MIL-STD-1553 Evolves with the Times

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Introduction

MIL-STD-1553 is a serial, time division multiplex data bus that has been used as the primary command and control data interconnect in military aircraft for the past three decades. MIL-STD-1553's robust performance, high level of interoperability, large installed based, and well established infrastructure of vendors has made MIL-STD-1553 the network of choice for military avionics systems.

The use of MIL-STD-1553 is not limited to military aircraft. MIL-STD-1553's use is pervasive in military ground vehicles, military ships, and satellite systems. All of these applications share common requirements for a deterministic, fault tolerant data bus that will operate in relatively harsh environments.

New Applications

Even after 30 years MIL-STD-1553 is finding its way into new applications. Airbus has selected MIL-STD-1553 for use in the flight control system for the A350 XWB aircraft (1).

MIL-STD-1553 combines a robust physical layer with a deterministic protocol making it ideally suited for use in commercial aerospace systems. In particular the galvanic isolation provided by transformers contributes to the superior EMI and lightning immunity of MIL-STD-1553. Isolation is even more critical in new composite aircraft where the skin of the aircraft no long provides an inherent Faraday shield as was the case with aluminum skinned aircraft.

One of the misnomers about MIL-STD-1553 is the perception that it is an expensive interface. The reality is that the cost of implementation of MIL-STD-1553 has decreased significantly over the last 10 years. There exists a mature ecosystem of MIL-STD-1553 suppliers that provide cost effective solutions for embedded controllers, cable harnesses, test and simulation equipment, and software tools. Why invent a new interface when there is one available that has over 30 years of flight experience.

Higher Data Rates

While MIL-STD-1553's 1 megabit-per-second data rate is still adequate for a large number of applications, there are systems that require higher rates. Two approaches to increasing the bandwidth of MIL-STD-1553 are gaining momentum. The first approach, referred to as "Turbo 1553", is to simply increase data rate without changing any of 1553's architectural features (modulation technique, line code, coupling methods, etc). The second approach, referred to as "High Performance 1553" or "HyPer-1553", is to implement a high frequency broadband waveform using alternate line codes and modulation methods. The second approach can also be extended such that it can coexist with traditional 1 Mbps 1553 on the same wire through the use of frequency division multiplexing.

Turbo 1553 – An Evolutionary Approach

MIL-STD-1553 has a well established set of design guidelines for a network operating at 1 Mbps. In addition to over thirty years of in service history there is a strong analytical foundation for these guidelines which is well documented in MIL-HDBK-1553A. (2) The key design variables in a 1553 network are bus length, number of stubs, location of stubs, and length of the stubs. The concepts defined in the standard and the handbook can be extended to data rates above 1 Mbps. The question becomes what impact would a higher data rate have on these design variables and the resulting performance of the network.

The first step towards an implementation of Turbo 1553 is to understand the impact of higher frequency on attenuation and phase distortion. Attenuation impacts the amplitude of the signal that is presented to the receiver, and as such impacts the resulting signal to noise ratio (SNR). SNR is a key benchmark in defining the throughput capacity and bit error rate (BER) of a network. Phase distortion, also referred to as jitter or zero crossing error, impacts the relative timing of pulses which in turn can lead to problems with inter-symbol interference which also has an impact on the bit error rate of the receiver.

Attenuation

Attenuation occurs due to the resistance, series inductance and shunt capacitance of the cables. The attenuation will include both a frequency independent component due to the resistance of the cable and a frequency dependent component due to the parasitic capacitance and inductance. The cable can be approximated as a low pass filter.

MIL-STD-1553 provisions for approximately 12.6 dB of signal loss in the bus cable, based on a minimum transmitter voltage of 6 volts and a minimum stub voltage requirement of 1.4 V (both measured peak to peak on the bus). MIL-STD-1553 defines the minimum stub voltage to be 1.3 dB above the terminal's maximum receiver threshold. Figure 1 illustrates the frequency response of 300 feet of MIL-STD-1553 cable from 300 KHz to 10 MHz. The attenuation through 300 feet of cable is -2 dB at 1 MHz and -5 dB at 5 MHz, both of which are well within the 12.6 dB link budget defined in MIL-STD-1553.

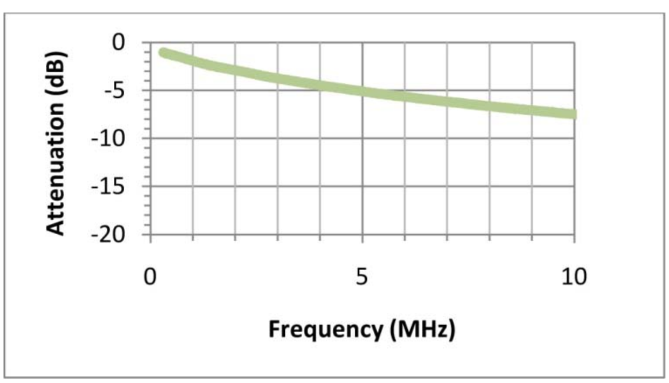

Figure 1. Frequency Response of 300 Feet of 1553 Cable

The signal attenuation will also be affected by the number of stub connections on the bus. Figure 2 illustrates the frequency response of a 460 foot bus with 10 stubs versus

460 of cable with no stub connections. At higher frequencies the attenuation will be influenced more by the presence of stubs connections.

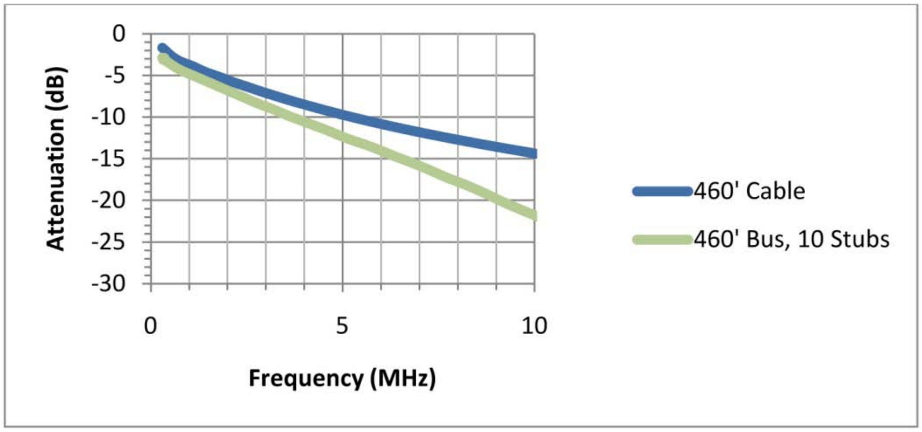

Figure 2. Insertion Loss of 460' Cable and 460' Bus from 300 KHz to 20.3 MHz

Phase Distortion

Phase distortion on a 1553 bus is primarily caused by two mechanisms: reflections. Dispersion is caused by variations in propagation velocity as a function of frequency. The amount of dispersion is determined by the characteristics of the cable (such as distributed capacitance). Reflections are caused by a mismatch in impedance on the transmission line due to stub connections. The impedance discontinuity at each stub connection will be based on the parallel combination of the stub impedance and the characteristic impedance of the main bus. As illustrated in Figure 3, a mismatch in impedance will split an incident wave into three components: a reflected wave, a transmitted wave, and a stub wave.

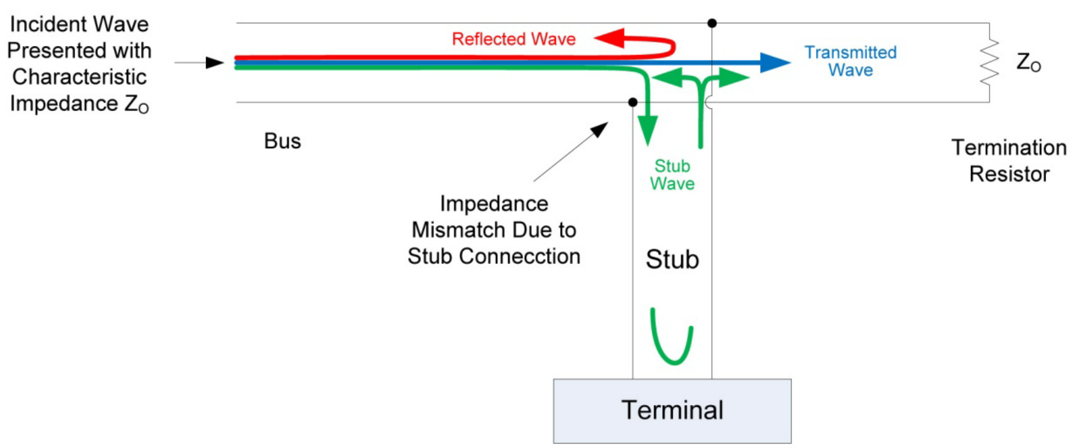

Figure 3. Reflections Caused by Impedance Mismatch

MIL-STD-1553 defines a terminal (communication end point) to have a high input impedance relative to the characteristic impedance, which will produce a large reflection coefficient at the boundary between the end of the stub cable and the terminal. The implication of this high reflection coefficient is that most of the energy in the "stub wave" will be reflected back towards the main bus. The reflected stub wave will add back into the incident wave with a phase shift due to the round trip delay down the stub cable and back. The benefit of the reflected stub wave is that it minimizes attenuation but this is accomplished at the expense of a slight phase distortion. As long as the length of the stub is kept reasonably short the phase distortion induced by the stub wave will be minimal.

A lower stub impedance will result in a higher reflection coefficient on the main bus. The impedance of the stub will be based on the input impedance of the terminal as seen through the stub cable. Figure 4 illustrates the effective stub impedance as a function of stub length. As the stub length is increased the effective impedance of the stub decreases dramatically, which will result in an increase in reflections on the main bus. Figure 4 shows that a direct coupled connection to a 1553 bus with a 20 foot stub cable will result in approximately the same effective stub impedance for a terminal with a 1000 ohm input impedance as with a terminal with a 2000 ohm input impedance.

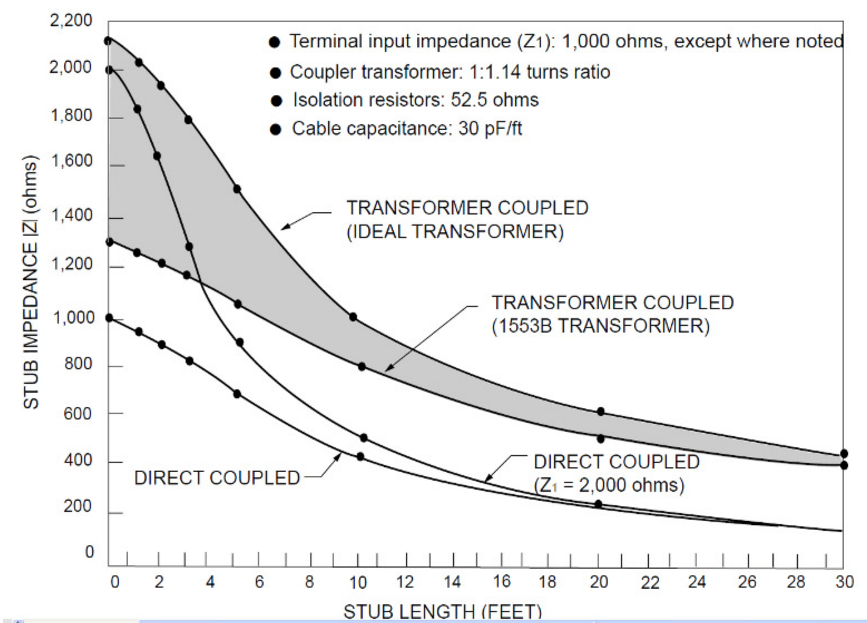

Figure 4. Stub Impedance Versus Stub Length

MIL-STD-1553 provides a second method for connecting to the main bus called transformer coupling. A transformer coupled connection utilizes an impedance matching coupling transformer along with isolation resistor to make the connection to the bus. The effect of the coupling transformer and isolation resistors is that the impedance of the stub looking into the bus is matched to the characteristic impedance. Providing a matched impedance looking into the bus will reduce secondary reflections on the stub and deliver the majority of the signal power to the bus. The second benefit of the coupling transformer is that the ratio is such that the effective stub impedance will be increased by a factor of 2 to 1 (based on the usage of a transformer with a turns ratio of 1.41:1). Figure 4 shows a significant increase in effective stub impedance for transformer coupled connections as compared to direct coupled connections. This use of bus couplers is one of the key architectural advantages of MIL-STD-1553 in terms of maintaining the fidelity of the transmission line on a multi-drop bus.

On long buses dispersion will contribute to the phase distortion in addition to reflections. The series resistance, parallel capacitance, and series inductance of the cable produce a non-linear phase response which will lead to a non-uniform group delay. Simply stated signals at different frequencies will take different amounts of time to propagate down the bus. In general, high frequency pulses propagate faster than lower frequency pulses.

A Manchester line code will utilize pulses at two primary frequencies (one at the baud rate and one at half the baud rate). A non-uniform group delay can result in intersymbol interference. Intersymbol interference occurs when a pulse in one symbol is delayed relative to a pulse in the next symbol. The result of intersymbol interference is a shift in the timing of subsequent edges in the waveform. This causes problems because the receiver uses the relative timing of the waveform transitions to recover the digital encoded data.

The amount of dispersion that occurs is a function of the frequency response of the cable and the length of the cable. MIL-STD-1553 defines the use of cable with reasonably good frequency response which allows for relatively long buses (100 meters and longer). Longer buses are also possible but care needs to taken in selecting the cable. A lower capacitance cable will produce lower attenuation and lower dispersion.

Test Results for Turbo 1553

Testing was performed on MIL-STD-1553 terminals operating at 4 Mbps (as compared to 1 Mbps). The result of the testing is that MIL-STD-1553 will operate reliably at 4 Mbps with excess margin. Figure 1 illustrates the test network that was used to evaluate MIL-STD-1553 running at higher speed. Various length stubs were used ranging in length from 1 foot to 5 feet. The length of the test network was 430 feet with 10 stub connections. The bus controller was implemented within terminal #1.

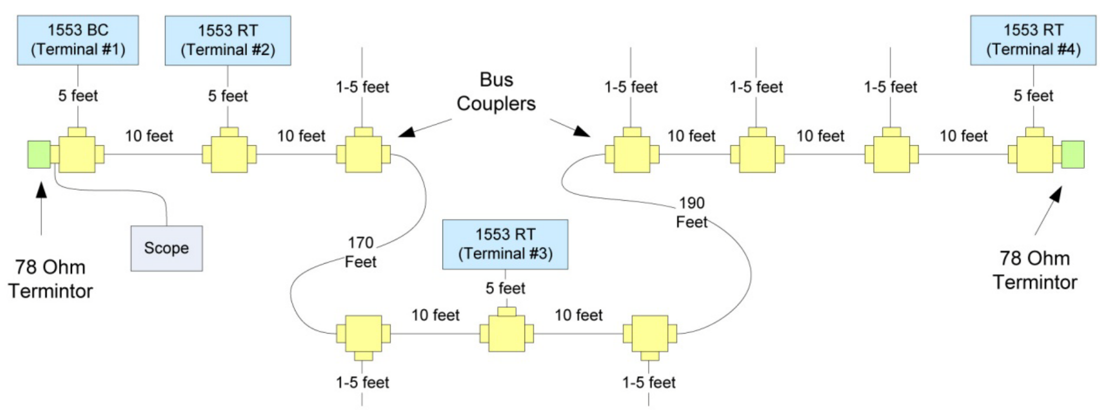

Figure 5. MIL-STD-1553 Test Network

Communication was tested between the Bus Controller (terminal #1) and three other terminals (1553 Remote Terminals). Terminal #2 is positioned to provide the least amount of attenuation but the largest amount of phase distortion due to the reflections. Terminal #3 provides a moderate amount of attenuation and phase distortion due to reflections. Terminal #4 was intended to provide the most attenuation and the largest phase distortion due to dispersion.

The bus controller was able to reliably communication with the three remote terminals. Scope measurements were made to measure the attenuation and phase distortion of signals from all three remote terminals. The result of the testing is that the waveforms are all well within the specified receiver specifications.

High Performance 1553 – A Revolutionary Approach

High Performance 1553 is a new technology that provides higher data rate communication over MIL-STD-1553 cabling. High Performance 1553 seeks to satisfy two goals: to enable high speed communication on a multi-drop bus, and to implement that communication such that it does not interfere with legacy 1 Mbps communication.

Technology

The data rate of a high performance 1553 system will be determined by the signal to noise ratio of the HyPer-1553 signal. DDC has conducted studies to determine the capacity of MIL-STD-1553 networks based on a prediction of the achievable signal to noise ratio. These studies take into account the signal loss of various bus configurations, EMI constraints (radiated emissions), and the expected noise environment. These studies have shown that there is sufficient bandwidth to implement a broadband system in which legacy 1 Mbps signals can coexist with new high speed signals supporting data rates up to 200 Mbps depending on the length of the bus and number of stubs. (3)

Multi-Drop Bus

A multi-drop bus has been viewed as the most cost effective topology for “low speed” networks because it eliminates the need for active hubs or switches. Implementation of a multi-drop bus becomes more difficult for data rates above 5 to 10 Mbps because of signal distortion. Realizations of “high speed networks” (such as Gigabit Ethernet) generally utilize point to point links with an active switched fabric, which avoids the challenges of a multi-drop bus but adds both cost and complexity to the system. The reality is that with the right technology a more efficient network can be implemented using a multi-drop bus.

HyPer-1553 combines the benefits of a multi-drop drop bus (reduced size, weight, power, and cost) with high data rates that have been historically restricted to a switched topology. The benefits of a multi-drop become even more dramatic in high assurance applications, such as commercial aircraft. In addition to the recurring manufacturing cost, an active switch will have very high development and qualification costs especially when you start to consider the implications of redundancy.

There is a gap between the low speed and high speed networks that is not effectively served by currently available COTS technology. High Performance 1553 is aimed at supplying a solution for “middle speed networks” with a data rate in the rage of 10 to 100 Mbps. High Performance 1553 provides reliable high speed communication on a multi-drop bus through the use of advanced signaling and filtering techniques.

Concurrent Operations

A key benefit of High Performance 1553 is the ability to extend the capabilities of existing systems that utilize MIL-STD-1553. High Performance 1553 provides these systems with the ability to add higher data rate communication without interfering with the operation of the reliable 1 Mbps MIL-STD-1553 interface. The fact that traditional MIL-STD-1553 and high speed HyPer-1553 share the same cable contributes to significant weight reduction, especially when you compare HyPer-1553 to other high speed solutions that require hubs and/or switches.

High Performance 1553 utilizes frequency division multiplexing to allow concurrent high speed and low speed communication. The Traditional 1 Mbps MIL-STD-1553 signal occupies the lower portion of the frequency spectrum, while the new high speed signal utilizes a frequency band above traditional MIL-STD-1553 (refer to Figure 6). The resulting signal to noise ratio will be dependent on the frequency band that is selected for the high performance 1553 waveform.

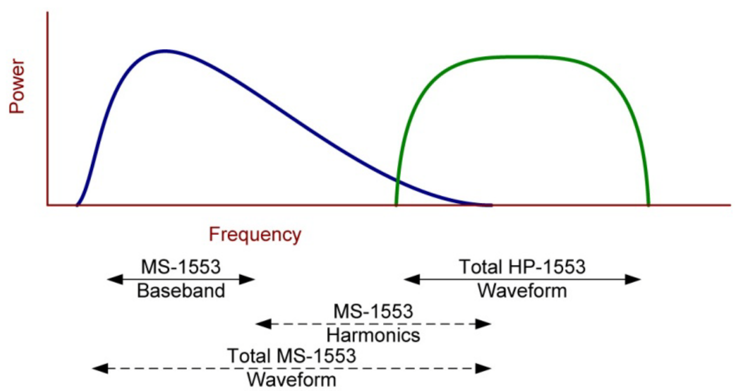

Figure 6. Frequency Spectrum

A legacy MIL-STD-1553 baseband signal (MS-1553) consists of four fundamental frequencies (250 KHz, 333 KHz, 500 KHz, and 1 MHz) plus harmonics. The frequency band of the high performance 1553 (HyPer-1553) waveform must be high enough to avoid the harmonics from the legacy MS-1553 signal. These MS-1553 harmonics will add to the noise presented to a HyPer-1553 receiver, thus reducing the signal to noise ratio and limiting the achievable data rate.

The upper bound of the HyPer-1553 frequency band will be constrained by signal loss through the 1553 cabling. Signal attenuation and distortion both increase as a function of frequency. Above a certain frequency a transmitted waveform will be attenuated to an extent that the receiver cannot differentiate the signal from noise (i.e. the signal to noise ratio becomes too low or negative).

The transmit level of the HyPer-1553 waveform is limited by the requirement to control the emission of radio frequency energy (RF emissions). Radiated emission levels are defined in MIL-STD-461 (applicable to military applications) and DO-160 (applicable to commercial aircraft).

The new high performance 1553 (HyPer-1553) waveform is implemented as a band limited signal such that it will not interfere with the lower frequency MIL-STD-1553 waveform (MS-1553). To a legacy MIL-STD-1553 terminal the HyPer-1553 signal appears as high frequency noise that will be filtered out by its receiver.

Future Upgrade Path

A common requirement driving system architectures is a desire to provision for future expansion. For data networks this implies that a portion of the communication bandwidth be reserved for additional capabilities that may be added in the future. HyPer-1553 provides the unique ability to implement a 1 Mbps bus today and then implement a much higher speed interface in the future utilizing the same cabling. This allows system architects to utilize a more cost effective 1 Mbps bus today without sacrificing future bandwidth availability.

Not Just a Concept

DDC successfully demonstrated an implementation of High Performance 1553 technology in a 2 hour flight onboard a USAF F15-E1 Strike Eagle fighter in December 2005. (4) HyPer-1553 was used to transfer imagery between a rugged computer mounted in the forward avionics bay and a smart bomb mounted on wing pylon station. The imagery data was transferred error free at 40 Mbps over existing 1553 cabling concurrently with legacy 1 Mbps transfers. The flight demonstration showed the viability of high speed communication on a multi-drop bus in harsh environments and the viability of concurrent operation with 1 Mbps 1553.

Figure 7. F-15E1 Taking off for HyPer-1553 Flight Demonstration

Adapting Commercial Technologies

It is very common for military/aerospace systems to make use of automotive components. Some of the environmental requirements are similar and the production volumes associated with automotive applications lead to relatively inexpensive chips. The challenge facing mil/aero systems designers is adapting these automotive chips to meet the specific requirements of aerospace applications in a cost effective manner.

FlexRay is an automotive communication system that appears to be appealing for use in aerospace applications. There are several manufacturers of embedded microcontroller chips with integrated FlexRay interfaces. FlexRay, which provides a 10 Mbps deterministic interface, would appear to be a strong candidate for use in real-time aerospace control systems except for the limitations of its physical layer.

FlexRay's physical layer is optimized for use in automotive applications which make use of low cost unshielded cables. The transmit signal level is constrained to a very low level in order to meet automotive emission requirements. The physical layer provides robust communication in automotive applications where distances are relatively short (less than 24m), however studies have shown that the physical layer of FlexRay is inadequate for use in aerospace applications where cable distances may exceed 100m. (5)

Time Triggered Protocol (TTP) is another example of a commercial communication interface that may be considered for use in aerospace applications. TTP defines a robust, deterministic protocol but does not define a physical layer. RS-485 has been the de facto standard physical layer for use with TTP in commercial applications but studies have shown that the performance of RS-485 to be unreliable for use in aerospace applications due to RS-485's low transmit level and loosely defined receiver characteristics. (6)

Both FlexRay and TTP suffer from weaknesses in their physical layers when considering them for use in aerospace applications. MIL-STD-1553 can be used as an enabling technology for extending the use of these commercial data buses into aerospace applications. MIL-STD-1553's existing 1 Mbps physical layer combined with the higher speed derivatives described above provide an ideal framework for adapting commercial communication interfaces for use in harsh aerospace environments. Combining commercial communication controllers with robust MIL-STD-1553 PHYs provides the best of both worlds. System designers can leverage economies of scale associated with commercial controller chips and still satisfy the challenging physical layer and harsh environmental requirements of aerospace applications.

TTP 1553 Test Results

DDC has demonstrated a communication system utilizing commercially available TTP controllers combined with MIL-STD-1553 physical layer transceivers running at 4 Mbps on a 430 foot bus with 10 stub connections (refer to Figure 8). The network was characterized for attenuation and phase distortion at various stubs. Eye diagram measurements were made, and bit error rate testing was performed.

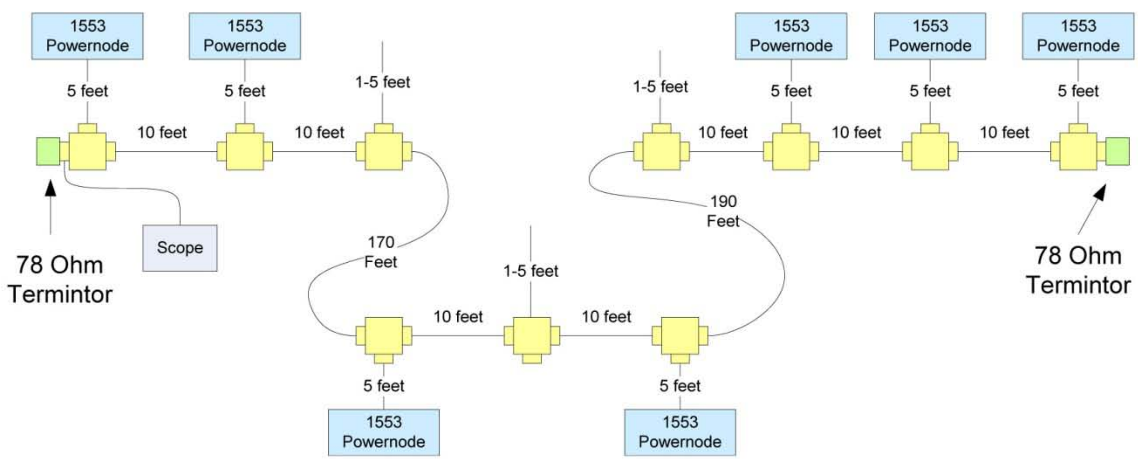

Figure 8. TTP 1553 Test Network

The results of the testing showed that MIL-STD-1553 can be utilized to provide TTP with a robust physical layer that is appropriate for even the most demanding aerospace applications such as flight control.

Summary of Solutions

Solution	Data Rate	Application	Concurrent 1 Mbps 1553
MIL-STD-1553	1 Mbps	Reliable, real-time, deterministic multi-drop bus	N/A
Turbo-1553	5 Mbps	New systems that require slightly higher data rates than 1 Mbps	No
HyPer-1553	50 to 100+ Mbps	New systems that require higher data on a multi-drop bus	No
HyPer-1553	10 to 50 Mbps	Incremental updates to systems already using 1 Mbps 1553	Yes

Conclusion

MIL-STD-1553's robust physical layer combined with emerging high speed derivatives serve as an ideal set of building blocks for a variety of applications. The superior isolation performance of MIL-STD-1553 makes it an extremely attractive solution for applications with severe EMI and lightning environments such as commercial aircraft. In addition the decades of in service flight history supports the notion that MIL-STD-1553 is well suited for critical real-time systems such as flight controls. The use of MIL-STD-1553 on the A350 aircraft is a testament to 1553's effectiveness for use in real-time, high assurance systems (1).

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Michael Hegarty
Principal Marketing Engineer
Data Device Corporation

For more information, contact Michael Hegarty at 631-567-5600 ext. 7257 or hegarty@ddc-web.com. Visit DDC on the web: www.ddc-web.com.

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DDC has also been granted certification by the Defense Supply Center Columbus (DSCC) for manufacturing Class D, G, H, and K hybrid products in accordance with MIL-PRF-38534, as well as ESA and NASA approved.

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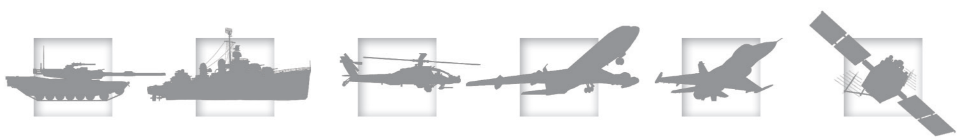

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Outside the U.S. - Call 1-631-567-5700

United Kingdom: DDC U.K., LTD
Mill Reef House, 9-14 Cheap Street, Newbury,
Berkshire RG14 5DD, England
Tel: +44 1635 811140 Fax: +44 1635 32264

France: DDC Electronique
10 Rue Carle-Herbert
92400 Courbevoie France
Tel: +33-1-41-16-3424 Fax: +33-1-41-16-3425

Germany: DDC Elektronik GmbH
Triebstrasse 3, D-80993 München, Germany
Tel: +49 (0) 89-15 00 12-11
Fax: +49 (0) 89-15 00 12-22

Japan: DDC Electronics K.K.
Dai-ichi Magami Bldg, 8F, 1-5, Koraku 1-chome,
Bunkyo-ku, Tokyo 112-0004, Japan
Tel: 81-3-3814-7688 Fax: 81-3-3814-7689
Web site: www.ddcjapan.co.jp

Asia: Data Device Corporation - RO Registered in Singapore
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Singapore 530327
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