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ASIC Implementation of Live Arc Fault SSTDR Tester

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Abstract

Arc Fault Circuit Breaker (AFCB) technology promises to minimize the destruction of wiring elements in aircraft caused by potentially dangerous arcing events. While AFCB technology can enhance aircraft wiring protection, it creates significant difficulties for the aircraft maintainer who must find the barely visible arc-traces and repair the causes of these arc fault events. Intermittent faults are very difficult to find using traditional fault location methods as they tend to hide by having the wiring system become fully-operational, usually when the maintainer is trying to locate the faults. What is needed is a set of tiny instruments that can be built into the critical electrical systems throughout the aircraft that can detect and locate arc-faults and intermittent problems on live wires.

LiveWire Test Labs, Inc., in conjunction with the US Air Force, US Navy, Sensata Technologies, and Minnesota Defense is developing an Application Specific Integrated Circuit (ASIC) with embedded Spread Spectrum Time Domain Reflectometry (SSTDR) technology for the detection and location of faults in complex electrical wiring systems. The SSTDR technology is 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). Signals from an AFCB will detect the arc fault and trigger the SSTDR ASIC to capture the event live for future analysis. 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. Preliminary test data on the prototype Wiring In-Line Maintenance Aid (WILMA) will be presented on intermittent fault data on live and un-powered wires.

The new ASIC is designed to fit into an 8mm x 8mm package. This implementation allows a complete instrumentation system to be constructed in a footprint smaller than a quarter. 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. The ASIC is expected to generate a new series of chip based instrumentation products that promise more accuracy and reliability at a very cost effective price. This new SSTDR ASIC, in conjunction with WILMA and the AFCB, 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.

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I. Introduction and Key Issues

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. NAVAIR spent $94 Million on No Fault Found (NFF) equipment removals due to wire faults being undiagnosed [5]. This leads to the drastic imbalance between scheduled and unscheduled maintenance, where fives times as much maintenance time was spent on unscheduled then 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].

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].

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 increased mission capable hours.

II. Arc Fault Circuit Breaker

Among the most difficult to diagnose problems are those that are intermittent, that occur only during a particular condition or strain and are unable to be reproduced on the ground. The vast majority of car owners have had similar experiences when they take a malfunctioning car to the mechanic, only to have it work properly in the repair shop. Detection of intermittent arcs (short circuits) in aircraft is the focus of recent research [11, 12, 13]. Wet arcs are caused when moisture seeps into cracked insulation, creating a conducting path for current. Wet arcs are normally simulated in the lab by dripping saline onto wires with cracks in the insulation. Dry arcs are caused by a wire fraying against and eventually making contact with a metallic structure, by two wires rubbing together, or by bits of metal making contact between two wires. Dry arcs are simulated in the lab by using a guillotine to short a razor blade across two live wires.

Low level, intermittent arcs are not normally detected by traditional thermal circuit breakers, which require enough current flow to heat up a thermally sensitive element in the breaker. Arc Fault Circuit Breakers (AFCBs) are being developed to identify the noise on the line associated with an arc and trip when an arc occurs. AFCBs are required on bedroom circuits in new home construction as of 2002, and are being considered for commercial products, specifically in-room air conditioners and heaters. Several electrical fires aboard aircraft have occurred that have led to a number of investigations [14]. The investigations concluded that protection from thermal circuit breakers is inadequate for the prevention of fires and further recommended the adoption of AFCB technology. Aircraft versions of AFCBs as one-to-one replacement for the existing thermal breakers have been in development over the past several years. They are under consideration for targeted implementation on commercial and non-commercial planes in the near future. A significant challenge associated with the AFCB is that it prevents or limits the extent of the arcing event, and thus the wire damage is so small that it may be extremely difficult to locate and repair. Difficulty in locating the fault results in reduced availability and reliability of the aircraft along with the additional costs associated with a lengthy search for the fault. This is a critical issue that may slow the acceptance and widespread deployment of AFCBs, as existing technologies have shortcomings in locating the fault.

There are several emerging sensor technologies that may help locate the small faults on the wire left behind when the AFCB trips. Time domain reflectometry (TDR), long the traditional method of solving the industry's most puzzling wiring problems, has the potential to detect very small changes in impedance, perhaps as small as those created by a wet or dry arc. While promising, these methods require an extremely accurate baseline for comparison with the arced wires. Recording and maintaining baseline TDR data archives for even a limited number of circuits for an airline or military fleet may prove to be an enormous and costly task. In addition, moving the wire, which is inevitable in the high vibration environment of the plane, can make impedance changes that are as large or larger than the fray, making these methods difficult to implement in practice [15, 16, 17]. The major shortcoming of TDR is that after the arc occurs, the impedance change at the arc location is very small, commonly less than a milliohm difference on a 200 Ω cable. The reflections are therefore necessarily minute. Spread Spectrum Time Domain Reflectometry (SSTDR) has been proposed for locating these intermittent arcs before or during the detection cycle of the AFCB [18]. The objective is to detect and locate the fault while it is occurring, when its impedance change is significant over that very short period of time (often a few milliseconds), and the resultant reflection is much easier to detect and analyze.

III. SSTDR Reflectometry

Several methods are available today for locating electrical faults. These include time domain reflectometry (TDR), frequency domain reflectometry (FDR) [19, 20], standing wave reflectometry (SWR), mixed signal reflectometry (MSR) [21], multicarrier reflectometry (MCR) [22], sequence reflectometry (STDR), spread spectrum reflectometry (SSTDR) [23, 24] and noise domain reflectometry (NDR) [25]. Reflectometry methods send a high frequency 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 [26].

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 No Fault Found problem. With the ability to locate the fault while the aircraft is in flight, fault 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, SSTDR (spread spectrum methods) 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 spread spectrum time domain reflectometry (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 feet on wires over 100 feet long. The entire test can be done in about 1 ms, well below the approximately 5 ms that fast duration 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.

Spread spectrum methods have been used extensively in communication systems, where a pseudo-noise (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 zero when not.) This basic concept can be applied with excellent precision to fault location on aging wiring.

The block diagram for the prototype STDR/SSTDR system is shown in Figure 1. The 1023-bit Maximum Length (ML) PN code running 58 Mbits/second is generated using a series of tapped flip flops. 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, so can 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 every very small phase (time) delay and create the equivalent of a TDR trace. Figure 2 shows the STDR response for an 80 foot wire that is short or open circuited on the end. Note the original positive peak that indicates the reflection that occurs where the high impedance circuit is attached to the wire and the negative peak that indicates the short-circuited 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 STDR/SSTDR system is used to locate the small, intermittent faults that can trip an AFCB, the system shows a low impedance (near short circuit).

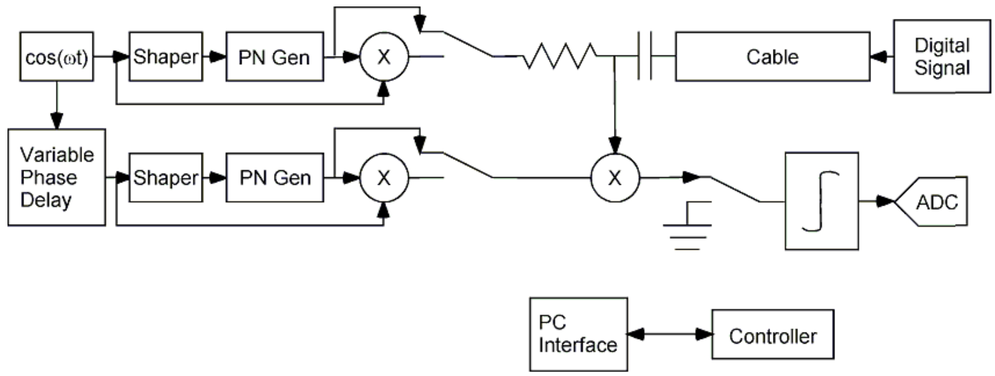

Figure 1: Circuit diagram for STDR/SSTDR system.

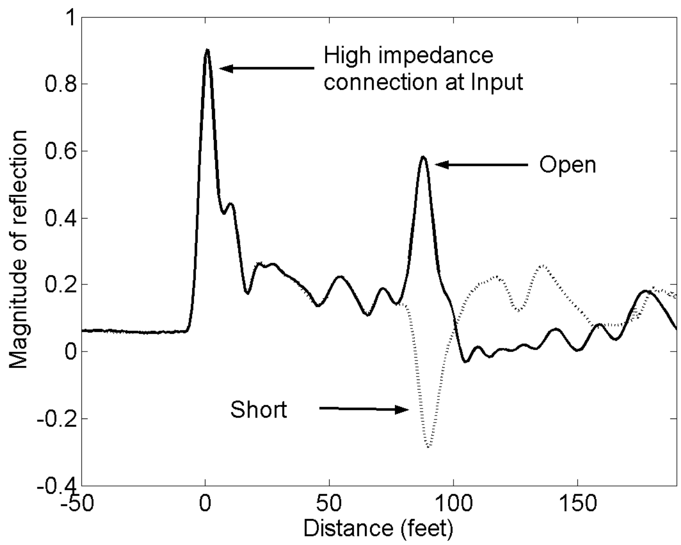

Figure 2 STDR response for an 80 foot wire (pair of 22 gauge wires bundled together with other wires) that is short or open circuited on the end.

LiveWire has built several prototype versions of the S/SSTDR tester, known as the LiveWire Service Pack or Wire In-Line Maintenance Aid (WILMA). The WILMA tester has been implemented in a 3" x 5" form factor and is shown in Figure 3. This prototype can be connected to the wiring temporarily and flown through a limited number of flights to capture and locate an intermittent electrical fault. It is battery operated and automatically captures data for approximately 8-12 hours.

The WILMA Mobile Service Pack has been tested on live 60 Hz power lines, 400 Hz aircraft power lines, 28 V DC, and for Radiated Emissions per Mil-Std 461E. Figure 4 and Figure 5 show the test data from RE-102 tests indicating that emissions are below the limits for fixed wing aircraft for critical flight frequencies (tests performed at AFRL in 2007). It is suitable to monitor 4 wiring channels per Mobile Service Pack. It is designed to record arc events in conjunction with AFCBs. Connections can be direct (requiring metallic contact with the conductors of the wires to be tested), or non-contact (where a clamp or tube is placed around the wire(s) to be tested) [27].

Figure 3 Prototype implementation of the S/SSTDR Tester or WILMA.

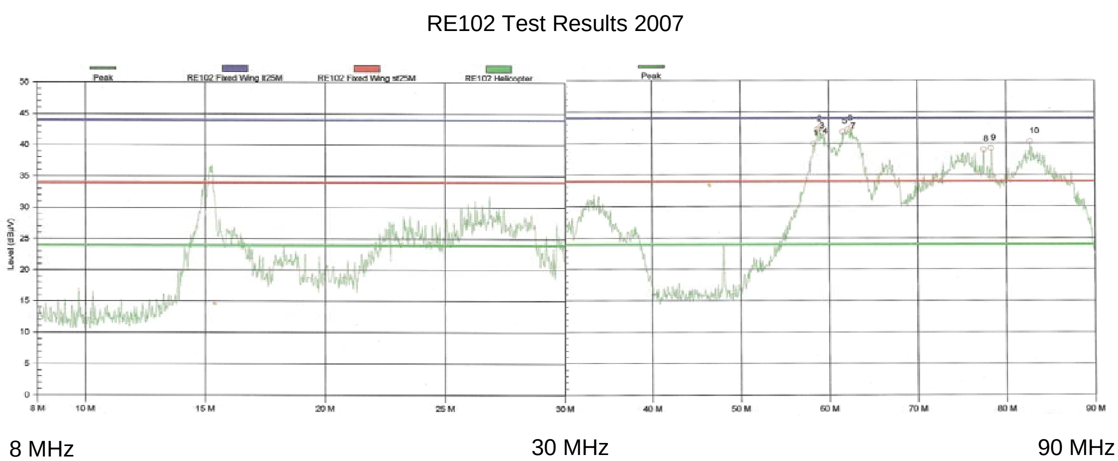

Figure 4 Test Data for Radiated Emissions (RE-102) for 8 to 90 MHz.

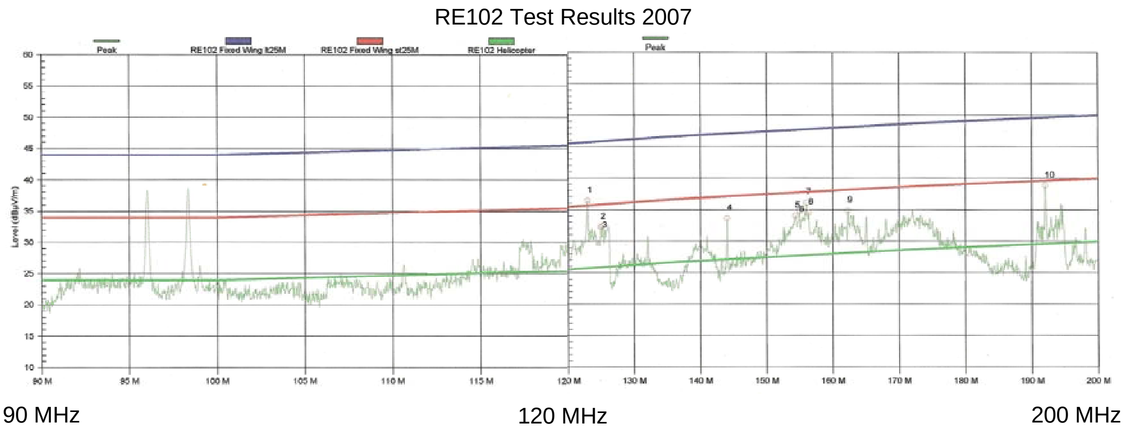

Figure 5 Test Data for Radiated Emissions (RE-102) for 90 to 200 MHz.

Additional technical information (including downloadable versions of the references in the footnotes) is available at www.ece.utah.edu/~cfurse.

IV. ASIC Developments

The Mobile Service Pack 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. Additional features include continuous full-time monitoring with arc detection for arc events that last at least 250 microseconds. Also needed is the ability to retain the data for downloading later to a maintenance system after the occurrence of the event. It should be flexible with respect to distance to fault ranges. It should be capable of operating in critical communications environments with low level signals as well as robust and attenuating environments with degradation of accuracy. Power usage, of course, must be as small as possible. The ASIC should be controllable via a common interface for compatibility to standard microcontrollers.

To meet the needs of the aviation community, LiveWire Test Labs, Inc., in conjunction with the US Air Force, US Navy, Sensata Technologies, and Minnesota Defense is developing an Application Specific Integrated Circuit (ASIC). The ASIC has embedded Spread Spectrum Time Domain Reflectometry (SSTDR) technology in a small form factor package for the detection and location of faults in complex electrical wiring systems. The SSTDR technology is 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). Signals from an AFCB will detect the arc fault and trigger the SSTDR ASIC to capture the event live for future analysis. 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. Preliminary test data on the prototype Wiring In-Line Maintenance Aid (WILMA) will be presented on intermittent fault data on live and un-powered wires.

In summary the major features of this chip are:

- 250 µsec Arc Detection
- 6mm x 6mm Die Layout
- Continuous Wire Monitoring
- 3.3 VDC Operation
- 350 mWatt Power Usage
- On Board A/D Circuit
- On Board Digital Controller
- On Board RAM
- ESD Protection
- 24 MHz SPI Control Interface

The ASIC has the following General Specifications:

- Test modes:
    - STDR (spectrum time domain reflectometry)
    - SSTDR (spread spectrum time domain reflectometry)
- Test frequencies: 1.5 MHz to 144 MHz
- Maximum wire length to be monitored:
    - dependent upon frequency used - up to 100 meters.
    - Minimum wire length: none
- Typical power injected on the wire: 40 nano-Watts (aerospace applications)
- Maximum power injected onto wire: 0.6 mW (non-aerospace applications)
- Accuracy: Typically +/- 1.5 feet (less for shorter cables)
- Chip packaging:
    - QFN (8x8 mm, 52-pin) and
    - TQFP (10x10 mm, 44-pin, 0.8mm lead pitch)

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 6). 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. 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, in conjunction with WILMA and the AFCB, 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. A function block diagram of the ASIC is seen in Figure 6.

Figure 6 Size comparison with "Smart Connector" and LiveWire SSTDR ASIC

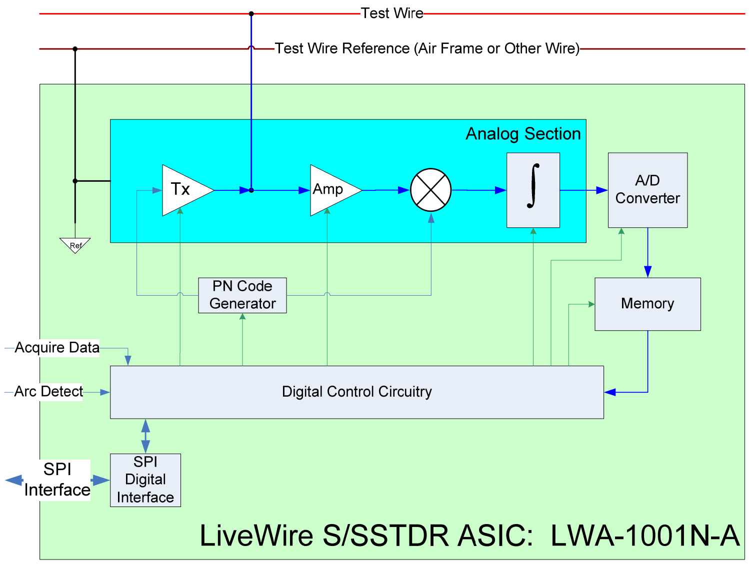

Figure 7 Functional Block Diagram of the LiveWire S/SSTDR ASIC.

Typical applications for the LiveWire S/SSTDR ASIC would be integration with an AFCB or into the smaller version of the LiveWire Mobile Service Pack such as a "Smart Connector." Many variations on these themes are possible. Either on a stand-alone basis or integrated with some other device, the LiveWire chip would be inserted into the electrical circuit to be monitored. Changes in the reflected signals are recorded and stored for off-line analysis, from which the nature of the fault, time of occurrence, and distance to fault are extracted.

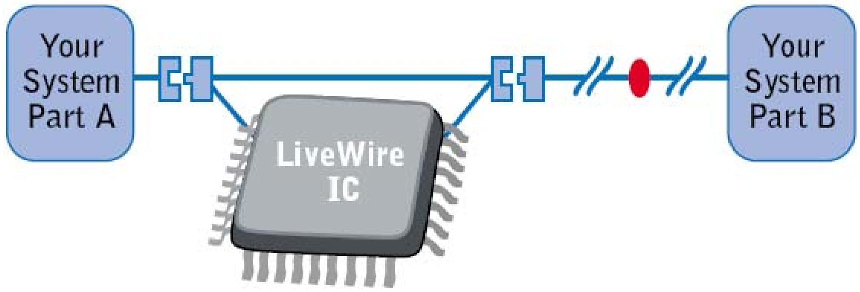

Figure 8 The SSTDR LiveWire ASIC is integrated into the system, typically added to existing electronics such as power distribution systems, 'Smart Connectors', or arc fault circuit breakers.

The schedule for chip development is:

Planned Task	Scheduled Completion
• Implement AS-9100 Quality Framework:	2nd Qtr '08
• First Prototype Chip Ready for Testing:	2nd Qtr '08
• Initial Verification ASIC Rev 1	2nd Qtr '08
• AFRL Qualification Testing (Rev 1*)	3rd Qtr '08
• ASIC Rev 2 Ready for Fabrication:	3rd Qtr '08
• Laboratory Demonstration ASIC (Rev 1*):	4th Qtr '08
• Software Development:	4th Qtr '08
• Aircraft Testing:	4th Qtr '08

* Assumes ASIC Rev 1 verification has no complications

V. Conclusions

The objective of this work is to develop a mixed-signal LiveWire ASIC that is capable of continuously monitoring electrical wiring on aircraft in order to locate intermittent electrical faults. This ASIC is intended to be integrated with arc fault circuit breakers, power distribution components, and also individual connectors. The ASIC uses spread spectrum reflectometry (SSTDR).

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