be measured.

Crosstalk interference occurs when several unshielded twisted pair copper lines corresponding to a number of users are contained in a binder, which ultimately connect the distribution point unit (DPU) to the CPE. An increase in the frequency increases electromagnetic coupling which causes significant crosstalk among these closely packed lines at higher frequencies. Depending on the position of disturbers with respect to the victim receiver, this crosstalk is classified as FEXT or NEXT, as shown in Fig. 1. NEXT refers to coupled signals that originate from the end opposite to that of the affected receiver. Although the FEXT interference decreases with line lengths, its impact remains significant and has adverse effect on the data rate performance.

Another major cause of rate degradation is crosstalk that originates from subscribers enjoying other services, and is referred to as alien crosstalk. Such crosstalk exists in practical situations mainly due to the coexistence of different DSL services such as G.fast and VDSL in the same binder. This alien crosstalk manifests itself as spatially correlated (i.e., correlated across lines) additive noise at each tone at the receiver of a vectored system. Hence, alien crosstalk is amenable in the vectoring framework by exploiting spatial correlation between different noise samples of the copper lines.

In downstream transmissions, a CPE can experience interference from other existing broadband services and through the usage of various electrical appliances in the vicinity. The common sources of such interferences are electric power sources, radio frequency interference (RFI) ingress, interference from home local-area network (LAN) and broadband over powerline communications (PLC). These interferences can be classified based on the duration as continuous and impulsive, and on occurrence interval such as repetitive and non-repetitive noise sources. The presence of these external interferences at the CPE causes significant performance degradation and algorithms for its mitigation are desirable.
Fig. 2: A schematic diagram of a multi-user multi-carrier DSL system with interference cancellation. There is no signal coordination among CPEs for joint processing. In the upstream, the received signals from CPEs at each tone are collected at the DPU as a single vector, on which a FEXT canceler is applied. In the downstream, transmit signals for each user at each tone are collected as a single vector at the DPU, and a precoder and NEXT canceler is applied before transmission. At the the CPE, NEXT cancellation is hard when multiple receiver are co-located without signal-level coordination. Echo canceler (EC) is applied in both time and frequency domains. DMT: discrete multi-tone; FEQ: frequency-domain equalizer; NEXT: near-end crosstalk; FEXT: far-end crosstalk; EC: echo canceler; IFFT: inverse fast Fourier transform; DAC: digital-to-analog converter; ADC: analog-to-digital converter.

IV. INTERFERENCE CANCELLATION TECHNIQUES

The capacity of communication over telephone lines is limited by crosstalk. Indeed up to the VDSL2 standard, data rates were below 100 Mbps. To increase data rates further, joint processing of all lines was used, in a point to multi-point topology. In contrast to wireless systems where the channels vary very rapidly, the DSL channels vary much slower. This assists in reducing the amount of training required, and allows interference cancellation of up to 512 lines in one large system, where both upstream and downstream joint processing are performed at the DPU. The DPU constructs a vector containing all the received/transmit symbols over all lines, and then processes them together to reduce the effect of crosstalk, as shown in Fig. 2. This vectored processing is applied at each tone (the DSL systems use 4096 tones), which is a very intensive computational task. Furthermore, for each vector symbol this processing needs to be done. The design of crosstalk cancelers should achieve the optimal data rate performance while limiting implementation complexity and energy consumption. The main components of the complexity are: computation and tracking of canceler coefficients, the memory requirement to store the canceler matrices and the application of canceler to the signal vector.

There several techniques for reducing interference. The simplest are linear techniques, where the transmitter (in the downstream) and receiver (in the upstream) performs a linear combination of the received signals. The simplest approximation was used by [14] and was used in early VDSL
deployment. Next in complexity is the zero forcing (ZF) solution which cancels all interference, by inverting the channel matrix and scaling the diagonal to meet the power constraints. Next in complexity is the the minimum mean square error (MMSE) linear canceler. It weights the interference from other lines and the other noises on the channel. These solutions are used upto G.fast 212 MHz \[10\]. Finally, a non linear precoder based on Tomlinson-Harashima precoder (THP) in the downstream or generalized decision feedback equalizer (DFE) in the upstream can be used to prevent power loss in the downstream and noise amplification in the upstream, respectively. This solution is complicated and has significantly higher complexity but is necessary for G.(mg)fast systems. Fig. 3 and Fig. 4 depict the data rates achievable using the various interference cancellation/ pre-coding techniques for different technologies.

Finally we would like to mention that in recent years there has been tremendous advances in massive MIMO wireless systems. These solution might find their way into future DSL systems. Further, we would like to mention that the fact that FEXT is higher than the direct signal suggests that treating the binder as a multiuser MIMO broadcast system in the downstream can lead to better points in the capacity region, where interference is used to amplify the desired signal. This is an interesting area of research for G.(mg)fast since it requires real-time solution of large convex optimization problems. Furthermore, the capacity region in this case is
**Fig. 4:** Average achievable user rate for various crosstalk cancelers. The binder is composed of 25 users with equal line lengths (20 m to 200 m). Other simulation parameters are described in the caption of Fig. 3.

**Fig. 5:** A sensor based cancellation schematic diagram [left] for external interference at the CPE with vectored precoding for FEXT cancellation in the downstream transmissions for the G.fast system. Transmit signals for each user at each tone are collected as a single vector at the DPU, and a precoder is applied before transmission for pre-compensation of crosstalk. At the CPE, a sensor probe is implemented as a noise reference. The external interference is captured at the sensor which gets couple to the main receive through a transfer function. The canceler has the task to estimate the coupling transfer function and then use the reference signal to mitigate interference from the main signal. The performance is evaluated [right] for different powers of external interference for the G.fast system 212 MHz system. The coupling transfer function is frequency dependent and has an imbalance of −40 dB for frequencies less than 30 MHz, 30 dBm/Hz between frequencies 30 MHz and 106 MHz, and 20 dBm/Hz thereafter.

only know under the approximation of Gaussian signaling.

More research is required for efficient crosstalk cancellation on DSL channels at higher frequencies including channel characterization. Iterative processing is another alternative to linear processing with reduced complexity and memory requirements [15]. Dynamic spectrum management improves the DSL performance by optimizing power allocation over the system bandwidth. Adaptation and tracking of crosstalk cancelers are important issues and require considerable attention in the context of DSL systems at higher frequencies.

For the mitigation of external interference, use of a noise reference sensor module can be effective at the CPE. Considering a linear model for external interference, a proof of concept was developed for VDSL system [13]. Data rate performance improvement is significantly higher, as shown in Fig. 5. Since the coupling for the sensor to the main channel is hard to model, deep learning based methods can be used for impulse noise cancellation in DSL systems.
V. CONCLUSIONS

In this article, we provided an overview of multi-gigabit rate transmission technologies over copper lines with a focus on interference cancellation. We highlighted the salient features of the upcoming DSL technologies and highlighted the key differences from its predecessors. We discussed various impairments that can be bottleneck in realizing high data rate transmissions. The crosstalk cancellation for DSL systems at extremely higher frequency poses new, challenging problems, and further research is needed to fully realize the goal of achieving multi-gigabit data rates over copper lines. Channel modeling for both NEXT and FEXT, and characterization of impulse noise at the higher frequency requires extensive measurement campaigns and statistical studies. We analyzed the impact of different interference cancellation techniques on the performance of DSL systems, and provided insights on new research direction in this area. A challenging problem is to deal with interference cancellation in a multi-pair full duplex DSL systems. Solving this problem, might be feasible only for certain topology and require proper power control. While at the DPU NEXT cancellation is a straightforward implementation of the multichannel echo canceler as is used in Gigabit Ethernet, the problem of the CPE receiver is significant, and data rates will be significantly degraded, especially when multiple receiver are co-located at the same floor.

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