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Spread spectrum sensors for critical fault location on live wire networks

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SUMMARY

Aging wiring networks have been identified as an area of critical national and international concern. One of the particularly challenging problems is the location of intermittent faults that cannot be replicated on the ground. This paper describes the application of spread spectrum fault location and wire health monitoring methods whose unique low-interference potential and high-noise immunity enable them to locate faults while networks are active. The analysis and feasibility of this method has been described in previous work, and this paper focuses on evaluation of the accuracy of the method and effects of branched wire networks on the sensor response. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: reflectometry; spread spectrum; wiring; fault location; health monitoring; aging

1. INTRODUCTION

Aging aircraft wiring has been identified as an area of critical national and international concern. Aircraft wiring problems have recently been identified as the likely cause of several tragic mishaps [1–3] and hundreds of thousands of lost mission hours [4,5]. Modern commercial aircraft typically have more than 100 km of wire [1]. Much of this wire is routed behind panels or wrapped in special protective jackets, and is not accessible even during heavy maintenance when most of the panels are removed. In addition to aircraft, nuclear power plants, overland transmission lines, high-speed trains, motor vehicles, ships, large industrial plants, communication infrastructure, homes and consumer products are subject to the risks of downtime and/or potential fire hazard from aging wiring. One of the difficult problems for aircraft maintainers is the location of intermittent faults. Vibration causes wires with breached insulation to touch each

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other or the airframe, pins, splices, etc. or corroded connections to pull loose, or 'wet arc faults' where water drips on wires with breached insulation causing intermittent line loads. These intermittent faults are often not replicable when the plane is on the ground, or the system is de energized, producing a 'no fault found' condition.

'Smart circuit breakers' [4] are one exciting new technology that reduces the chance of fire by sensing the current or voltage on the wire and tripping when excess noise from a small arc is detected. These breakers are being installed in both commercial and military planes over the next several years and are also required for US home wiring in bedroom and air conditioner circuits. Many large industrial plants, nuclear plants, etc. are also anticipating switching over to these breakers on a large scale. While these breakers are a dramatic leap forward in safety, they bring with them a very serious maintenance problem. In order to be effective, the breaker must trip when the damage to the wire is minimal, often too small to locate.

Some of the most publicized methods for locating faults on wires are time domain reflectometry (TDR) [6], standing wave reflectometry (SWR) [7], frequency domain reflectometry (FDR) [8,9], impedance spectroscopy [10], high-voltage, inert gas [11], resistance measurements, and capacitance measurements. At the present time, these test methods cannot reliably distinguish small faults such as intermittent failures on non-controlled impedance cables without the use of high voltage. In addition, the signal levels required to reliably perform these tests might interfere with aircraft operation if applied while the aircraft is in use [4]. A different test method is needed that can test in the noisy environment of aircraft wiring, and that can be used to pinpoint the location of intermittent faults such as momentary open circuits, short circuits, and arcs.

An emerging class of spread spectrum sensors has been demonstrated to be effective for locating faults on live wires [4,12,13], including both wet and dry arcs that cause the arc fault circuit breaker to trip [13]. Spread spectrum sensors transmit a digital pseudo noise (PN) code down the wiring, where it is reflected nearly instantaneously. The resultant signal and its echo are correlated with a delayed copy of the PN code, which gives a peak in the correlation corresponding to the location of the fault. This system is ideal for locating intermittent faults, as it can run continuously without interfering with the signals already on the wiring. When a fault occurs, it is a near short-circuit for a few milliseconds, after which it is a small anomaly with minimal reflection. Using spread spectrum methods, the fault can be found while it is substantial, rather than looking for it after the fact, when it is too small to locate.

This paper will focus on analysis of the spread spectrum system for realistic live wiring networks, and measurement of the potential and observed errors in the system. Knowledge of the system parameters and how they affect performance is critical for designing optimal systems for specific application areas. The basic spread spectrum method is described in Section 2, and analysis of the system parameters and how they affect the accuracy, signal-to-noise ratio, latency, etc. is presented. Section 3 describes additional sources of error in realistic conditions including the effect of non-controlled impedance cable carrying a Mil-STD 1553d data signal. Networks of wires that produce multiple reflections are discussed in Section 4.

2. SPREAD SPECTRUM FAULT LOCATION

2.1. Basic method

The spread spectrum concept is normally applied to cellular telephone communication. Direct sequence spread spectrum (DSSS) communication uses a high-speed pseudo-noise (PN) digital code multiplexed with existing digital data to spread the spectrum, increase the number of simultaneous users on the line, and reduce the effects of noise and jamming. A PN code is a set of ones and zeros that appear random, but are actually very carefully designed. They have very high self-correlation and very low correlation with other signals, other codes, and with delayed copies of themselves. This gives them the ability to reduce interference with other 'users' and to resist 'jamming' and provides the unique ability to test live wires in flight without either interfering with the avionics signals or being corrupted by them. The full analysis of this method is presented elsewhere [4,12,13].

The spread spectrum sensing circuit is shown in Figure 1, and its basic concept is this: A PN code is sent down a wire or cable, where it is reflected back at open- or short-circuits, junctions, and any other impedance discontinuities. The PN code can be very, very small (well below the noise margin) compared with existing signals on the line, yet its reflections (delayed copies of the PN code) can still be detected. The delay of the PN code (which is proportional to the distance to the discontinuity) can be found by correlating the delayed PN code with a time-shifted copy of itself. If the codes are synchronized, a large peak is observed, and if they are not synchronized, very low values are observed. The height of the peak corresponds to the magnitude of the discontinuity, and the delay at which is observed corresponds to the location of the discontinuity.

The feasibility of this system for locating faults associated with arc fault circuit interrupters is shown in [4,12]. As a test method, spread spectrum has also been previously applied to unpowered (dead) DSL lines [14] and live low-frequency (60 Hz, three phases) power lines [15]. In the DSL and power line frequencies, it can be thought of as a frequency division multiple access (FDMA) scheme. The line carries two frequencies, one low (60 Hz), and one high (PN code), which do not interfere with each other, because they are far apart in frequency.

There are two versions of spread spectrum sensing. Sequence time domain reflectometry (STDR) uses the PN code as the test signal exactly as described above. Spread spectrum time

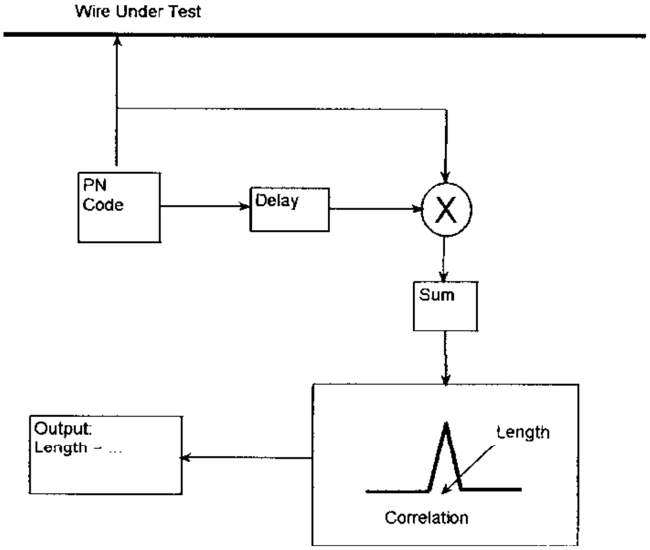
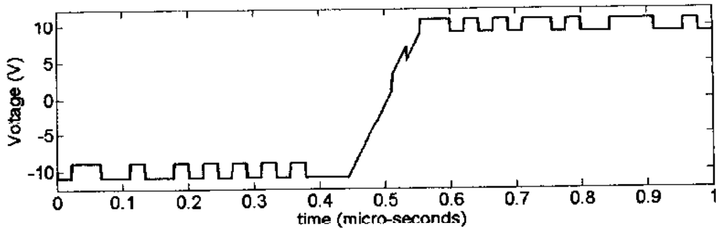
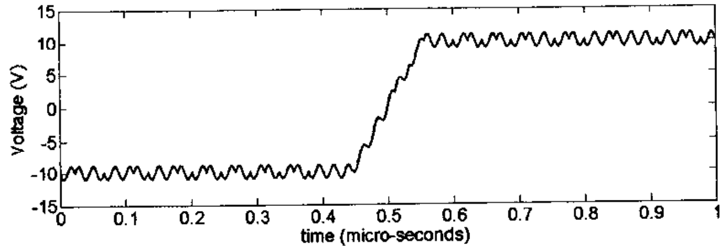


Figure 1. Sequence (STDR) test system. For SSTDR, the input signal is a sine wave modulated PN code.



STDR



SSTDR

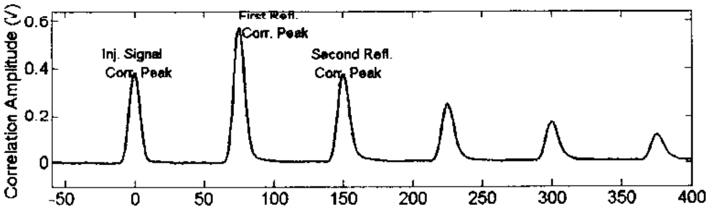
Figure 2. ML Code 1V RMS STDR and SSTDR signal at 58 MHz, with a 10 V RMS signal at 30 MHz.

domain reflectometry (SSTDR) uses a sine wave modulated PN code as the test signal, with everything else being the same.

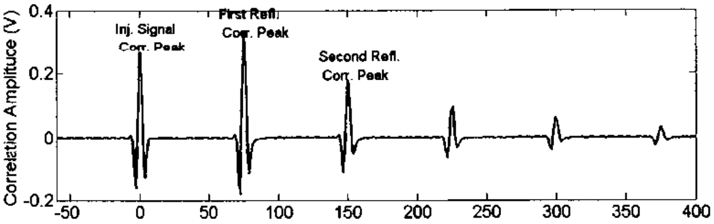
Figure 2 shows 1 V RMS STDR and SSTDR signal, respectively, in the presence of a 10 V RMS digital signal. The combined incident/reflected signal is correlated with the PN code (which, unlike communication applications, is immediately available without the need for fancy synchronization schemes). This correlation is high if the two codes are synchronized, and low if they are not. In the existing design [4,12,13] a variable analog phase shifter and integrator provide this correlation, but there are several simpler methods of performing this correlation that are now being demonstrated as part of our ongoing research. The result of the correlation is a set of peaks that correspond to the length of the wire, as shown in Figure 3. The correlation peaks are positive if a high impedance is encountered and negative for a low impedance. Their location tells how far down the wire the discontinuity was encountered, and multiple peaks will be seen if there are multiple reflections, as there normally are in the case of branched networks of wires. Figure 3(a) shows the peaks for the STDR system, and Figure 3(b) shows the peaks for the SSTDR system. SSTDR multiplies the PN code with a sine wave before transmitting it onto the line, and the combined incident/reflected signal is correlated with original signal. As with STDR, the correlation peaks correspond to the length of the wire as shown in Figure 3(b).

2.2. Data analysis

The peaks in Figure 3 provide information about the location of reflections within the system. Each point in the curve of Figure 3 is a step in the phase shifter controlling the test PN code generator, and the precision of these steps therefore controls the accuracy of the test system. If a simple peak detection algorithm is used, it is highly likely that the peak will be missed. A better method of locating the peaks is to use a curve fitting algorithm to fit the sampled data to a



(a) STDR



(h) SSTDR

Figure 3. STDR and SSTDR responses for a 75 foot wire (RG58 coaxial) that open-circuited on the end.

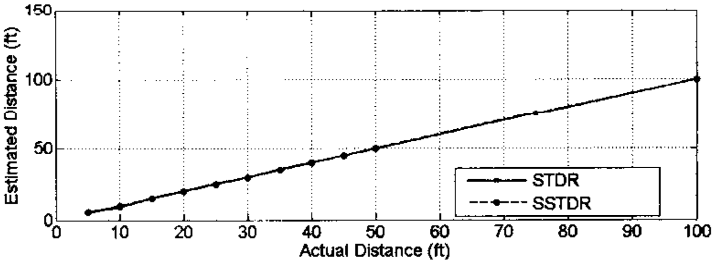


Figure 4. Calculated distance versus actual distance for RG58 cable with 60 Hz 28 V signal.

known or pre-measured peak shape, and determine the peak location from this curve. Several such methods have been described and compared [16]. Curve fitting was used to improve the data analysis for this paper. Accuracy of about 30 cm was obtained using only the rough peak detection algorithm and was improved to about 3 cm using the curve fitting algorithm. Figure 4 shows the results obtained for the length of the wire using curve fitting. This method was used to obtain the results in the following sections.

3. ACCURACY OF S/SSTDR SYSTEM

3.1. Prototype specifications

An S/SSTDR system was prototyped and tested [4]. A 58 MHz, 1023-bit maximum length (ML) PN code was used for STDR and was modulated by a 58 MHz sine wave for SSTDR. The magnitude of the test signal was 28 and 21 mV RMS for the STDR and SSTDR tests, respectively. More details of the prototype development can be found elsewhere [4].

3.2. Controlled impedance cable

Cables such as shielded wires (including coaxial), twisted pair, and ribbon-organized wiring are characterized as controlled impedance, because the impedance and velocity of propagation (which are dominantly controlled by the shape, size, and location of metallic structures in and near the wiring) change very little down the length of the wire. Typical velocities of propagation may vary by about 10%, depending on the wire type and gauge, so it is important to know the type of wire being tested. By contrast, the vast majority of wiring is made up of individual wires bundled together in a relatively random fashion. If wires were 'paired' for test purposes, the impedance and velocity of propagation of the wiring would vary as the wires randomly wove their way through the bundle, sometimes close together and sometimes far apart. Since all reflectometry methods require a calibration factor related to velocity of propagation, this variation necessarily causes error in the measurements of wire length. For a bundle of thirty-six 22-gauge wires, this variation is 0.3%. [16] Other types of error were also analyzed. When multiple tests of the exact same setup were taken, the variation is less than 1 cm. When the same wire is disconnected and reconnected, the variation can be as much as 1 cm. [16] Thus, the error from the variation in velocity of propagation is the dominant error in these measurements.

Tests were made to determine the measured compared with actual length of the cable for controlled impedance 75 Ω coaxial cable. The maximum error is about 3 cm for both open- and short-circuited cables using either STDR or SSTDR when the cable is un-powered. When the cable is connected to a 60 Hz 28 V power supply, the capacitor in Figure 1 must be used, which makes the peaks in the STDR less distinct and gives it an error of about 6 cm. It should be noted that the same errors are observed when the capacitor is in line, whether or not the power is turned on. The SSTDR is relatively immune to this capacitor, and its error remains 6 cm, even in the presence of 60 Hz power. Similar results are seen for 400 Hz 115 V power, and would be expected for any low-frequency power bus.

3.3. Uncontrolled impedance cable

An uncontrolled impedance bundle of twenty-two 22-gauge wires tied every 6–12 inches (15–30 cm) was used to evaluate the accuracy of the system with uncontrolled impedance cable. The measured versus actual length of the cables are shown in Figure 5. Compared with Figure 4, it is clear that the uncontrolled impedance cable has more errors. Consistently, the results for both STDR and SSTDR are 50% worse than for controlled impedance cable. The maximum errors are 4.5 cm for both methods with either open- or short-circuits when the capacitor is not in line with the circuit. When the capacitor is used (with or without power), the SSTDR errors remains about 4.5 cm, while the STDR error is about 15 cm. This is no doubt due to variation of the velocity of propagation throughout the bundle. Moving the bundle around, bending it over metal objects, etc. changes the values of the specific points, but the worst case errors remain about the same.

3.4. Effect of Mil-STD 1553 data signal

For both controlled and uncontrolled impedance cables, the application of 60 Hz power on the cable had no observable effect on the results, other than that it required the use of a protective capacitor on the front of the circuit that modified the STDR response and made it less accurate for curve fitting. The Mil-STD 1553 data signal is not as forgiving, however, since it has

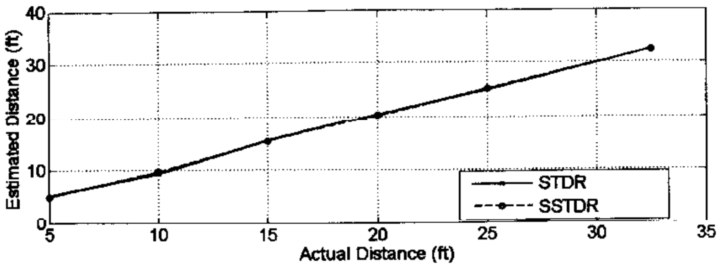


Figure 5. Calculated distance versus actual distance for bundled 22 gauge cable with 60 Hz 28 V signal.

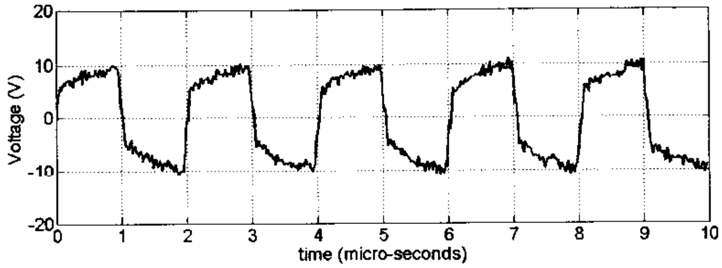


Figure 6. SSTDR signal (21 mV rms) superimposed on a 5V Mil-STD 1553 data signal.

Table I. Accuracy of STDR and SSTDR when running on uncontrolled impedance cable 7.62 m long with Mil-STD 1553 data signal. The STDR magnitude is 28 mV rms, and the SSTDR magnitude is 21 mV rms.

Mil-STD 1553 (V)	STDR (dB)	SSTDR (dB)	Error (cm)	Error (cm)
0	0	0	0	0
0.5	−25	−27	24	0
1	−31	−33	320	3
2.5	−39	−41	738	0
5	−45	−47	2600	6
10	−51	−53	500	6

frequency components in the same band as both the STDR and SSTDR test signals. The Mil-STD 1553 data bus carries a 1 MHz digital data signal with 100 ns rise and fall time, and voltages from 4.5 to 20 V_{pp} with a 17.5 dB noise margin [17]. A 21 mV SSTDR signal superimposed on a 5 V Mil-STD 1553 data signal is shown in Figure 6.

In order to evaluate the effect of the relative magnitude of the test signal on the test results, the magnitude of the Mil-STD signal was varied, since our prototype board was built with a set output level of the S/SSTDR signals. Table I shows the accuracy versus signal level for both STDR and SSTDR. Both signals must be below the 15 dB noise margin of the 1553 signal in order to be able to be used on a live data bus without interfering with the Mil-STD 1553 signal. At about 25 dB below the test signal (10 dB below the noise margin), STDR has a maximum error of 24 cm, which would still be considered useable for aircraft maintenance. When the STDR signal is smaller than that, the errors become unacceptable, and the method is no longer useable. SSTDR, on the other hand, has errors less than 6 cm down to 53 dB below the 1553 signal, demonstrating the advantages that SSTDR for high frequency noise immunity. This advantage occurs, because there is minimal spectral overlap between the SSTDR and the Mil-STD 1553 signal.

4. S/SSTDR RESPONSE TO NETWORKS

4.1. *Multiple reflection analysis*

Since this system is meant to run on live wire networks, it is critical to be able to handle realistic branched networks. One such network is shown in Figure 7, along with the S/SSTDR responses of the network. It is clear that even a simple network has multiple reflections, each of which shows up at the appropriate time to represent the physical location of the discontinuity. Several peaks (such as from the end of each cable, in this case) overlap on each other. If cable lengths were not identical, the peaks could still overlap partially or completely, and if read using merely a peak detection method, would indicate wire lengths that are not correct.

4.2. *Effect of multiple junctions*

One way to determine if there are multiple overlapping peaks or not is to understand the magnitude of the reflections that occur from each junction in the branched network. A junction between two identical wires will have an equivalent load impedance of half the impedance of the cables making up the junction (25 Ω in the case of 50 Ω wires, for instance). The reflection coefficient Γ gives the magnitude of the reflected wave:

$$\Gamma = (V_{\text{reflected}}/V_{\text{incident}}) = (Z_L - Z_0)/(Z_L + Z_0) \tag{1}$$

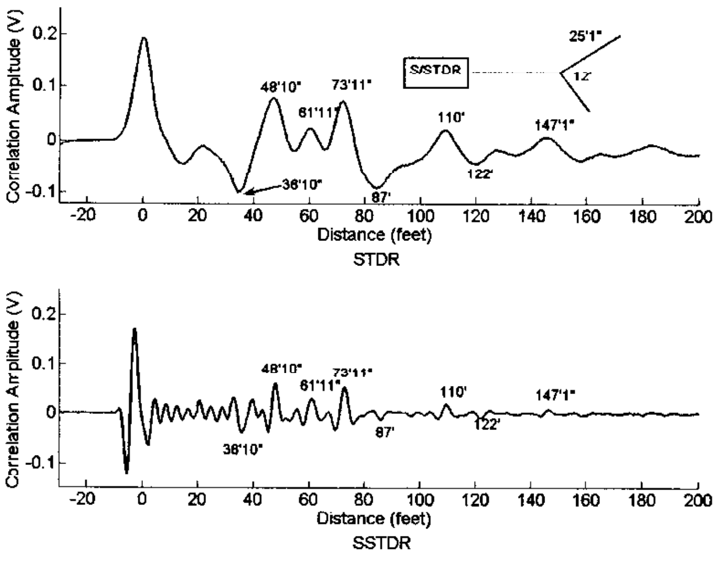


Figure 7. S/SSTDR responses for a branched wire network (the corresponding branched network is represented on the top right-hand-side of the figure).

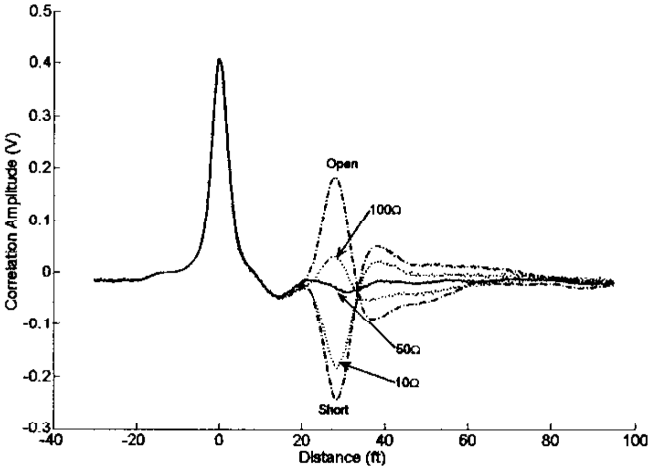


Figure 8. Magnitude of the reflection of STDR for an impedances ranging from short to open on a 50 Ω RG58 coaxial.

where Z_L is the load impedance (25 Ω), and Z_0 is the characteristic impedance (50 Ω). Thus, the magnitude of the reflected wave is −one-third of the incident wave. The negative sign indicates the phase of the reflected wave, and the fact that peak will be inverted.

The reflections from load impedances from 40 to 2 kΩ on a 50 Ω 30-ft-long (9-m) wire can be calculated from standard transmission line analysis [18], or can be measured, as shown in Figure 8. The magnitude of the smallest reflections that can be measured depends on the signal-to-noise ratio of the measurement system, but typically we find that we can measure impedance changes of the order of 10 Ω reliably.

In a network of wires, each junction on the line decreases the magnitude of the voltage reflected from the end of the line. The voltage that passes from the source through the junction is two-thirds of the incident voltage. Assuming that 100% of this voltage is reflected at the open end, another two-thirds will be lost going back through the junction. The total magnitude of the reflection received from the end of the cable will be 4/9. For N junctions, the amount received will be $(4/9)^N$. In practice, it becomes difficult to see beyond two junctions in the network, thus limiting the complexity of networks that can reasonably be measured. Algorithms to analyze these networks are available, but are beyond the scope of this paper [19].

4.3. *Reflection from arcs*

Wires that experience either wet or dry intermittent arcs during flight are of particular interest in this application. Wet arcs occur when insulation is compromised (radial cracks, chafes on adjacent wires, etc.) and water or other conductive fluid drips onto the damaged insulation, creating a conducting path for the current and a wet arc. Dry arcs occur when two adjacent wires with damaged insulation touch, or when a wire with damaged insulation touches the metal airframe and shorts out. This is normally replicated in the lab by cutting into the wire with a razor blade until it arcs. It has been found that wet arcs are of the order of 2–5 Ω in magnitude, and dry arcs can range from 5 Ω to nearly short-circuits [4]. The best way to find these arcs is to subtract the response before the arc occurred from the response during the arc, and to locate the are from the difference data. This has been found to be a very effective method of locating intermittent faults [13].

4.4. Effect of ambiguity

The responses from networks of wires necessarily have a number of possible cases of ambiguity, where two different wiring networks produce the identical measured response. For instance, in a simple Y-shaped junction it is impossible to tell which arm of the 'Y' is broken. There are few other cases of true ambiguity, however significant challenges remain in the analysis of network structures that have lengths where the reflections or multiple reflections are integral multiples of each other. These create S/SSTDR peaks that overlap, and an ideal method of analyzing overlapping peaks has yet to be developed. If the network topology is known in advance (as it would be on new planes), or if several possible network topologies can be compared with the expected topology in a data sheet, the correct topology can be chosen. Without this *a priori* information, simple networks can be fully resolved, but more complex networks will simply be able to give a 'distance to fault' that will need to be checked on each branch of the network that contains a wire at that distance.

5. CONCLUSIONS

Spread spectrum reflectometry methods have been demonstrated to be effective for measuring the length of both controlled and uncontrolled impedance cables, typical of those found on aircraft. This method can be used for locating intermittent failures on live aircraft wires, potentially in flight. Typical errors are of the order of 3 cm for controlled impedance cable and 6 cm for uncontrolled impedance cable. Since the width of one aircraft panel is of the order of 60 cm, this is more accuracy than would normally be required. This accuracy was observed for both STDR and SSTDR either with or without 60 Hz 28 V power. With Mil-STD 1553 data signals, the SSTDR method retained its accuracy, while the STDR system functioned properly only for signal-to-noise ratios 25 dB and up, demonstrating the expected advantage of the SSTDR method in the presence of noise.

Analysis of networks of wires was observed to be possible, but not without at least some ambiguities. The maximum number of junctions in a branched wire network that a single sensor can measure is typically 3–4, which limits the complexity of the network that can be analyzed.

This method has a strong possibility of being adapted for fault location on many other types of cables and networks.

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