

# Intermittent Fault Location on Live Electrical Wiring Systems

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## ABSTRACT

Intermittent wiring faults are among the most frustrating, time consuming, and expensive problems to diagnose in electrical systems. These sporadic problems occur when wires are wet, vibrating, under pressure, or when the system is in a particular configuration during use. Then when the system is stable and/or powered down, the problems disappear. The best and often the only time to locate these faults is while the faulty wiring is live and in operation. This paper will describe new technology for locating intermittent faults on live wiring systems without interfering with their operation. Spread spectrum time domain reflectometry (SSTDR) has been developed for locating these intermittent faults on live aircraft wires. A pseudo noise (PN) code is injected on the wire, well below the noise margin of the system. The PN code can be self-correlated to give the characteristics of the wiring system – its branches, loads, sources, etc. When an intermittent fault occurs, SSTDR detects and locates the fault. Unlike systems that use voltage and current measurements to detect faults, this method locates impedance changes to the wiring system. It is therefore complimentary to current/voltage analysis methods commonly used for arc fault circuit breakers. It is also highly immune to electromagnetic interference and noise caused by switching loads, etc. This technology is currently being miniaturized into an application specific integrated circuit (ASIC) that can be inte-

grated into many types of electrical systems. The methodology, specifications, and simulated performance of the ASIC are described in detail. Methods to integrate this technology into existing and new electrical systems are also described.

## INTRODUCTION

Aging electrical wiring systems have been identified as an area of critical national concern [1], [2]. For aircraft, where both preventative and responsive maintenance are taken very seriously, aging wiring is a very expensive problem. Electrical wiring problems in the US Navy cause an average of two in-flight fires every month, more than 1,077 mission aborts, and over 100,000 lost mission hours each year [3]. Each year the Navy spends from one to two million man-hours finding and fixing wiring problems [4]. A majority of the man hours spent locating faults are on intermittent faults that occur in flight but are not easily replicated on the ground. New arc fault circuit breakers (AFCB) have been developed that are capable of detecting the fault and tripping the circuit before severe damage is done. Although AFCBs will improve the safety of the aircraft, they promise to be a maintenance nightmare, as the faults left behind are too small to detect with typical fault location methods.

This has had a significant impact on the US Navy. The Navy spent \$94 Million on No Fault Found (NFF) equipment removals in one year due to wire faults being undiagnosed [5]. This leads to a drastic imbalance between scheduled and unscheduled maintenance, where five times as much maintenance time was spent on unscheduled than on planned maintenance in 2004 on 10 Navy platforms. About 30% of this was specifically due to wiring. [6]

Unfortunately, electrical wiring failures are not an uncommon event. In 2005 the NAVAIR flew 921, 658 flight hours with a mean time between wiring failures of 637 hours, giving roughly 4 failures per day. Time spent by maintenance technicians trying to rectify these failures amount to 7.3 hours per flight hour for aircraft older than twenty years. [7]

## CAUSES OF WIRING FAULTS

The majority of aircraft wiring failures are caused by chafed wires that result in a short circuit [5]. This type of failure is typically intermittent, due to vibration of the wire against a metal structure or another wire resulting in a "dry arc". Another typical cause is the ingress of moisture into damaged insulation, resulting in a "wet arc". Short circuits (both wet and dry arcs) as well as open circuit or high impedance discontinuities can be detected and located by the method proposed in this project. Other reports substantiate this data in other fleets [6, 8, 9].

## IMPACT OF WIRE FAULT LOCATION TECHNOLOGY

The objective of the LiveWire project is to integrate sensors that can locate intermittent (and non-intermittent) faults on live (or dead) electrical wiring. It has been predicted by others [10] that Smart Wiring Systems can produce massive savings for the Navy by reducing in flight fires and subsequent loss of aircraft by 80%, reducing maintenance man hours by between 200,000 to 400,000 per year, and generating savings of around \$34.5 Million annual savings from mission aborts and increase mission capable hours.

## THE TECHNOLOGY: SPREAD SPECTRUM SENSORS

Several methods are available today for locating electrical faults. These include time domain reflectometry (TDR), frequency domain reflectometry (FDR) [11][12], standing wave reflectometry (SWR), mixed signal reflectometry (MSR) [13], multicarrier reflectometry (MCR) [14], S/SSTDR [15][16] and noise domain reflectometry (NDR) [17]. Reflectometry methods send a high frequen-

cy signal down the wire, where it reflects off impedance discontinuities such as open or short circuits, junctions, loads, etc. and returns like an echo to the sending end of the wire. The time delay between the incident signal and this echo tells the distance to the impedance change. Each of the different reflectometry methods uses different types of incident waveforms in order to test the wires and different types of sensors to receive the echo and compare it to the incident signal. [18]

All of these methods are able to locate "static" faults (otherwise known as "hard" faults), those that are present at the time the test is being done. Unfortunately, in very dynamic electrical environments such as aircraft, the vibration, turning on/off of electrical loads, and moisture ingress can cause faults to occur in flight that cannot be replicated on the ground. These intermittent "no fault found" (NFF) conditions are extremely expensive, time consuming, and frustrating for the maintainer, since they cannot be replicated on the ground. Today, typically maintenance protocols call for replacement of three or more avionics boxes before the wiring itself is ever considered to be the culprit. Only after these expensive, time consuming, and ineffective repairs will the wiring be troubleshot. Methods that can locate faults while the aircraft is in flight are now emerging, and promise to significantly reduce the NFF problem. Being able to locate the fault while the aircraft is in flight means that the information can be given to the maintainer when the aircraft returns to the ground, enabling quick and accurate repair. S/SSTDR, MCR, and NDR can all be used while the aircraft is in flight. Of these, S/SSTDR are the furthest along in their development path. Circuit board versions of these systems are currently available for handheld, on ground maintenance equipment, and are currently undergoing the pre-flight testing required for use on live aircraft in flight.

The SSTDR technology that is the basis of the LiveWire system has been demonstrated to locate open and short circuits and intermittent faults such as wet and dry arcs with an accuracy of +/-1.5 foot on wires over 100 feet long. The entire test can be done in about 1ms, well below the approximately 5ms that wet arcs last. This can be done without interfering with existing signals on the aircraft, and without interference from the existing signals and electromagnetic interference these aircraft present to the test system. The specific parameters for each system can be adjusted by changing the length, frequency, and integration time of the PN code.

S/SSTDR methods have been used extensively in communication systems, where a PN code is used to code the data for wireless transmission. A PN-code looks like a random sequence of digital bits (1023 bits long, in our case) that can be superimposed on the existing aircraft signal or power line at a very, very low level, well below the noise margin of the system. To the signal, it appears as zero-mean noise, so small that it does not interfere in any way with the system. This PN code is not truly random, however. It has some very special mathematical qualities that make it easy to detect, even in a noisy environment. (The cross correlation of the PN code with itself is 1 when synchronized and 0 when unsynchronized.) This basic concept can be applied with excellent precision to fault location on aging wiring.

The basic S/SSTDR system uses a 1023 bit Maximum Length (ML) PN code running 58 Mbits/second. The 30 mV (RMS) PN code (which may be modulated) is added to the 115 V 400 Hz aircraft signal. Since this signal is zero mean and is well within the noise margin of the aircraft signal, there is no interference between the PN code and the 400 Hz signal. The PN code is also highly immune to noise from the 400 Hz generator and the live loads on the line and can therefore provide accurate results in realistically noisy situations. A multiply and integrate circuit is used to perform the correlation in hardware, and an analog phase shifter is used to shift the original PN code to find the correlation for each very small time delay and create the equivalent of a TDR trace. Figure 1 shows the STDR response for an 80 foot wire that is short or open circuited on the end. The SSTDR response is similar in nature, but the shape of the pulses is different. Note the first positive peak at zero that indicates the reflection that occurs where the high impedance circuit is attached to the wire. Then a positive (for open) or negative peak (for short) indicates the end of the wire. The height of the peaks indicates the magnitude of the fault, the polarity indicates whether it is a high or low impedance fault, and the distance between them indicates the distance to the fault. Hard faults (open and short circuits) can be located to within 3-5 inches on controlled impedance cables and 6-8 inches on uncontrolled impedance cables. When the S/SSTDR system is used to locate the small intermittent faults that can trip an AFCB, the system shows a low impedance (about 30% of a short circuit).

The S/SSTDR system has been tested on live 60 Hz power lines, 400 Hz aircraft power lines, 28 V DC, and Mil Std 1553 data lines, and for radiated emissions per Mil-Std 461E. RE-102 tests of this device indicate that emissions are below the limits for fixed wing aircraft for critical flight frequencies. Connections can be direct (requiring metallic con-

tact with the conductors of the wires to be tested), or non-contact (where a clamp or tube is placed around the wire to be tested). [19] Additional technical information (including downloadable versions of the references in the footnotes) is available at [www.ece.utah.edu/~cfurse](http://www.ece.utah.edu/~cfurse).

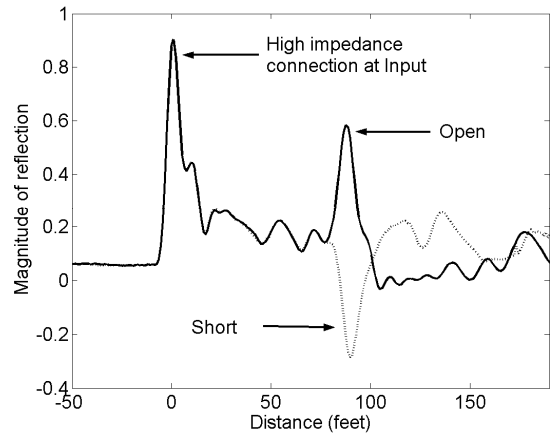


Figure 1 — STDR response for an 80 foot wire

## IMPLEMENTATION OF S/SSTDR

LiveWire has built several prototype versions of the S/SSTDR tester, known as the Wire In-Line Maintenance Aid (WILMA). The WILMA tester has been implemented in a 3" x 3.75" form factor and is shown in Figure 2. This WILMA can be connected to the wiring temporarily and flown for a single flight to capture and locate an intermittent electrical fault. It is battery operated and automatically captures data for approximately 6-8 hours.

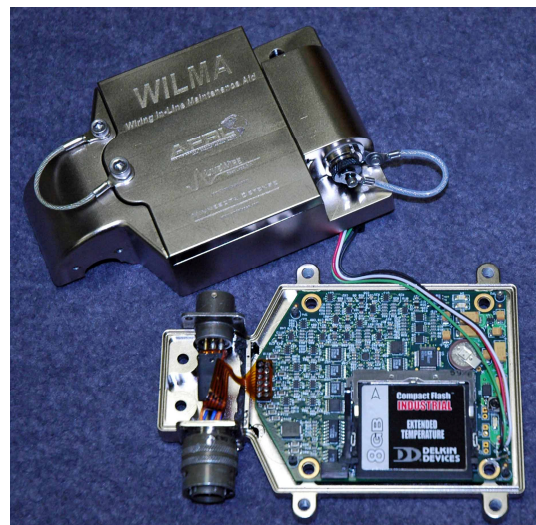


Figure 2 —S/SSTDR WILMA Tester

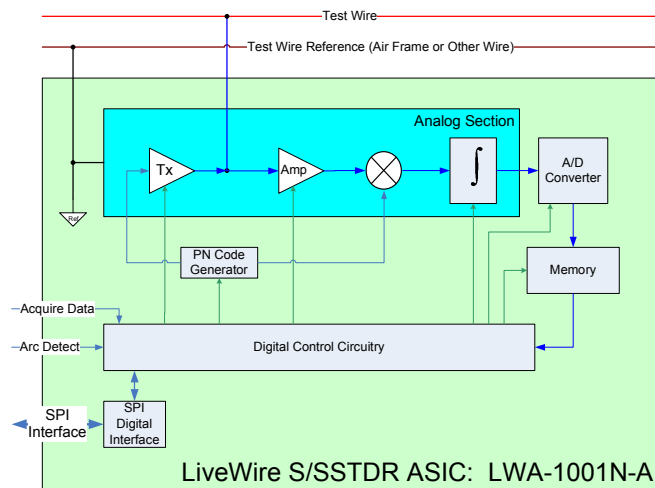
## ASIC DEVELOPMENT

The WILMA is suitable for monitoring intermittent problems in a troubleshooting mode. However,

there is additional need for this technology in a smaller form factor that can be installed permanently on an aircraft in multiple critical locations. LiveWire Test Labs, Inc., in conjunction with the US Air Force, NAVAIR, Sensata Technologies, and Minnesota Defense, is developing an ASIC with embedded SSTDR technology in a small form factor package for the detection and location of faults in complex electrical wiring systems.

The SSTDR ASIC will be capable of monitoring powered wiring systems arcs and intermittent shorts without interfering with either power transmission or communication signals. It can detect arcs on live wires that last 250 microseconds or more by continuously monitoring the test wire (most arc events last about 500 microseconds).

The projected power usage for the new SSTDR fault detection system is approximately 350 milliwatts. Faults can typically be located to +/-1.5 feet over 100 feet of wire/cable, but the system may be adjusted to optimize these distances. A functional block diagram of the ASIC is seen in Figure 3.



**Figure 3** — Functional Block Diagram of the Live-Wire S/SSTDR ASIC.

The major features included in this chip are:

- S/SSTDR continuous wire monitoring at 1.5 to 144 MHz
- Maximum wire length 300 feet
- Power injected: 40 nW to 6 mW (based on application)
- 350 mW Power Usage, battery operated
- 250  $\mu$ sec Arc Detection
- 3.3 VDC Operation
- On board A/D, RAM, digital controller
- ESD Protection
- 24 MHz SPI Control Interface

- 6mm x 6mm Die Layout
- Chip packaging:
  - QFN (8x8 mm, 52-pin) and
  - TQFP (10x10 mm, 44-pin)

The new ASIC is designed to fit into an 8mm x 8mm package. It interfaces with common microcontrollers with a 24 MHz SPI Interface. This implementation allows a complete instrumentation system to be constructed in a footprint smaller than a quarter (see Figure 4). The size and weight of this instrumentation allows many such devices to be placed throughout the aircraft with minimal impact with respect to size and weight. In particular, this ASIC may be built into AFCBs to provide arc fault protection and fault location in a single integrated solution.



**Figure 4** — Size comparison with “Smart Connector” and LiveWire SSTDR ASIC

The ASIC is expected to generate a new series of chip-based instrumentation products that promise more accuracy in fault location and reliability for aviation at a very cost effective price. This new SSTDR ASIC should bring major benefits to aviation by reducing wiring based accidents, reducing maintenance time, and at the same time reducing the cost of maintaining aircraft.

The schedule for chip development is:

**PLANNED TASK SCHEDULE TO COMPLETION:**

Implement AS-9100 Quality Framework:	Done
Rev. 2 ASIC Ready for Fabrication:	3rd Qtr '08
Software Development:	4th Qtr '08
Prototype Chip Ready for Testing:	4th Qtr '08
Initial Verification ASIC:	1st Qtr '09
Arc-Fault and ASIC Integration:	1st Qtr '09
AFRL Qualification Testing:	2-3rd Qtr '09

## CONCLUSIONS

The objective of this work is to develop a mixed-signal SSTDR ASIC that is capable of continuously monitoring electrical wiring on aircraft in order to locate intermittent and static electrical faults. Test results from the circuit-board SSTDR prototype show that this method is capable of locating intermittent faults on wires up to 300 feet long with an accuracy of +/- 1.5 feet. The SSTDR ASIC is on schedule for completion at the end of 2009. The first version has been designed, fabricated, and tested, and the second version has been designed and is currently being fabricated. Further information on the performance of this ASIC is expected at the conference.

## ACKNOWLEDGEMENTS

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Dr. Smith (PhD '03) is one of the founders of LiveWire Test Labs, Inc. LiveWire Test Labs is developing instrumentation systems to locate faults and hazards in wiring systems. LiveWire's Technology is based on the spread spectrum sensing technology being developed at the University of Utah. Dr. Smith has focused his career on solutions to difficult wire test issues and has over fifteen years experience providing cable and wire harness test equipment for commercial and military applications. Dr. Smith has been awarded multiple patents in the field. [[www.livewiretest.com](http://www.livewiretest.com)]



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Dr. Kuhn joined LiveWire Test Labs, Inc. in April 2006 as a Principal Engineer to help the team with the design and development of LiveWire wiring integrity instrumentation. Prior to joining LiveWire Test Labs, Dr. Kuhn was a Principal Systems Engineer, Systems Architect, and Six-Sigma Black Belt with GE Healthcare's Interventional, Cardiology and Surgery Division at GE Healthcare, his responsibilities included the research, design and development, of the OEC Mobile C-arm X-ray imaging systems and the related family of products. [[www.livewiretest.com](http://www.livewiretest.com)]

