10 Gb/s Adaptive Receive-Side Near-End and Far-End Crosstalk Cancellation Circuitry

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Abstract—**As serial I/O data rates scale above 10 Gb/s, crosstalk between neighboring channels degrades system bit-error rate (BER) performance. This paper presents receive-side circuitry which merges the cancellation of both near-end and far-end crosstalk (NEXT/FEXT) and can automatically adapt to different channel environments and variations in process, voltage, and temperature. NEXT cancellation is realized with a novel 3-tap FIR filter which combines two traditional FIR filter taps and a continuous-time band-pass filter IIR tap for efficient crosstalk cancellation, with all filter tap coefficients automatically determined via an on-die sign-sign least-mean-square (SS-LMS) adaptation engine. FEXT cancellation is realized by coupling the aggressor signal through a differentiator circuit whose gain is automatically adjusted with a power-detection-based adaptation loop. A prototype fabricated in a general purpose 65-nm CMOS process includes the adaptive NEXT and FEXT circuitry, along with a continuous-time linear equalizer (CTLE) to compensate for frequency-dependent channel loss. Enabling the crosstalk cancellation circuitry while operating at 10 Gb/s over coupled 4-in FR4 transmission line channels with NEXT and FEXT aggressors opens a previously closed eye and allows for a 0.2 UI timing margin at a BER = 10^{-9}. Total power including the NEXT/FEXT crosstalk cancellation circuitry, CTLE, and high-speed output buffer is 34.6 mW, and the core circuit area occupies 0.3 mm^2.**

I. INTRODUCTION

At data rates at or above 10 Gb/s, both intersymbol interference (ISI) due to channel frequency-dependent loss and crosstalk interference due to multi-channel coupling must be considered in order to ensure adequate system bit-error rate (BER). While equalizers are effective in cancelling ISI, topologies such as receive-side FIR filters and continuous-time linear equalizers (CLTLE) don't improve the signal-to-crosstalk ratio, motivating the use of dedicated circuitry to cancel both near-end crosstalk (NEXT) and far-end crosstalk (FEXT).

An effective approach to cancel NEXT involves passing the known aggressor transmit data through an FIR filter to sum with the incoming signal at the victim receiver. One key limitation of this approach is that the NEXT signal is only canceled out to the span of the FIR filter, leading to relatively long 5-7 tap implementations [1], [2]. At the receiver side, efficient cancellation of FEXT is possible by passing the aggressor signal through a high-pass filter which acts as a differentiator to emulate the FEXT signal [3]-[5]. With these crosstalk cancellation schemes, in order to seamlessly support operation with different channels and allow for robustness to variations in process, voltage, and temperature, adaptive tuning of all the filter coefficients is required.

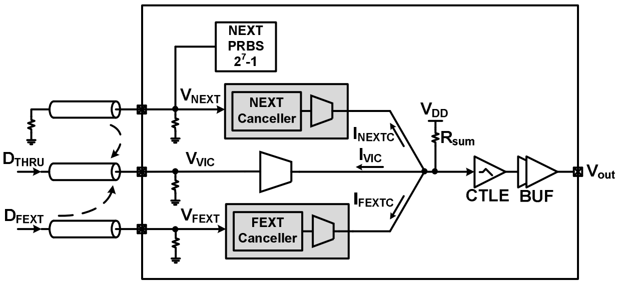


Figure. 1. Receive-side adaptive NEXT and FEXT cancellation circuitry.

For systems where both NEXT and FEXT exist, efficient merged NEXT/FEXT cancellation schemes are required which allow for simultaneous operation and independent adaptation to ensure robust operation. This paper presents receive-side circuitry which merges the cancellation of NEXT and FEXT and can automatically adapt to different channel environments and variations in process, voltage, and temperature. Section II gives an overview of the proposed receive-side adaptive NEXT/FEXT cancellation circuitry, which also includes a continuous-time linear equalizer to compensate for channel loss without masking the crosstalk cancellation impact. The adaptive NEXT cancellation scheme, which utilizes a novel 3-tap FIR filter which combines two traditional FIR filter taps and a continuous-time band-pass filter IIR tap for efficient crosstalk cancellation, is detailed in Section III. Section IV discusses the FEXT cancellation scheme which couples the aggressor signal through a differentiator circuit whose gain is automatically adjusted with a power-detection-based adaptation loop. Experimental results of the merged crosstalk cancellation system, fabricated in a GP 65-nm CMOS process, are shown in Section V. Finally, Section VI concludes the paper.

II. NEXT/FEXT CANCELLATION SYSTEM ARCHITECTURE

Fig. 1 shows a block diagram of the proposed receive-side adaptive NEXT and FEXT cancellation circuitry. The victim data signal, V_{VIC}, which includes both FEXT and NEXT coupled from adjacent channels, passes through a transconductance buffer stage that feeds a current-mode summer where both NEXT and FEXT are cancelled. In order to generate the NEXT cancellation current, the known

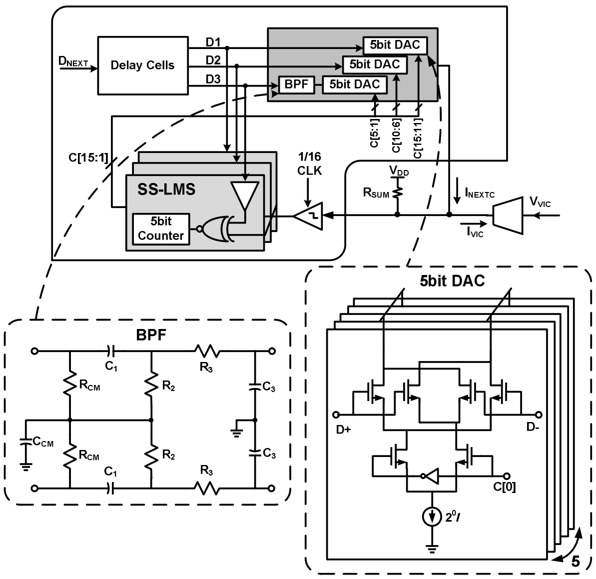


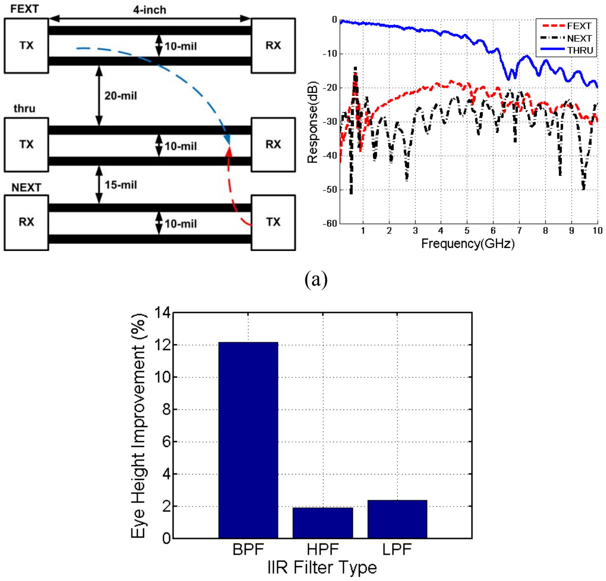
Figure. 2. Adaptive NEXT cancellation filter.

aggressor transmitter data passes through a novel 3-tap FIR filter which combines two traditional FIR filter taps and a continuous-time band-pass filter IIR tap for efficient crosstalk cancellation. FEXT cancellation current is generated by passing the parallel received FEXT signal, V_{FEXT}, through an adaptive-gain differentiator circuit. A CTLE follows to cancel the through-channel ISI without distorting the effectiveness of the cross-talk cancellation circuitry. Finally, a 50 Ω output buffer drives the equalized signal off-chip.

The crosstalk-cancellation circuitry has two modes of operation, data transfer and crosstalk cancellation adaptation mode. During crosstalk cancellation adaptation mode, the NEXT and FEXT cancellation circuitry are tuned sequentially, with further tuning details provided in the following sections. Data transfer mode is activated after the crosstalk cancellation circuitry has been calibrated, with the NEXT and FEXT cancellation control codes frozen.

III. NEXT CANCELLATION CIRCUITRY

NEXT cancellation is achieved with the 3-tap FIR filter shown in Fig. 2. Data from the aggressor transmitter is delayed with CML latches to generate the filter tap input signals that drive current-mode output stages with 5-bit differential current control per tap. This allows a constant output common-mode at the summer, independent of the specific tap weightings. Utilizing an approach similar to wireline transmitters which employ mixed FIR/IIR filter taps [6], the proposed NEXT emulation filter uses two traditional FIR taps and one band-pass IIR tap in order to better match the crosstalk transient response with only three filter taps. Before driving the current mode output stage, the third IIR tap data first passes through a passive RC bandpass filter with a 4.8 GHz center frequency and 2 GHz bandwidth. The 10 Gb/s simulation results of Fig. 3, which utilize measured s-parameter models of a NEXT/FEXT testbench consisting of three 4” differential channels, show that employing the band-pass IIR tap offers 12% eye height improvement relative to a traditional 3-tap FIR filter implementation. Also, the band-pass IIR tap performs superior to potential low-pass and high-pass IIR tap implementations.



(a)

(b)

Figure. 3. (a) Crosstalk cancellation test PCB consisting of three differential 4-in channels. (b) 10 Gb/s eye height improvement, relative to a traditional 3-tap FIR filter, by including an IIR tap.

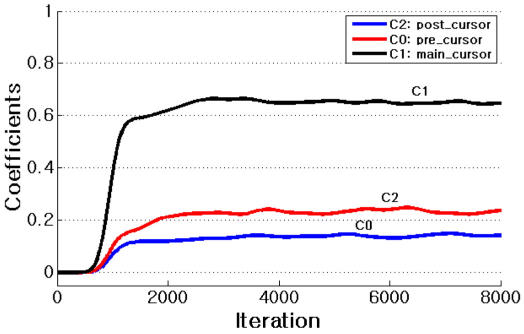


Figure. 4. NEXT cancellation filter coefficients convergence behavior with the SS-LMS adaptation loop.

The NEXT cancellation filter is calibrated by activating the aggressor transmitter to drive data onto the channel, while both victim and FEXT signals are deactivated. Under this condition, the crosstalk cancellation summer output represents the difference between the NEXT coupling on the victim channel and the emulated NEXT from the cancellation filter. Sampling the summer output provides information to drive a sign-sign least-mean square (SS-LMS) adaptation loop that sets both the FIR and continuous-time filter tap coefficients to emulate the NEXT signal. Rather than have the adaptation loop run with a full-rate clock [2], which can result in excessive power, the crosstalk cancellation summer output is sub-sampled with a 1/16-rate clock. Utilizing the Fig. 3 testbench, the simulation results of Fig. 4 show that the three filter taps converge within 2000 iterations.

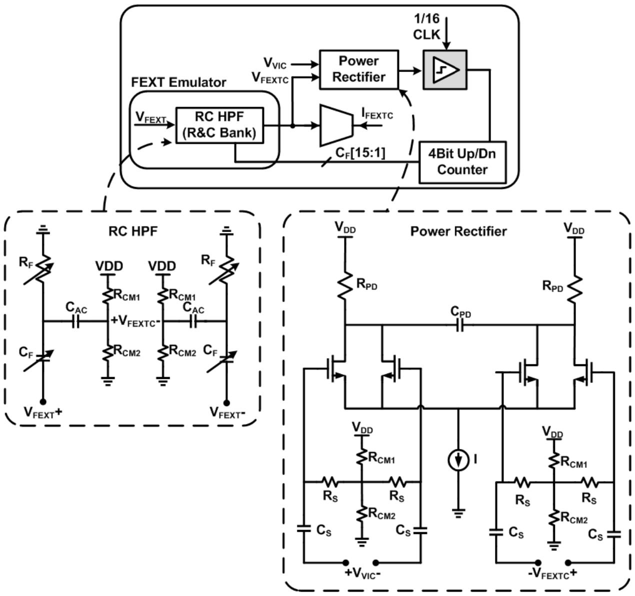


Figure. 5. Adaptive FEXT cancellation filter.

IV. FEXT CANCELLATION CIRCUITRY

Fig. 5 shows the FEXT cancellation circuitry, where the FEXT aggressor is passed through a tunable RC-highpass filter which acts as an adaptive-gain differentiator circuit to emulate the coupling that occurs on the victim channel. The high-pass filter pole frequency is adjustable from 2.7 GHz to near 20 GHz, with a 3-bit manually-controlled band-select resistor bank and a 4-bit adaptively-controlled capacitor bank. This emulated FEXT signal is AC-coupled to drive a current-mode output stage which is connected to the shared crosstalk cancellation summer.

Adaptation of the FEXT cancellation filter is achieved by activating the aggressor transmitter at the far-end to drive data onto the channel, while both the victim and NEXT signals are deactivated. Under this condition, a rectifying power detector circuit compares the victim signal with the FEXT aggressor signal passed through the passive RC differentiator [7], [5]. Similar to the NEXT cancellation, the power rectifier output is sampled with a 1/16-rate clock and the obtained error signal controls a 4-bit counter to adjust the digitally-controlled capacitor bank to set the power of the FEXT emulation signal equal to the FEXT coupled onto the victim signal. Relative to tuning the differentiator gain in the current-mode [5], this method of tuning the RC values to adjust the FEXT emulation signal gain saves power and offers a more stable output common-mode for the shared crosstalk cancellation summer. Utilizing the Fig. 3 testbench, the simulation results of Fig. 6 show that the capacitor code converges within 2000 iterations.

V. EXPERIMENTAL RESULTS

The receive-side crosstalk cancellation circuitry, consisting of the NEXT and FEXT cancellation systems and a CTLE for ISI compensation, was fabricated in a GP 65-nm CMOS process. As shown in the Fig. 7 chip micrograph, this circuitry consumes a core active area of 0.3 mm^2. In order to analyze the performance of the crosstalk cancellation circuitry, the Fig. 3 PCB testbench is used with three 4-in differential channels with 5.8 mil trace width and a 10 mil differential separation. The middle victim channel has both NEXT and FEXT aggressors at 15 mil and 20 mil spacing, respectively.

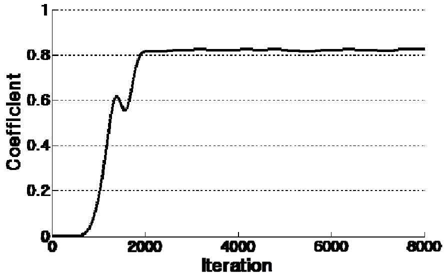


Figure. 6. FEXT cancellation filter digitally-controlled capacitor bank convergence behavior with the power-detection-based adaptation loop.

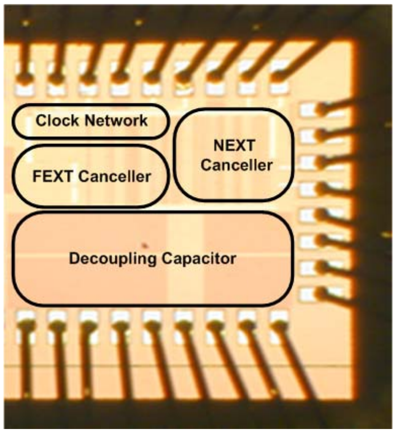
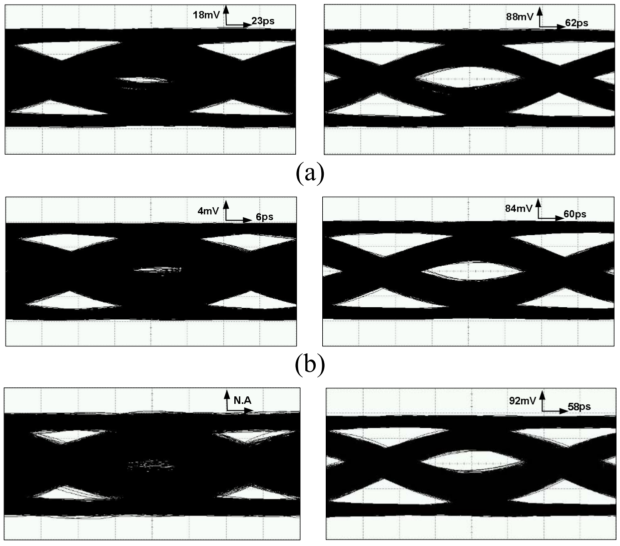


Figure. 7. Chip micrograph showing the receive-side NEXT and FEXT crosstalk cancellation circuitry.

Testing with NEXT only is achieved by having both the NEXT aggressor and victim transmitters send independent 10 Gb/s 2^7-1 PRBS data onto their respective channels, while the FEXT aggressor is quiet. As shown in the eye diagrams of Fig. 8(a), activating the NEXT cancellation circuitry enables a previously near-closed eye to open to near 22% eye height relative to the 400 mVpp driver swing. Disabling the NEXT aggressor and enabling both the FEXT aggressor and victim transmitters to send independent 10 Gb/s 2^7-1 PRBS data onto their respective channels allows for independent FEXT testing. For this case, Fig. 8(b) shows that the FEXT degrades the eye slightly more than the NEXT. However, by activating the FEXT cancellation circuitry, the previously near-closed eye is opened to near 21% eye height. With both NEXT and FEXT aggressors enabled the output eye is completely closed, but enabling both of the cancellation circuits allows for a similar 23% eye height. The measured system BER of Fig. 9 correlates with the observed eye diagrams, with poor BER for the case when both NEXT and FEXT is present and the crosstalk cancellers are disabled. Activating both the cancellation circuits results in 0.2 UI timing margin at a



(a)

(b)

(c)

Figure. 8. Measured 10 Gb/s eye diagrams with crosstalk filters off (left) and on (right): (a) NEXT only, (b) FEXT only, and (c) both NEXT and FEXT.

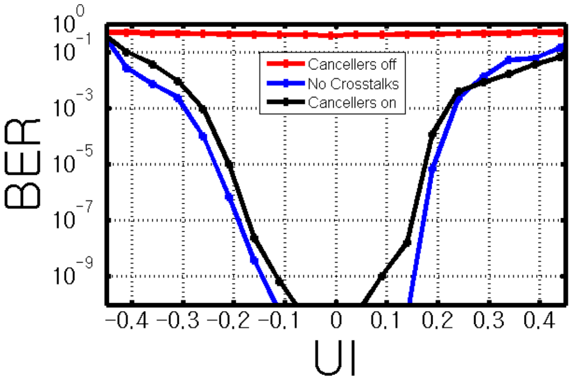


Figure. 9. Measured 10 Gb/s BER bathtub curves for the three 4-in differential channels testboard for 2^7-1 PRBS data.

BER=10^{-9}, which is comparable to the 0.3 UI observed for the case of no crosstalk aggressors.

Table I summarizes the performance of the prototype receive-side crosstalk cancellation circuitry and compares it to other recent designs. Relative to the work of [2] and [4], which only considered one type of crosstalk, the proposed design is able to efficiently cancel both NEXT and FEXT with the ability to adapt the cancellation filter parameters. Table II shows the measured power breakdown at 10 Gb/s, with a total power of 34.6 mW or 3.46 pJ/b. The majority of power is consumed in the NEXT canceller due to the CML latches employed in the FIR filter, suggesting that further improvements in power are possible by moving to a CMOS implementation.

VI. CONCLUSION

TABLE I. Performance Comparison

	[2]	**[4]**	**This Work**
CMOS Technology	130-nm	65-nm	65-nm
Supply Voltage (V)	1.2	1.1	1.1
Data Rate (Gb/s)	5	12	10
Area (mm^2)	0.426	0.04	0.84
Output Swing (mV_{pp})	400	500	400
Power (mW)	177	11.5	34.6
Crosstalk Cancellation Type	NEXT	FEXT	NEXT & FEXT
Adaptation	Yes	No	Yes
BER	10^{-12}	10^{-8}	10^{-9}
Signaling	Diff.	Single-Ended	Diff.

TABLE II. 10 Gb/s Power Breakdown

Block	**Power (mW)**
NEXT Canceller	18.5
FEXT Canceller	1.5
Clocking	6.8
CTLE	1.3
Output Buffer	6.5
Total Power	34.6

This paper presented receive-side circuitry which merges the cancellation of NEXT and FEXT and can automatically adapt to different channel environments and variations in process, voltage, and temperature. Efficient NEXT cancellation is achieved with only three filter taps through the inclusion of a continuous-time band-pass filter IIR tap in the NEXT cancellation filter. Utilizing independent SS-LMS and power-equalizing loops for NEXT and FEXT adaptation, respectively, allows for the optimization of both cancellation filters. Overall, the proposed circuits provide the potential for increased robustness to crosstalk in systems where both NEXT and FEXT exist.

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