Proceedings of the 7th International Caribbean Conference on Devices, Circuits and Systems, Mexico, Apr. 28-30, 2008

IDENTIFICATION OF HIGH SPEED JITTERED DIGITAL INTERCONNECTS USING BICOHERENCE SPECTRA

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Abstract— **Interference due to narrowband and broadband sources in mobile computing platforms have the capability to degrade overall wireless performance. Identification of these radio frequency interference (RFI) sources allows for mitigation and improved wireless performance. While shielding gives some immunity, interference sources operating within the same platform as sensitive radio receivers presents challenges far and above traditional electromagnetic compatibility (EMC) of device integration. In this paper, bicoherence, a signal processing analysis algorithm, is used to identify the presence of high-speed interconnects in radiated platform emissions. This paper uses a practical example of RFI found in current wireless platforms and shows that detection is feasible in Gaussian and non-Gaussian additive noise environments.**

I. Introduction

The convergence of computing and communications brings together two traditionally independent subsystems in current mobile wireless platforms: namely, the electromagnetic interaction of high-speed interconnects (I/O) with sensitive wireless radio receivers that result in diminished wireless performance. Gutmann [1] has shown that the design of mobile platform components must take into account the electrostatic and electromagnetic coupling into the target platform's RF bands of operation given the increasing trend in I/O bus speeds.

High speed digital interconnects and their associated base clocks are sources of potential radio frequency interference (RFI) due to harmonics overlapping into frequency bands intended solely for wireless communications. These RFI sources have unique characteristics associated with their power spectral densities, phases, base clock frequencies, or statistical properties (i.e. mean, variance, skewness, and kurtosis) that can be leveraged for RFI source identification in order to gate eventual RFI mitigation. M. Nassar et al. in [2] have shown that myriad filtering is effective in mitigating the non-Gaussian impulsive nature of RFI and restoring wireless performance. Specifically, this study focuses on the use of higher order statistical signal processing (HOSSP)—namely, the bicoherence—to uniquely identify RFI signal characteristics and determine the potential for impact upon a radio channel of interest.

High-speed I/O signals have non-idealities due to variations in symbol rise and fall times termed timing jitter. Timing jitter in the high-speed I/O signal can not be identified by the power spectrum. However, timing jitter can be detected by using high order statistics. Sharfer and Messer [3] detected timing jitter by using the bispectrum of sampled data. They showed that the presence of jitter introduces a nonzero contribution to the discrete bispectrum in the outer triangle of the principal domain. Based on this observation, they proposed a binary hypothesis test as a detection method. Other information such as the corresponding symbol rate (R_s) or frequency (f_i) of the input signals can not be obtained from computation of the bispectrum. It is the unique detection of this symbol rate by an HOSSP estimator that leads to meaningful RFI signal identification and triggers further parameter estimation of impulsive noise statistics for improved wireless performance [2].

A waveform's symbol rate can be estimated by many approaches such as the instantaneous phase detector [4], the delay and multiply detector [5], the spectral correlation detector [6], and the higher-order spectra detector [7]. While these approaches detect the symbol rate of unknown digital communication signals, the detection of RFI in the presence of alternate non-jittered interference or low signal to noise (SNR) data signals can not be obtained by using the approaches mentioned above. In contrast, the identification method proposed in this paper can estimate the symbol rate of the jittered data signal by using polyspectral analysis in the presence of alternate Gaussian or non-Gaussian contributions.

Bicoherence is useful to detect system nonlinearities and to study phase relations of their harmonic components. By observing the phase coupling introduced by nonlinearities, bicoherence spectra can detect machine faults as researched in [8], [9]. While the extraction of unique pulmonary pathology features associated with musical lung sounds as explored in [10]. In general, HOSSP techniques have wide applicability and offer increased analysis capabilities necessary for determining potential platform or system impacts.

In this paper, bicoherence is used to identify RFI source characteristics. A distinct line pattern is observed by using the estimated bicoherence. This paper found that the line pattern is related to the period of input sources. The proposed identifier relies on the line pattern in the estimated bicoherence by using

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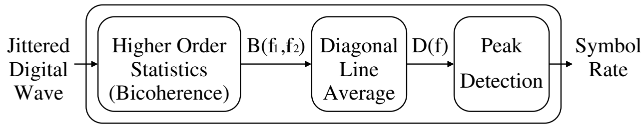


Fig. 1. Proposed identifier for jittered digital wave with higher order statistics

diagonal line average and peak detection units to identify the source. A case study of the experimental PCI express signal will be used to show that the proposed identifier can detect the presence of the signal.

II. Bicoherence

The bispectrum and bicoherence of a discrete-time signal are periodic functions described in two frequency indexes,(f_1, f_2). The bispectrum $S(f_1, f_2)$ of a process $\{x(k)\}$ is defined as [11]:

$$S(f_1, f_2) = E\{X(f_1)X(f_2)X^*(f_1 + f_2)\}, \tag{1}$$

where $E\{\cdot\}$ is the expectation operator, $X(f_i)$ is the complex Fourier coefficient of the process $x(k)$ at frequency f_i and the $X^*(f_i)$ is its complex conjugate.

The normalized bispectrum is defined as [11]:

$$B(f_1, f_2) = \frac{S(f_1, f_2)}{[P(f_1)P(f_2)P(f_1 + f_2)]^{1/2}} \tag{2}$$

where $P(f_i)$ is the power spectrum at frequency f_i of the process. The magnitude of the normalized bispectrum, $|B(f_1, f_2)|$, is called the bicoherence. The bicoherence quantifies the presence of quadratic phase coupling (QPC) between any two frequency components in the process due to their non-linear interactions. Two frequency components are said to be quadratically phase coupled with bicoherence close to or greater than 1 when there exists a third frequency component whose frequency and phase are the sum of the frequencies and phases of the first two components.

III. Identifier

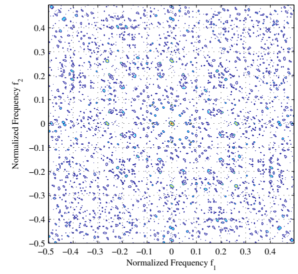
The proposed identifier for a high speed jittered digital I/O is composed of three key elements: bicoherence unit, diagonal line average unit, and peak detection unit as shown in Fig. 1.

A. Bicoherence

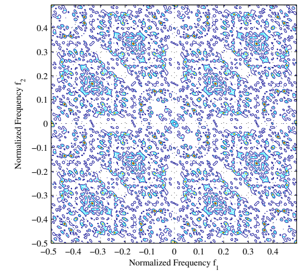
The bicoherence unit produces an estimated bicoherence of $B(f_1, f_2)$ at frequency f_1 and f_2 of input signal x. The definition and the estimation of bicoherence are given in [11].

A Gaussian process, pseudo random bit streams (PRBS), and the RFI signals of interest were simulated in order to compare and analyze their corresponding bicoherence. Under the Gaussian assumption, the bicoherence is zero. Estimated bicoherence based on a finite number of samples of Gaussian process are shown in Fig. 2 (a).

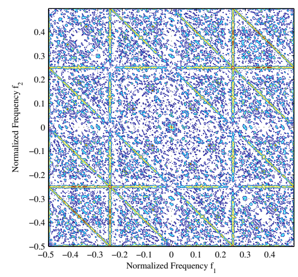
An ideal PRBS signal, with symmetric shape or identical rise and fall times, was simulated and the expected values of bicoherence of the ideal PRBS are shown in Fig. 2 (b). Non-ideal PRBS signal, with asymmetric shape or different rise



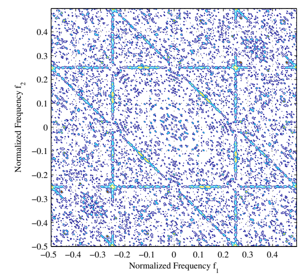
(a) Gaussian



(b) Ideal PRBS



(c) Non-ideal PRBS with different rising and falling time



(d) Non-ideal PRBS with unit interval jitter

Fig. 2. Estimated bicoherence in Gaussian and PRBS signals

and fall time, exhibits distinct line patterns as shown in Fig. 2 (c) and Fig. 2 (d). By changing the data rate of PRBS, we observed that the diagonal line also shifts according to the data rate. We also observed that the cross point between the extended diagonal line and the x or y axis indicates the data rate of PRBS. Thus, the data rate of a non-ideal digital wave can be estimated by bicoherence.

B. Diagonal Line Average

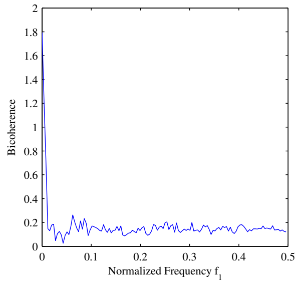
Diagonal line average recognizes the distinct line in the estimated bicoherence by using line averages at diagonals as

$$D(f) = E[B(f_1, f_2)], \text{ when } \quad f = f_1 + f_2, f_1 > 0, \; f_2 > 0, \text{ and } f_1 > f_2 \tag{3}$$

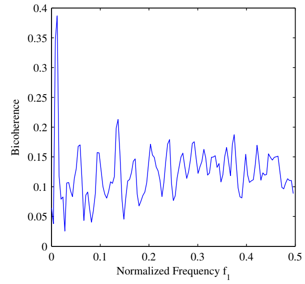
Figure 3 shows the diagonal line average of the estimated bicoherence in Gaussian and PRBS signal.

C. Peak Detection

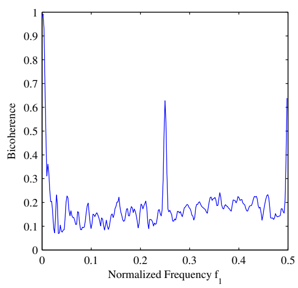
The peak detection unit searches for the peak value of input above a threshold. The frequency near zero is ignored since it is a direct current (DC) component and is not related to the frequency variation of the RFI source. Hence, by setting the threshold at 0.5, the peak detection unit yields no detection. While at a threshold of 0.25, the unit yields detection of ideal and non-ideal PRBS, respectively. The peak detection unit can indicate the data rate of digital wave. Therefore, this proposed identifier can not only detect non-ideal digital waves but also estimate the corresponding data rate.



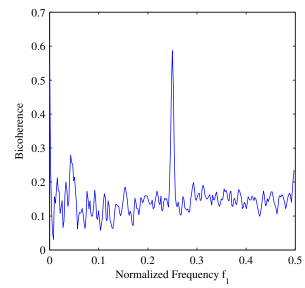
(a) Gaussian



(b) Ideal PRBS



(c) Non-ideal PRBS with different rising and falling time



(d) Non-ideal PRBS with unit interval jitter

Fig. 3. Diagonal averages of the estimated bicoherence in Gaussian and PRBS signals

IV. Case study: PCI express

The PCI express bus is widely used in mobile platforms to communicate at high speed data rates to exchange information between components. Practically, the various sources of deterministic or random jitter such as signal reflection, cross talk on transmission lines, and non-linear properties of electronic components give rise to non-ideal PCI express signals. The case study shows the estimation of the data rate of the PCI express using bicoherence.

The high speed digital sampler of 20 GHz obtained digital samples of the PCI express bus signal of 5.25 GSPS. The estimated bicoherence of the measured PCI express signal is shown in Fig. 4. The pattern in the figure is similar with the pattern in non-ideal PRBS as shown in Fig. 2 (c) and Fig. 2 (d). It implies that the measured PCI express signal is non-ideal.

The diagonal line average of the estimated bicoherence of the measured PCI express shows two peaks as shown in Fig. 5. Ignoring the values near zero frequency, the peak detection unit produces a peak frequency value of 0.2617. The frequency values are normalized to a sampling frequency of 20 GHz/sample. Thus, the estimated data rate is 5.234 GHz/sample (= 20 GHz/sample $\times$ 0.2617), which is close to the data rate of PCI express. The difference between the estimated and real data rate came from the limited size of FFT in the bicoherence computation.

In order to gauge the capability of PCI express signal detection, sine wave and Gaussian noise data was added to the PCI express signal data. Fig. 6 shows the detected

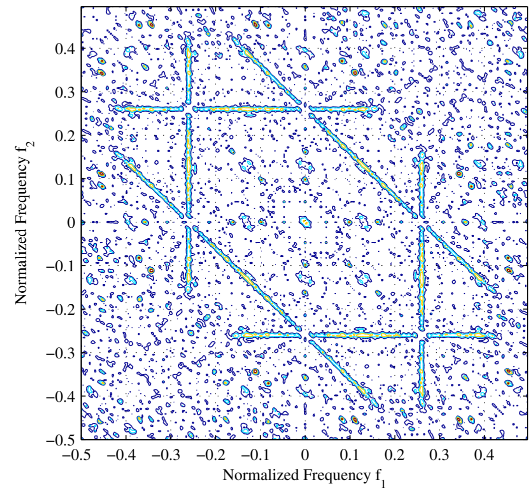


Fig. 4. Estimated bicoherence of measured PCI express (Sampling frequency: 20 GHz, PCIe Frequency: 5.25 GSPS)

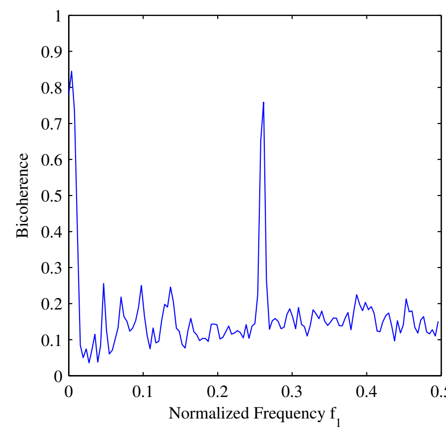


Fig. 5. Diagonal line average of bicoherence in measured PCI express signal

frequency value with respect to signal-to-noise ratio (SNR). At the high SNR, the identifier with both noise estimates derives the correct frequency value of 0.2617. The identifier with the Gaussian noise can not estimate correct frequency value at the low SNR. The peak value at the corresponding frequency according to the SNR is shown in Fig. 7. In general, the performance of the peak detection unit is sensitive to the threshold value. The PCI express with sine wave noise above -40 dB and Gaussian noise above 25 dB can be detected by setting the threshold of 0.5. This results show that this identifier is robust to sine wave noise.

V. Conclusion

This paper found that the estimated bicoherence in non-ideal waves shows the distinct line pattern, which is related to the input data rate. The line pattern information is utilized in the proposed algorithm to estimate a data rate. A case study of PCI express signal shows that measured PCI express bus

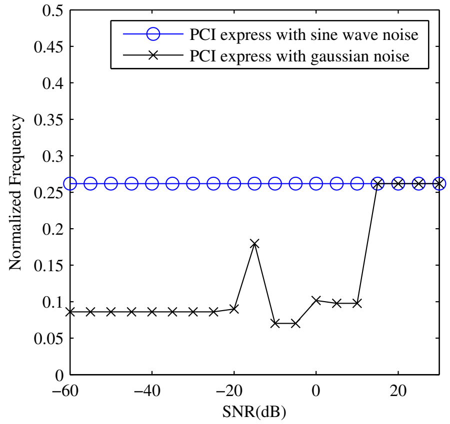


Fig. 6. Peak frequency value in diagonal line average of bicoherence in measured PCI express signal with platform noise

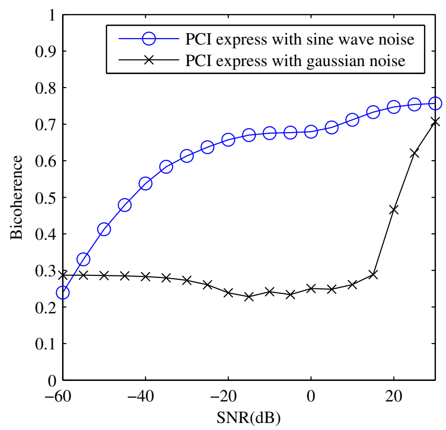


Fig. 7. Peak values in diagonal line average of bicoherence in measured PCI express signal with platform noise

signal is non-ideal and the data rate of PCI express is found by the proposed identifier. The proposed identifier demonstrates not only detection of jittered digital waves but also estimation of its data rate.

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