Multipoint intermittent fault detection of electronic interconnections using channel sounding techniques

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Abstract. Intermittent faults (IFs) in electrical interconnection are short duration transients. These faults are random, non-predictable and non-stationary in nature making them hard to troubleshoot using traditional equipment. They can be detected only if the test equipment has test coverage both in time and area at that instant. This paper proposes a novel approach of intermittent fault detection by injecting a wideband signal and using channel-sounding techniques. A novel Direct Sequence Spread Spectrum (DS-SS) technique is presented for multipoint IF detection and health monitoring. Digital communication sounding technology and its methods devised for detection and classification of an IF, and channel characterisation by its transfer function is discussed in detail. A combination of transmitter and receiver provide an effective tool for continuously monitoring of the multi-point interconnect. The proposed method has been tested using a functional prototype having pre-induced IFs. Intermittent signal is generated by applying external vibration on the connector and intermittency is detected by acquiring and processing the propagated signal. The results demonstrate the effectiveness of the method in detection and classification of intermittent interconnections.

Keywords: fault diagnosis, maintenance engineering, condition monitoring, integrated circuit interconnections, circuit faults, vibrations, electric connectors.

1. Introduction

With increasing complexity of digital electronic circuits, the probability of occurrence of faults has also increased. The most common fault in these circuits occur in electronic interconnections. Faults cause the system to operate far away from its optimal point and reduces its efficiency. It is critical to identify them due to safety concerns specially in aerospace applications [1].

System faults are broadly classified into three categories: permanent, transient and intermittent faults (IFs) [2]. IFs are electrical spikes developing due to ageing interconnects, cuts, rubs, or loose contacts. They occur in an unpredictable manner and are safety critical [3].

Manufacturing imperfections, poor design and system degradation are main causes of IFs which are in turn precursors of permanent failure [4, 5]. These are random and non-reproducible incidents, and are not usually identified by visual or traditional instruments for electronic/electrical interconnects. When the fault is intermittent, it could not be present at the time of testing and will be tagged as No Fault Found (NFF) [6]. Industries are suffering from NFF failures due to lack of necessary levels of confidence and efficiency of the methods used in detecting these events. Traditional test equipments used to detected anomalies like multi-meters
detect only steady or invariant signals. While digital oscilloscopes can detect changing signals based on the sampling function, problem with an IF is that it occurs for a very small duration, making it difficult to detect unless a very high sample rate it used which is beyond the capabilities of traditional digital oscilloscopes. A 2012 survey of 80 aerospace organizations ranked IFs as the highest perceived cause of NFF [7]. The survey results gives a strong motivation to develop a novel algorithm for electronic interconnection faults using channel sounding techniques.

2. Methodology

The current state-of the-art IF detection during maintenance testing includes latching continuity testing, analogue neural network technology and time domain reflectometry. Reflectometry is widely used for high power electrical wirings and could not be used for interfaces, lose solder joints and other electronics circuits. It relies on transmitting electromagnetic waves across the wire and in turn observing the reflections $R$.

$$R = \frac{(Z_1 - Z_2)}{(Z_1 + Z_2)},$$  \hspace{1cm} (1)

where $Z_1$ and $Z_2$ are impedances of two electrical mediums. These reflections depend on the variation of impedance in the wire system. Time duration between the incident and reflected wave is used to locate the fault. Magnitude of reflections is used to determine if it is a potential fault or not. The drawback of reflection based techniques is that any change in the wire material (e.g., connection in circuit) reflects the incident waves resulting in erroneous fault determination. Moreover, they requires high voltage pulses which can’t be applied to low voltage digital circuits.

Recently, direct-sequence spread-spectrum (DS-SS) modulated signals are used instead of high voltage signals in employing digital signal processing techniques to locate faults [8]. It uses low voltage signals and does not interfere with online signals and could be used in-situ, but it still suffers from reflection occurring at all points of interconnections in the circuit making it unsuitable for electronic circuits like PCBs, solder joints, interfaces, and similar interconnections. Kim et al. used DS-SS frequency shift keying (FSK) modulation technique to overcome reflectometry issue of reflections and false alarms [9]. Although the false alarms problem was solved but still it could not be used for mesh and complicated architecture of multipoint and does not give channel characterisation or degradation information. Taylor and Faulkner initially proposed DS-SS modulation technique, and outlined optimal signal processing and frequency domain correlation for the on-line test in high voltage power line carrier [10]. Furse et al. employed a slightly different use of the spread spectrum for detecting live wire problems [11]. This paper presents a novel method of IF detection and characterisation to overcome the above mentioned issues. The DC signal is spread with DS-SS and send into interconnection system for IF detection and channel measurement. This could be used for multipoint interconnections and to diagnose wire health after de-spreading to retrieve an intermittent signal at output of the system that are not extractable using traditional equipments like oscilloscope, reflectometry,neural network based bespoke equipment or voltmeter. The transients caused by IFs in the wire would disrupt the DS-SS signal sent over interconnection from the transmitter. The DS-SS signal retrieved at the receiver end would contain intermittent signal information. IF will eventually be deducted from the signal by de-spreading i.e. multiplying it with the PN-code. Only same PN-code will de-spread the signal which has been used for spreading, each node will have unique PN-code. The communication technology and its devised method for detection and extraction of faults information in terms of duration and occurrence frequency, and channel impulse response for characterisation of wire channels is described in detail. The simulation of the prototype system is performed and experiments were conducted on the rig. Finally conclusions and future scope of the work has been discussed.
3. Communication Sounding Approach for Intermittent Fault Detection

System impulse response technique is used to get the frequency response of the system. This is used in many applications and most electronics systems are designed with the consideration of transfer function or impulse response. This is also used to get channel response to see behaviour of channel over frequencies of interests for reliable communication. This concept could be used to get frequency response of wire or other interconnection system and see behaviour of response over wider band of frequencies to estimate deterioration or degradation. The impulse response will give the channel response over wide range of frequencies. Any crack or degradation could be detected by impulse response. Small wire degradation might not effect DC or low frequencies but higher bandwidth response can be used to estimate wiring and interconnection system. In time domain, the channel can be described as complex impulse response $h(t, \tau)$ as shown in Figure 1.

$$\begin{align*}
\text{Figure 1. Channel impulse response.}
\end{align*}$$

Equation (2) shows the relation between input and output of channel, where, $x(t)$, $y(t)$ are input/output, and impulse response $h(t, \tau)$ and ‘$\ast$‘ is the convolution. To de-convolve $x(t)$ from $y(t)$ in time domain is bit complicated but this could be expressed in the frequency domain as

$$Y(f) = H(f) \cdot X(f) \implies H(f) = \frac{Y(f)}{X(f)}. \quad (3)$$

$X(f)$, $Y(f)$ are the Fourier transforms of $x(t)$ and $y(t)$. It is more convenient to calculate impulse response or the transfer function for discrete time signal using $z-$transforms defined as

$$X(z) = \sum_{n=0}^{\infty} x(n)z^{-n}; \quad H(z) = \frac{Y(z)}{X(z)} = \frac{y_0 + y_1z^{-1} + \ldots + y_{n-1}z^{-(n-1)} + y_nz^{-n}}{x_0 + x_1z^{-1} + \ldots + x_{n-1}z^{-(n-1)} + x_nz^{-n}}. \quad (4)$$

Where $X(z)$ is $z-$transform of $x(n)$, and $H(z)$ is the transfer function.

4. Orthogonal codes

A pseudo noise code (PN code) has a similar spectrum as that of a random noise but it is generated deterministically. PN codes are generated by using shift registers with modulo-2 arithmetic. Most widely used sequences in DS-SS systems are Gold codes, Kasami codes, Barker codes, and Hadamard codes [12]. Hadamard codes are perfectly orthogonal and are optimal codes to avoid interference among users in the link from base station to terminals. This paper uses a Hadamard code for channel sounding. To obtain the orthogonal set, the approach is to select these codes from rows or columns of a Hadamard matrix. A Hadamard matrix is $2^k \times 2^k$ square matrix of elements belong to $(1, -1)$ set. The simplest matrix of 2 orthogonal Walsh-Hadamard sequences is given by

$$H(2) = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \quad (5)$$

The code of user 1 is the first column and the code of user 2 is the second column. Clearly the first column $(1, 1)$ is orthogonal to the second column $(1, -1)$. This matrix is eventually extended using a recursive technique. For $2^N$ users, the matrix is found from the code matrix for $2^{(N-1)}$ users, according to

$$H(2N) = \begin{bmatrix} H_N & H_N \\ H_N & -H_N \end{bmatrix} \quad (6)$$
Orthogonal codes are used for spreading in communication systems where the receiver is perfectly synchronized with the transmitter. The de-spreading operation is ideal, as the codes are completely de-correlated. Hadamard matrices are square matrices with entries either $+1$ or $-1$. If $N$ is a nonnegative power of 2, the $N \times N$ Hadamard matrix $H_N$, is defined recursively as given in Equation (6).

$$H_N H_N^T = N I_N,$$

where $I_N$ is the identity matrix of size $N \times N$. The code generator block outputs a row of $H_N$. The output is bipolar. The code length parameter $N$ must be a power of 2 and is specified by the user. Moreover the index of the row of the Hadamard matrix, which is an integer in the range $[0, 1, \ldots, N - 1]$, called as the code index parameter is also user specified.

5. DS-SS Sounding technique for IF Detection

DS-SS sounding technique for IF detection in multi-points electronic interconnection system sends a DC constant unit signal input and spreads it with pseudo-random noise (PN), orthogonal codes to wider band. Hadamard orthogonal sequence is used for spreading in this system because receiver is perfectly synchronized with the transmitter. De-spreading operation is ideal, as the codes are completely de-correlated and PN is completely removed. As input to diagonalize the system is a constant DC signal, the output will be a transfer function that gives channel impulse response using channel sounding technique. The complete system is shown schematically in Figure 2. A carrier signal based approach to detect IF has been investigated earlier by one of the authors in [13]. This approach is an advanced version of similar underlying ideas.

Figure 2. Block Diagram of Multi Node IF Detection using Channel Sounding.

Figure 3. Two point intermittent fault detection model.

6. Simulation

The simulation model of the DS-SS sounding technique is developed in MATLAB/Simulink (see Figure 3). It could be modeled with as many test points as required but only two test points has been simulated to show how it could be used to test multi point interconnections. It consists of two transmitters, two receivers, and two test nodes of IF. In our model we have also included Additive White Gaussian Noise (AWGN) to make it more realistic. We have simulated it with two intermittent connection and showed how DS-SS detects IF and it also shows that cross talk with other point does not de-spread, thus eliminating the false alarm in multi node configuration.
The system consists of three sub blocks: transmitter, channel, and receiver. Each transmitter and receiver use the same orthogonal codes to spread/de-spread input signal as described in previous section. Every transmitter spreads a constant voltage signal with different Hadamard codes and propagates through an electronics interconnection system for IF and feature detection. De-spreading unit removes pseudo-noise (PN) by multiplying it with same generated PN code.

7. Simulation results
To monitor the signals at inputs/outputs, scopes are connected to the input and output as shown in Figure 3. Scope 1 and 2 are connected with node 1 with same PN codes, 3 is connected to output with different PN code’s signal than transmitter while 4 is connected to perfectly synchronised PN code with transmitter. A constant value input signal of unit magnitude is connected to all inputs. Intermittent signals from node 1 are regenerated by removing DS-SS signal are shown in Figure 4. As Scope 3 is connected to different PN code it is not able get intermittent signal and the output is noisy. Scope 4 shows the perfectly synchronised PN code.

![Figure 4](image.png)

**Figure 4.** Simulation results: (a) Scope 1: Signal showing channel IF. (b) Scope 2: Channel IF. (c) Scope 3: Poor de-spreading due to wrong orthogonal code. (d) Scope 4: Perfectly synchronised PN code.

8. Validation
This algorithm has been validated by acquiring data to Simulink model from National Instrument (NI) 6363 X-series data acquisition system. This system has both analogue and digital input/outputs. Experimental setup is shown in Figure 5. DS-SS signals are generated in Simulink model and sent to interconnections system through NI-6363. Ethernet male and female socket on shaker has been used as test rig, to introduce intermittency in DS-SS signals. The signals are acquired back by same NI system for de-spreading and intermittent feature extraction. For further details regarding the experimental setup see [14]. This intermittent fault detection system has been described by using a block diagram as shown in Figure 6. Two PN
codes are used for two node IF detection. A DC unit signal is spread and DS-SS signals are sent to a multipoint ethernet socket on the test rig. PN codes are removed by multiplying/de-spreading to get intermittent interconnection information as described in simulation results.

![Figure 5](image)

**Figure 5.** (a) Test-rig (b) Ethernet connector on shaker.

![Figure 6](image)

**Figure 6.** Block diagram of testrig.

Same Simulink model is used for this experiment as described in the Simulation section earlier. The results are described in Figure 7. Scope 1 and 2 shows the results of same interconnection loop at node 1 with same PN codes synchronisation, whereas Scope 3 and 4 shows the results of second node but with two different PN codes.

![Figure 7](image)

**Figure 7.** Test results: (a) Scope 1: Node 1 with same PN code de-spreading. (b) Scope 2: Node 1 with same PN code de-spreading. (c) Scope 3: Node 2 with different PN code de-spreading. (d) Scope 4: Node 2 with same PN code de-spreading.
9. Conclusions

Multipoint intermittent interconnections can be detected by using DS-SS schemes and it could be classified with respect to band of intermittence that linked with external vibration. It also reduces human factor’s mistake to put wrong node for IF detection because only same PN code could only be used to extract IF information. The characteristics of IF could also be detected with respect to amplitude and frequency and these could be used to predict the interconnection degradation or manufacturing faults. It is low power and very efficient technique that could be used in-situ for multi-nodes. This method is generalized and filter banks can be used to segment different possible bands of spectrum. In future we would focus on adding wavelets banks to segment different possible bands of spectrum for further analysis of intermittent signal. This work could be carried out by wavelets transforms, or Short Time Fourier Transform (STFT); to determine the sinusoidal frequency and phase content of local sections of a signal as it changes over time and this could be used to detect intermittency, and to find root causes.

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