An Embedded Test & Health Monitoring Strategy for Detecting and Locating Faults in Aerospace Bus Systems

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Abstract

A new test & measurement strategy for on-line health monitoring of Mil-Std-1553 data bus is proposed. The method monitors the signal quality at multiple points on the data bus and uses the voltage measurements to detect and locate defects. The on-line monitoring method supports defect detection and location on the main backbone of the bus and in transformer coupled branches. The method does not require excessive data processing but some communication between measurement points is required. The advantage of this method is that it supports detection of intermittent defects which can not be located using off-line measurement. It also provides the ability to detect defects on whole data bus harness. The method is complemented with a supporting test involving an externally generated test signal to find certain defects which require multiple measurements. The measurement method is designed to work independently on the data bus using embedded electronics without disrupting the normal operation.

***Keywords**: On-line measurement; wiring; health monitoring; Mil-Std-1553.*

1. Introduction

The difficulties associated with wire harness testing are often underestimated when developing wider system test strategies. Following installation, wiring systems are not normally serviced whilst moving parts and hydraulics are replaced on a regular basis. This pushes the use of wiring beyond the replacement intervals acceptable for most other components. Degradation and failure in these wiring systems is hence a major reliability concern and is increasingly becoming an important maintenance cost issue. Alone in the US Navy it is estimated that 1.8 million person-hours per year is used to troubleshoot and repair its aircraft wiring systems [1].

Many of the defects on wiring harness occur only in certain environments. For example, many aircraft wiring faults occur in-flight but are not visible during maintenance checks on the ground. These intermittent defects [2] require on-line monitoring techniques to help ground maintenance diagnose and rectify faults. Smart wire systems, which are under development, will monitor cables continuously and will even be able to correct faults as they occur [1, 3].

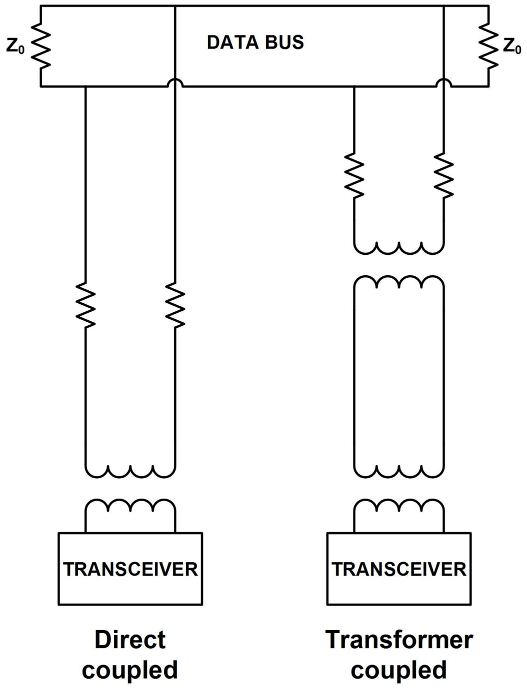

Figure 1 Device connection methods for Mil-Std-1553 data bus

There is now a clear increase in the use of electronic devices and sub-systems that all require physical communication infrastructures. This trend has lead to the use of data buses which allow multiple devices connected together through one physical wire. The Mil-Std-1553 [4] standard for data bus systems was initially designed for aircraft but has been used in space applications and numerous different military applications [5]. The data bus uses half-duplex data transmission with a 1 MHz data rate over twisted shielded pair (TSP). The characteristic impedance (Z_0) of the TSP is around 78 Ω and the backbone of the bus is terminated with resistors of value $Z_0 \pm 2\%$. Devices are connected to the bus through either a directly coupled interface or a transformer coupling, both of which are illustrated in figure 1. Transformer couplers are more commonly used today because they allow longer branches. Although the data rate is not as high as in recently developed communication systems the bus system is still widely used and accepted.

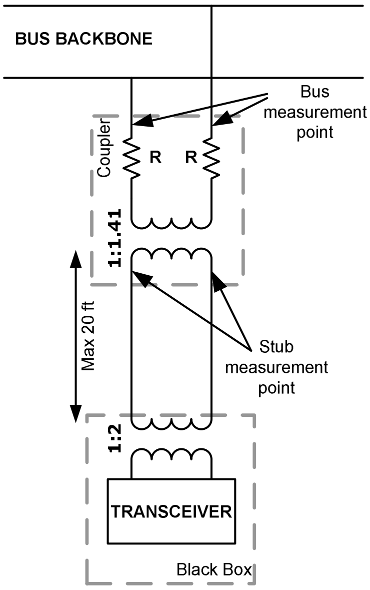

Figure 2 **Measurement points in the coupler**

A further feature of the Mil-Std-1553 data-bus system is software driven Built-In-Test (BIT) that is primarily designed and supplied to locate malfunctioning Wiring Replaceable Assemblies (WRA) and Line Replaceable Units (LRU). BIT does not feature test hardware and executes test routines on a software only basis only. The supported BIT is hence not specifically focused on the location of faults in the data bus harness which has caused it to report faults in WRAs when there is no defect present. The indirect impact is hence a perceived unreliability of the BIT that contributes to further increases in maintenance costs.

The most recent research in wire fault location is around reflectometry methods and the use of inductance and capacitance sensors [6]. The most commonly used reflectometry method is Time Domain Reflectometry (TDR), which is well suited to the location of opens and shorts on a single wire, but can not be used on-line due to the need for a high voltage stimulus and inability to locate defects in wire branches [7]. Spread spectrum time domain reflectometry (SSTDR) has been the most promising reflectometry method for wire testing [8]. SSTDR is capable of detecting faults on-line (power and data wires) and on branched wires. Capacitance and inductance sensors are also very accurate in locating faults on single wires but they are not capable of supporting on-line measurements and fault detection in branched wires [6, 9].

The problem with the Mil-Std-1553 bus harness is that the branches where WRAs and LRUs are connected to the bus through passive components. This is the main source of difficulty associated with the adaptation of reflectometry methods for detecting branch defects. Today the most reliable test strategies for data bus systems are through the use of specific test equipment for off-line testing e.g. [10]. The method presented in this paper is based on a measurement system that has access to multiple measurement points on the bus unlike in reflectometry and capacitance methods where measurements are based on single point sampling. The measurement method is designed to work through simple analog IC measurement blocks that are part of wireless sensor network (WSN) nodes inside the couplers. This paper presents the measurement method that can be applied to a general physical construction of network components.

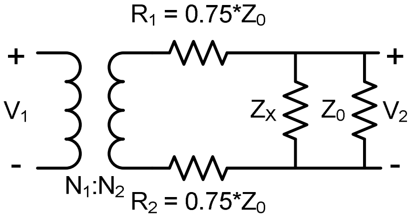

Figure 3 **Simplified model of the coupler when connected device is transmitting signal**

The paper is organized as follows. The second chapter presents the measurement method. The third chapter presents the simulation results and the fourth chapter discusses future directions. The final two chapters present conclusions and acknowledgements.

2. Online measurement method

The on-line test strategy is built around monitoring the quality of the data signal and exercising the bus through an external test signal. Although passive monitoring of the data signal quality can be used to detect and in some cases locate defects on the bus system, some defects requires additional measurements and controlled test stimuli. Both measurement methods are based on detecting changes in the impedance of the bus system.

2.1 Effect of the defects on the bus system

The measurement method is designed to locate the following defects on the bus backbone and on the bus stubs (cables used to connected devices):

- One wire open
- Both wires open
- Short between wires
- Short to shield
- Terminator defects
- Coupler component defects

Most of the defects cause impedance changes of the bus system that effect signal integrity through parametric changes in voltages, currents and reflections on specific wires. The best way to monitor these impedance changes is to monitor voltage differences in the couplers. The measurement points in the coupler can be seen in figure 2.

A simplified DC model of a coupler can be used to examine the effects of typical defects on the bus system. Coupler models have been placed in two categories. The first supposes that the device connected to the coupler is transmitting a signal. The second model covers the case where the device is receiving a signal. In figures 3 and 4 Z_0 and Z_X are used to represent the characteristic impedance of the cable, R_1 and R_2 are the isolation

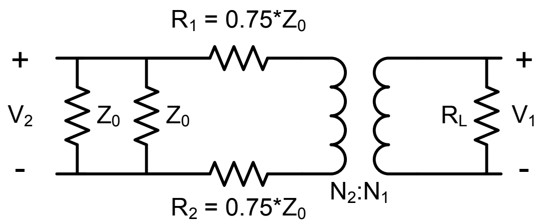

Figure 4 **Simplified model of the coupler when connected device is passive**

resistances of the coupler, R_L is the load resistance of the connected device and N_1:N_2 is the ratio of the turns within the transformer.

When the connected device is transmitting a signal the voltage ratio between the measurement points is

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} \frac{Z_0 \| Z_X}{R_1 + R_2 + Z_0 \| Z_X} \tag{1}$$

When no defects are present $R_1 = R_2 = 0.75^* Z_0$ and $Z_X = Z_0$, and the voltage ratio is stable.

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} \frac{0.5Z_0}{0.75Z_0 + 0.75Z_0 + 0.5Z_0} = \frac{N_2}{N_1}\frac{1}{4} \tag{2}$$

Defects on the bus cause the impedance Z_X to differ from Z_0. Here Z_X is shown as xZ_0 where x is proportional to the impedance error in Z_0. Substituting the other Z_X with xZ_0 in (1) we get

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} \frac{Z_0 \| xZ_0}{R_1 + R_2 + Z_0 \| xZ_0} = \frac{N_2}{N_1} \frac{0.5}{2.5x + 1.5} \tag{3}$$

The effect on the impedance change can be seen in figure 5. If the impedance goes low, e.g. a short defect, the voltage ratio approaches 0, and if the impedance goes high, e.g. open defect, the voltage ratio approaches the value $0.4^*N_2/N_1$. Similarly, the calculated impact of the defects on one of the insulation resistances R (R_1 or R_2) can be seen in figure 5. For example a 25% decrease of the R value causes 10.4% change on the voltage ratio V_2/V_1.

Figure 4 shows a simplified DC model of the coupler when the connected device is passive or receiving a signal. The voltage ratio derived from the figure is:

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} \frac{R_1 + R_2 + \left(\frac{N_1}{N_2}\right)^2 R_L}{\left(\frac{N_1}{N_2}\right)^2 R_L} \tag{4}$$
$$= \frac{N_2}{N_1}\left[1 + \left(\frac{N_2}{N_1}\right)\frac{R_1 + R_2}{R_L}\right]$$

By monitoring the voltage ratio, defects can be located in the coupler components as well as in the stub. Defect affecting the stub can be seen as an impedance change in R_L and a defect on the isolation resistors can be seen as resistance change on either R_1 or R_2 (equation 4).

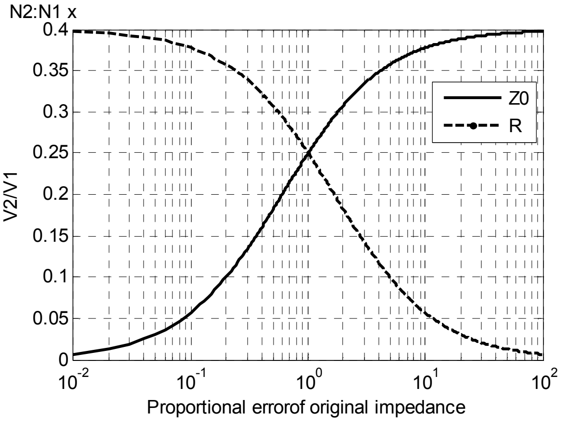

Figure 5 **Effect of the defect to the voltage ratio on stub**

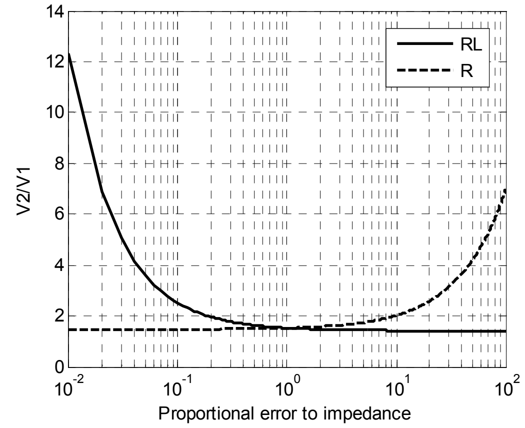

Figure 6 **Effect of the defect to the voltage ratio on stub**

Figure 6 plots the voltage ratio as a function of the impedance change due to insulation resistance R and R_L. The values used are $N_2/N_1 = 1.41$, R = 58 and R_L= 3000. The ratio V_2/V_1 is equal to 1.524 when no defect is present. This ratio increases when R_L decreases due to for example, a short between wires. The ratio V_2/V_1 also increases when R increases, for example because of an open on isolation resistance connection. A small increase in R_L is harder to detect. A 25% increase in R_L causes only a 1.4% change to V_2/V_1. Also a 25% decrease of R causes only a 0.9% change in V_2/V_1.

In TSP cables one possible defect is that one of the wires are shorted to the shield. In normal conditions this defect would have no measurable effect but in certain EMI conditions this might cause a high data error rate [2]. Physically a short to the shield causes the potential of the shorted wire to be forced to same potential as the shield with the differential signal on the TSP forced to mimic a single ended output. To detect the short to shield, the peak-to-peak voltage (V_{PP}) on both wires should be monitored and compared. A large difference, e.g. 1 V, in V_{PP} between wires reveals the short to shield defect.

When square wave signals are inherent to the electrical activity, a defect can cause a change in the pulse width. There are two defects that can cause this bus fault. The first is due to an open wire defect and second due to a short between wires. When one wire is open, the signal does not continue on the wire with the defect but in the defect-free wire the signal will continue through the terminator to the other end of the defect. The signals on both wires are at the same potential but delayed in the defective wire. When the voltage differences between the wires are examined a pulse with a shorter than normal pulse width can be observed. Another issue which affects the pulse width is the pulse shape on different wires. This is due the reactance components, mostly capacitance between wires, and the capacitance to the shield, on the TSP. Capacitive elements are charged on the non-defected side of the TSP with no charge process on the defected side. In a cable with one wire open, the signal pulse undergoes distortion. This distortion manifests itself as an overshoot on the non defected side of the cable, whilst on the defective side it reduces the rise time of the signal. Again if the voltage difference between wires is examined, a short width pulse can be seen. Shorts between the wires also cause changes in the pulse width that can be seen in every coupler from the coupler which transmits the signal to the coupler before the defect. The pulse width depends on the distance from the measurement point to the defect.

2.2 Passive monitoring of the data bus

On the data bus there can be up to thirty-three devices connected and some of these devices may use the same coupler. The measurement method requires voltage monitoring in every coupler on the bus to obtain reliable results. The signal quality on the bus and on the stubs is monitored non-intrusively and the monitoring system is designed to work independently so that it does not affect the system during normal use.

The Mil-Std-1553 data bus uses a 1 MHz half-duplex Manchester coded data transfer. Manchester coding allows the data and clock information to be transferred concurrently by representing a bit by a low-to-high or high-to-low transition, depending of the bit value. The data word is 20 bits long and every word begins with a three bit long synchronising string after a 4-20 µs long gap between data words. The synchronisation bit is high for 1.5 or 2 µs depending of the first actual bit of the data word. Because of the predictability of the synchronisation bit it is used for measurement of the quality of the data signal.

Measurement of the data signal quality is carried out simultaneously in every coupler on the bus system. The monitoring in couplers is achieved through the measurement points shown in figure 2 using capacitive coupling. Capacitive coupling to the bus does not affect the bus impedance if small enough capacitors are used.

The following voltage properties of the synchronisation bit are used to detect defects on the bus system:

- Differential peak-to-peak voltage between wires
- Peak-to-peak voltage on both wires
- Pulse width of the differential voltage

These properties are used directly and also as parameters within analytical and simulation studies to map the impact of specific defects and their location. A flow chart was generated from the simulation results and seven different fault triggers identified. A fault trigger is a measured property from the bus system which indicates a defect on the bus and it can be considered as the first symptom of a defect. The fault triggers are:

1. Differential voltage on bus ($V_{d(bus)}$) = 0 and differential voltage on stub ($V_{d(stub)}$) $\neq 0$
2. $V_{d(bus)} \neq 0$ and $V_{d(stub)} = 0$
3. $V_{d(bus)}/V_{d(stub)}$ < nominal value in transmitting stub
4. $V_{d(bus)}/V_{d(stub)}$ > nominal value in transmitting stub
5. $V_{d(bus)}/V_{d(stub)}$ < nominal value in passive stub
6. On stub: peak-to-peak voltage on single wire >> another wire ($|V_{s(stub[1])}| >> |V_{s(stub[2])}|$ OR $|V_{s(stub[1])}| << |V_{s(stub[2])}|$)
7. $V_{d(bus)}/V_{d(stub)}$ > nominal value in transmitting stub

The measurement results from a coupler are compared to fault triggers in the order shown. If measurement values exceed the trigger threshold, the reason for the fault is further analysed through calculations and with further measurements if required. This is implemented in every coupler on the bus system.

Fault trigger 1 detects only if there is a short between wires on the stub. Fault trigger 2 detects if there is short between wires on the bus near the coupler. Fault trigger 3 detects too high isolation resistance on the coupler if the coupler is not attached to the terminator. If the coupler generating trigger 3 is attached to a terminator, one extra measurement is required to identify if the defect is associated with an isolation resistance that is too high or with termination that is too low.

Fault trigger 4 can be used to detect several different defects. For diagnosing correctly however, measurement data is required from other couplers and in some cases further measurements are needed. The flow chart to detect specific defects after trigger 4 is shown in figure 7.

Trigger 5 detects coupler component problems (e.g. the isolation resistance too low) or an open on the bus close to the coupler depending of the numerical value of $V_{d(bus)}/V_{d(stub)}$. Trigger 6 detects only if there is one wire connected to the shield on the stub. And finally fault trigger 7 detects if the isolation resistance is too high on the coupler or there is a defect on the transformer.

2.3 Extending measurement capability with an external test signal

An external test signal is used when more measurements are required to locate a defect on the bus system. The external test signal enables controlled measurements during on-line testing and can also be used for off-line testing of the test bus.

During on-line measurement, the best way to insert the test signal is to send it between Mil-Std-1553 data words. The time gap between the data words is from 4 to 12 µs

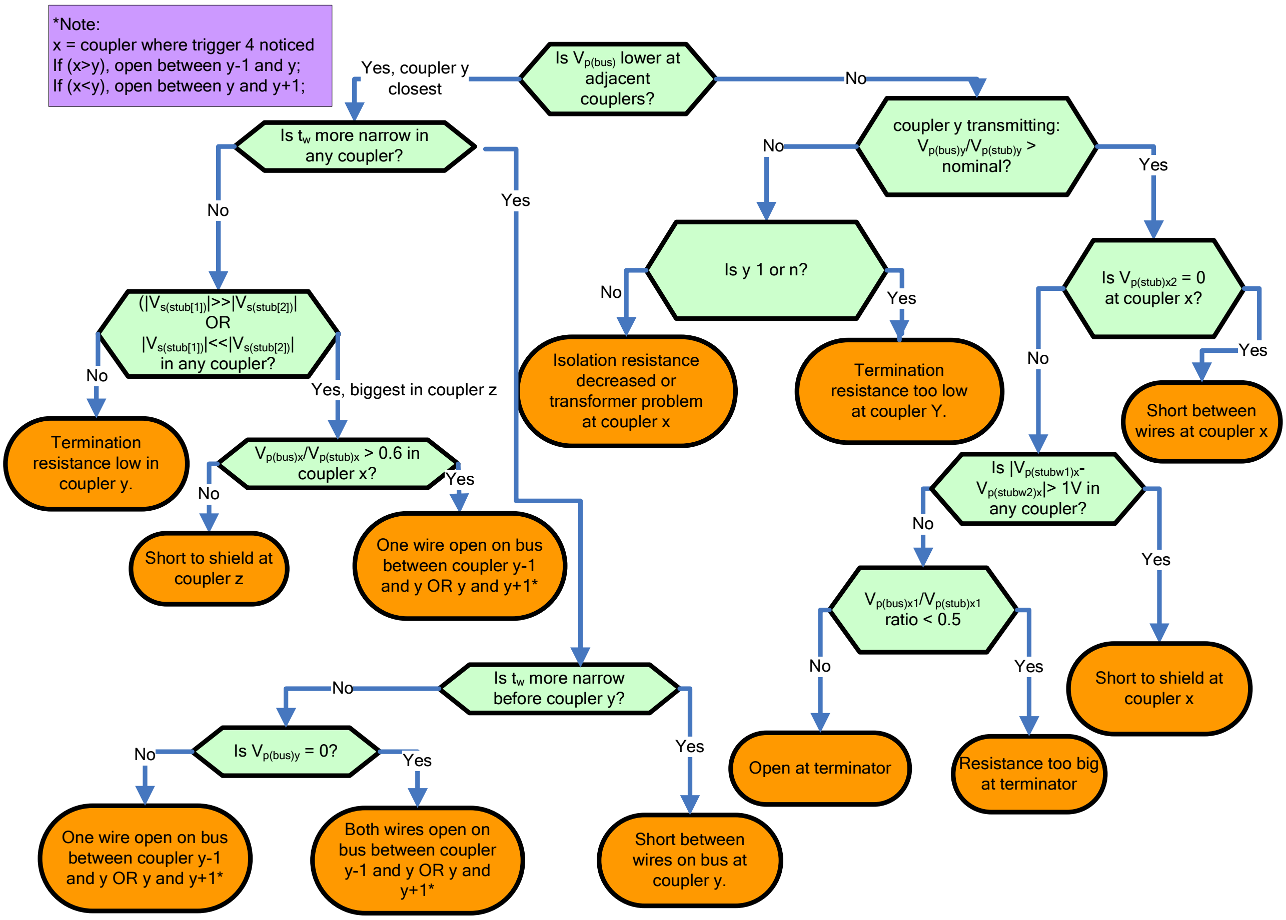

Figure 7 **Flow chart to detect defects when trigger 4 is detected**

which sets some frequency restrictions for the test signal. To get adequate measurement results a 4 MHz sine is used. In the case of lower frequencies there would be only a couple of signal periods available to take measurements that would make the resulting data less reliable. The peak-to-peak amplitude of the test signal was set to 100 mV which does not interfere with the bus system.

The test signal is capacitively coupled to the stub measurement point shown in figure 2. Feeding the test signal to the stub, rather than the bus, allows better detection of defects. Measurement of the external test signal is carried out at the same points as in monitoring the data signal quality. The measured properties are differential peak-to-peak voltage between wires and the peak-to-peak voltage on single wires.

2.4 Combining the two measurement methods

The presented measurement methods are designed to work on bus systems that have measurement points in every coupler. The measurement points will need a communication media available to transmit measurement data.

The quality of the data-signal is measured continuously in every coupler. If a fault trigger is activated in a coupler the measurement method will attempt to find the defect. A master coupler is defined to control the measurement procedure. After fault trigger activation the fault information from all the couplers which detect a fault is combined on the master coupler which is used to indentify and locate the defect. If more measurement data is needed, the master initiates the use of an external test signal in the required nodes. From the final measurement results the defect is located and identified.

In the off-line self-test measurement method the test procedure is straightforward. The test signal is transmitted in every coupler one at a time and measured at the next coupler so that all the connections are validated during the test.

3. Simulations

The data bus system was simulated by Orcad 9.0 which uses the PSpice circuit simulator. The simulation results were further analyzed in spreadsheets. The data for the simulation models were gathered from the standard [4] and additionally from cable datasheets.

The simulation model consists of four devices connected to the bus through couplers. Between each coupler there is 15 m of wire. From the device there is 0.3 m of wire to the coupler. Passive devices were modelled using a 3 kΩ resistance and the transmitting device by two resistors and a current source, which drives Mil-Std-1553 specific data words. The wire simulation model was created from data in an application note [11].The exact wire model, as used in Mil-Std-1553, was not appropriate as the main

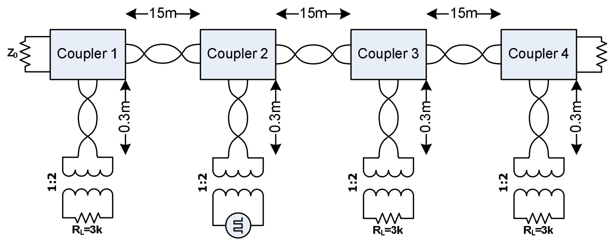

Figure 8 **Simulation model of the from Orcad**

properties did not match that provided by the wire manufacturers. The simulation model is shown in figure 8.

Open defects were modelled as 50 MΩ series resistances. Shorts between wires were modelled with 0.1 Ω shunt resistances between wires and the short to shield with the same resistance to ground. Termination defects were modelled by changing the resistance value of the termination resistances and also the isolation resistance.

Defect simulation results were compared to results from defect free simulations. These simulation results were used to generate prognostic / diagnostic flow charts.

4. Future directions

The next step in the development of the test method is to do the experimental measurements with laboratory equipment to prove the efficiency. Measurement electronics will be designed and implemented after results are acquired from experimental measurements. The implemented electronics must be low-power and be capable of accurate and reliable measurements. Reliability can be increased with self and cross reference methods.

Building the whole measurement system requires research on communication methods between wires. There are two methods which are feasible; use the bus wire or use wireless methods between couplers. The use of a wireless sensor network (WSN) has been identified as promising in monitoring aircraft engines [12]. The power requirements also need further research. Finally, alternative power sources have to be studied for example harvesting energy from the data bus or from the environment.

5. Conclusions

The target of this study was to identify on-line measurement methods for aerospace bus systems with the capability to take measurements in every coupler in the system. The measurement method was designed to be feasible using simple analog electronic circuits with a microcontroller. The measurement method requires on-line monitoring of the data signal quality and measurements based on a test stimuli. On-line monitoring of the data bus is achieved by passively monitoring the quality of the data signal on the bus system. Defects can be located using the monitoring data but in some cases an external test signal is needed.

6. Acknowledgements

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