SAE Aerospace
An SAE International Group

AEROSPACE INFORMATION REPORT

AIR5683

Issued 2007-02
Reaffirmed 2011-11

High Performance 1553 Research and Development

RATIONALE

This SAE Aerospace Information Report (AIR) captures technical work accomplished over several years by an industry group that studied the feasibility of extending the data carrying capacity of MIL-STD-1553 buses.

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1. SCOPE

MIL-STD-1553 establishes requirements for digital command/response time division multiplexing (TDM) techniques on military vehicles, especially aircraft. The existing MIL-STD-1553 network operates at a bit rate of 1 Mbps and is limited by the protocol to a maximum data payload capacity of approximately 700 kilobits per second. The limited capacity of MIL-STD-1553 buses coupled with emerging data rich applications for avionics platforms plus the expense involved with changing or adding wires to thousands of aircraft in the fleet has driven the need for expanding the data carrying capacity of the existing MIL-STD-1553 infrastructure.

1.1 Purpose

This SAE Aerospace Information Report (AIR) will examine the characteristics of MIL-STD-1553 buses relative to their ability to carry data at significantly higher data rates when compared to MIL-STD-1553. Practical issues such as frequency response of 1553 bus networks and their components, signal-to-noise ratio, EMI constraints, and concurrent operation with existing MIL-STD-1553 will be discussed.

Various telecommunication standards that could be appropriate for adaptation to MIL-STD-1553 buses are discussed.

Early research by various companies into increasing the data carrying capability of existing MIL-STD-1553 buses is summarized as well as ongoing research.

Potential applications that could benefit from increased bandwidth on MIL-STD-1553 buses are discussed.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

This report assumes familiarity with MIL-STD-1553B (or AS15531).

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AS15531 Digital Time Division Command/Response Multiplex Data Bus

AS1773 Fiber Optics Mechanization of a Digital Time Division Command/Response Multiplex Data Bus

AS5653 High Speed Network for MIL-STD-1760

AS5652 10 Mbit/sec Network Configuration Digital Time Division Command/Response Multiplex Data Bus

2.1.2 U.S. Government Publications

Available from the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, http://assist.daps.dla.mil/quicksearch/.

MIL-STD-1553B Department of Defense Interface Standard for Digital Time Division Command/Response Multiplex Data Bus, Rev. B

MIL-HDBK-1553A Multiplex Applications Handbook, Rev. A

MIL-STD-1760D Department of Defense Interface Standard for Aircraft/Store Electrical Interconnection System, Rev. D

MIL-STD-461E Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, Rev. E

2.1.2.1 U.S. Air Force Publications

Available from USAF ASC/ENOI, 2530 Loop Road West, Wright Patterson AFB, OH 45433-7101, http://assist.daps.dla.mil/quicksearch/.

MIL-STD-001553B(USAF) w/CHANGE 5 Digital Time Division Command/Response Multiplex Data Bus, Rev. B, Notice 5, 8 February 2006.

NOTE: This standard has limited distribution (Distribution Statement D) and is Export Controlled.

2.1.3 ITU Publications

Available from International Telecommunications Union, Place des Nations, 1211 Geneva 20, Switzerland, Tel: +44-22-730-5111, http://www.itu.int/publications/default.aspx.

ITU-T G.992.1 Asymmetric digital subscriber line (ADSL) transceiver

ITU-T G.993.1 Very High Speed Digital Subscriber Line (VDSL) Transceivers

ITU-T G.993.2 Very High Speed Digital Subscriber Line Transceivers 2 (VDSL2)

2.1.4 UPA Publications

Available from Universal Powerline Association, 3 Bridge Street, Kings Cliffe, Peterborough, UK, PE8 6XH, Tel: +44(0)1780-470003, http://www.upaplc.org.

OPERA Specification Part 1 - Technology

OPERA Specification Part 2 - System

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Aerospace Technical Report.

2.2.1 SAE Presentations and White Papers

These papers are posted on the SAE AS-1A4 web page under Reference Documents.

"An Investigation into Using the MIL-STD-1553 Wire Bus at the AS-1773 20Mbps Data Rate", White Paper by D. Slocum, UTMC, December 2000

"Signaling Techniques for High-Speed Data Transmission over Existing AS15531 Networks", White Paper by F. Trans, Mobile Dynamics, April 2000

"The Use of Discrete Multi-Tone (DMT) Signaling for Data Transmission on Existing AS15531 Networks", White Paper by B. Graber, SBS Technologies, August 1998

"Continuing Communications Technology Studies into Enhanced Data Throughput Capabilities on Existing AS15531 Cable", Presentation by B. Graber, SBS Technologies at SAE AS-1A, April 2000

"High Performance and Cost Effective Avionics Upgrade Approach" by W. Wilson, ASC/ENAS, United States Air Force, Wright-Patterson Air Force Base, william.wilson@wpafb.mil.af, July 2002

"Ensuring Viable Combat Avionics Bandwidth Extension Using Mil-Std-1553 Interface", by W. Wilson ASC/ENAS, United States Air Force, Wright-Patterson Air Force Base, william.wilson@wpafb.mil.af, presentation given to SAE AS-1A, July 2002

2.2.2 Industry White Papers and Articles

ASSC/110/2/85 Draft 1, Study of Maximum Signalling Speed for Def Stan 00-18 (Part 2)/US MIL-STD-1553B Data Buses, February 1997

ASSC/110/2/97 Draft 1, Further Study of Maximum Signalling Speed for Def Stan 00-18 (Part 2)/US MIL-STD-1553B Data Buses, March 1998

ASSC/110/2/111 Draft 1, Continued Study of Maximum Signalling Speed for Def Stan 00-18 (Part 2)/US-MIL-STD-1553B Data Buses, February 1999

ASSC110/5/2 Issue 2, Engineering Bulletin on the Operation of Def Stan 00-18 (Part 2)/US MIL-STD-1553B Data Buses at Enhanced Data Rates, June 2000

ERA Report 2006-0010, Study of Maximum Signalling Speed for Def Stan 00-18 (Part 2)/US MIL-STD-1553B Data Buses, December 2005 (a compilation of the 4 ASSC papers listed above)

"Extending MIL-STD-1553 bandwidth: a study of impairments, EMI, and channel capacity" by M. Hegarty, Data Device Corporation, hegarty@ddc-web.com, April 2004

"High Performance 1553" by M. Hegarty, Data Device Corporation, hegarty@ddc-web.com, April 2005

"Netopia and the Standardization of VDSL2" by P. Simmons, Netopia Inc., http://www.netopia.com/products/technologies/vdsl2_technical_brief.pdf

"OPERA Technology White Paper", by the OPERA Consortium, http://www.upaplc.org, February 2006

"1553, Still a Key Standard" by C. Adams, Avionics Magazine, January 2000

"Data Communications Pumping the Bus" by C. Adams, Avionics Magazine, December 2003

"1553 Ever Faster," by C. Adams, Avionics Magazine, December 2004

"Backgrounder", Edgewater Computer Systems Inc., April 2006,
http://www.edgewater.ca/downloads/Edgewater.Wiredbackgrounder.pdf

"Test Report on the F-15 Flight Demonstration of HyPer-1553™ Technology", by T. Decker, decker@ddc-web.com, and S. Wilson, steven.h.wilson@boeing.com, April 2006

2.3 Definition of Terms

LEGACY 1553: The traditional method of sending and receiving data at 1 Mbps using bi-phase Manchester encoding and command/response protocol defined in MIL-STD-1553.

HIGH PERFORMANCE 1553: A method of sending data over a MIL-STD-1553 data bus infrastructure at substantially higher data rates than MIL-STD-1553. Other names for High Performance 1553 include: HP-1553, Extended 1553, Fast 1553, High Speed 1553, MIL-STD-1553B Notice 5 and MIL-STD-1553C.

CONCURRENT OPERATION: Operation of both Legacy 1553 and High Performance 1553 on the same bus at the same time.

DIGITAL SUBSCRIBER LINE: A technology designed to transmit digital data over telephone lines by utilizing frequency bands unused by analog voice communication.

POWERLINE COMMUNICATIONS: A technology designed to transmit digital data over electric power lines by utilizing frequency bands unused by AC power.

2.4 Abbreviations

ADSL	Assymetric DSL
ANSI	American National Standards Institute
ASSC	Avionics Systems Standardization Committee
BC	Bus Controller
CAP	Carrier-less Amplitude Phase
DMT	Discrete Multitone
DSL	Digital Subscriber Line
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
ETSI	European Telecommunications Standards Institute
FEC	Forward Error Correction
HDSL	High bit rate DSL
HP-1553	High Performance 1553
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol

ITU International Telecommunication Union

Kbps Kilobits per second

LRU Line Replaceable Unit

Mbps Megabits per second

MT Monitor Terminal

OFDM Orthogonal Frequency Division Multiplexing

OFP Operational Flight Programs

OPERA Open PLC European Research Alliance

PLC Powerline Communications

QAM Quadrature Amplitude Modulation

QoS Quality of Service

RT Remote Terminal

VDSL Very high speed DSL

WRA Weapon Replaceable Assembly

3. BACKGROUND

The terms used in this report are consistent with MIL-STD-1553. MIL-STD-1553 is used for control and monitor of interoperable avionics subsystems found on thousands of military aircraft, ground vehicles, and stores. Each terminal on the bus is configured as Bus Controller (BC), Remote Terminal (RT), or Monitor Terminal (MT). Only one active Bus Controller is allowed at any given time.

3.1 The MIL-STD-1553 Bus

The MIL-STD-1553 bus is constructed as a linear tapped bus. The main transmission line is terminated at both ends with a resistor value that matches the nominal 78 ohm characteristic impedance of the cable. The stub connections appear as unterminated bridge taps on the main transmission line and are either direct coupled or transformer coupled, both of which are required to have isolation resistors. Direct coupling requires 55 ohm resistors while transformer coupling requires a resistor with the value of 0.75 Zo or 58 ohms for a cable impedance of 78 ohms. Figure 1 shows the MIL-STD-1553 terminal connections and configuration of the bus.

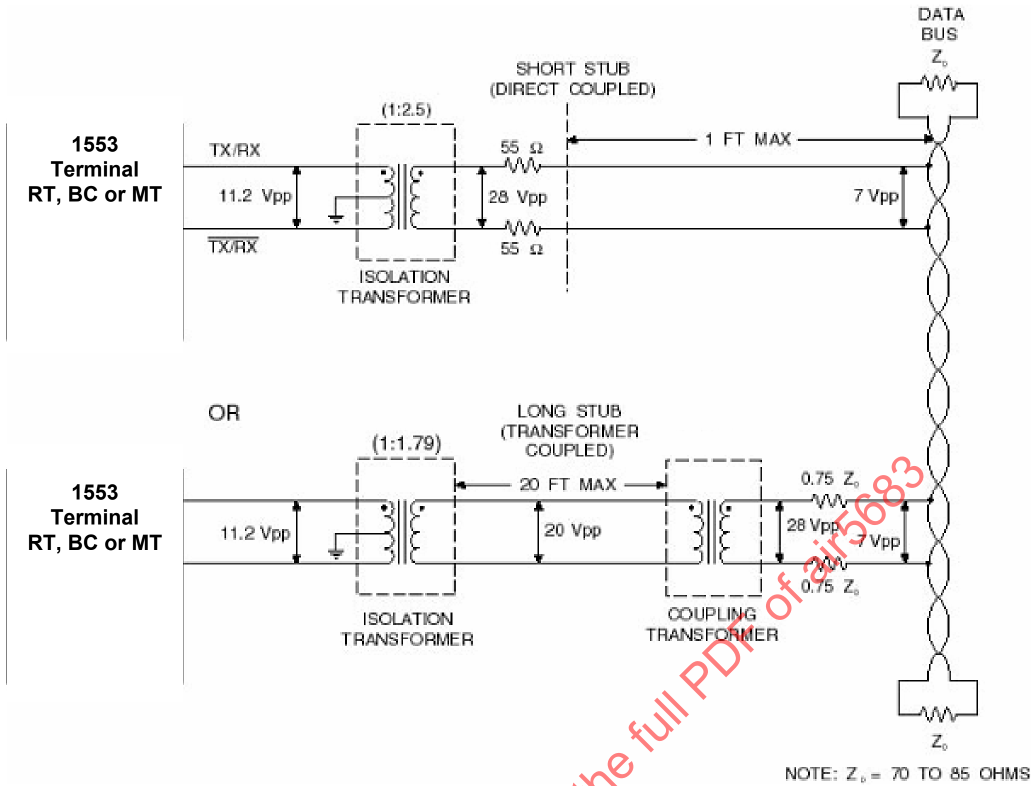

FIGURE 1 - MIL-STD-1553 TRANSFORMER AND DIRECT COUPLING

The coupling transformers are a key architectural element of 1553. The purpose of the coupling transformers is to match the impedance of the stub when an LRU is transmitting onto the main bus and to reduce the impedance mismatch on the main bus due to the stub impedance. The coupling transformers are designed to pass one megabit per second 1553 data. These transformers are not specified to carry higher frequency signals and their ability to do so varies from one manufacturer to another.

3.2 Potential Applications for High Performance 1553

There are many potential application areas for HP-1553. The most likely places for this technology to be used are where it is difficult or too expensive or time-consuming to replace or add wiring in existing platforms. In some platforms, the added weight of the additional wiring may be undesirable. Here are some possible applications:

3.2.1 Weapons and Sensors

One area where it is difficult to replace or add wiring is in the fuselage and wings of fighters and bombers. The current weapons interface installed in most platforms is MIL-STD-1760. MIL-STD-1760 is a well established Aircraft-to-Store interface. MIL-STD-1760 utilizes the 1 Mbps MIL-STD-1553B digital multiplex bus. Although a 1 Mbps bus is adequate for the transmission of basic command/status information, it will not be adequate for many of today's Network Centric applications. For example, current "smart" missiles and guided bombs require alignment data and targeting information from the Stores Management Computer at initialization. This can be accomplished with 1 Mbps MIL-STD-1553, but it can take an excessive amount of time particularly if there is a fully loaded compliment of smart stores on board. It may also take an unacceptable amount of time (i.e., latency) to provide new targeting coordinates during flight, should that become necessary. By employing HP-1553 on the existing MIL-STD-1760 interface, a significant amount of time could be saved downloading this information, and much more data could be transmitted in the same amount of time.

As evidence of the need for additional bandwidth in weapons interfaces, there is another Task Group within the SAE AS-1 Aircraft Systems & Systems Integration Committee (the AS-1A2 Networks and Requirements Task Group) working on a high speed extension to MIL-STD-1760. While the AS-1A2 and AS-1A4 Task Groups have common objectives, there are some important differences. High Speed 1760 will employ a modified version of Fibre Channel operating at 1 Gbps over copper coax (see AS5653). The topology of High Speed 1760 will be a mesh fabric which has throughput advantages over a linear tapped bus. However, applying High Speed 1760 to existing aircraft will usually require that new wiring be added in aircraft, pylons, and stores. For that reason, the use of High Speed 1760 may be limited to applications on new aircraft and stores where the new wiring can be much more easily added while they are being manufactured.

NOTE: HP-1553 should not be confused with Enhanced Bit Rate 1553 (EBR-1553). EBR-1553 is functionally similar to MIL-STD-1553B. EBR-1553 operates at 10 Mbps but it runs on a different physical layer (an RS-485 star topology). EBR-1553 does not transmit higher speed data over existing MIL-STD-1553B wires like HP-1553. EBR-1553 was developed by the AS-1A1 MIL-STD-1553 and Derivatives Task Group (see AS5652).

3.2.2 Digital Video/Imagery

A possible application for HP-1553 would be the transmission of digital video or imagery. Video and imagery can be very bandwidth intensive depending on the resolution and update rate. A 1 Mbps bus can be used to transmit digital images, but the loading on the bus and the latency resulting from the transfer time can become excessive. Compression techniques can be employed to reduce the file size and therefore the transfer time but that requires additional hardware or software and there is still added latency due to the time required to compress and decompress the image. In addition, some applications may not be able to use compression due to the loss of information in the video stream. HP-1553 would allow video or imagery to be transmitted uncompressed in much less time than Legacy 1553 providing higher image resolution and/or higher frame rates.

3.2.3 Communication Systems

With the advent of higher bandwidth RF links that will be employed in next generation radio systems, a 1 Mbps bus internal to the platforms will become a bottleneck. Many new platforms will employ COTS-based high speed networks such as 100BaseTx or 1000BaseT Ethernet for such applications, but many existing platforms are not equipped to handle such an interface. For those platforms that are only set up to support MIL-STD-1553, HP-1553 would be a good choice for extending the bandwidth to/from the communication system.

3.2.4 Memory Loader/Verifiers

Many avionics boxes fielded today have their Operational Flight Programs (OFPs) loaded and reloaded via MIL-STD-1553. The time required to load these boxes can already be tens of minutes. With larger and larger programs being created and more memory is being installed in the boxes, this problem is expected to get worse. A logical choice for speeding up the load time for these boxes would be to employ HP-1553. OFP load times could be significantly reduced without having to replace or add wiring in the platform.

3.2.5 General Avionics

Sometimes a legacy 1553 bus becomes so heavily loaded with data that the addition of more messages is not possible because it would push the loading over 100%. In these situations HP-1553 can provide an avenue for incremental growth without having to add another MIL-STD-1553 bus or implement a whole new high speed network. Since High Performance 1553 traffic will be invisible to regular MIL-STD-1553 traffic and vice versa, the existing Avionics will be completely unaware of any HP-1553 traffic that is added. This allows the system designer the ability to add new capabilities to the bus without having to re-architect or repartition the existing bus. This can save enormous amounts of time and money in upgrading legacy platforms that are at or near data carrying capacity on their current bus structure.

It is worth noting that adding HP-1553 to an existing Avionics box does not require any additional I/O pins or front panel space, which could be problematic for boxes that need a new higher speed interface but have little or no spare I/O on their front panels. Many times these boxes will have outlived their usefulness and when a new high-speed interface is needed the entire box must be replaced. Other times the box may be able to accommodate a new interface but it does not have enough spare I/O or the available I/O is not the right kind.

3.3 Quantitative Capability Objectives

The quantitative capability range (i.e., goals) being sought by different applications for High Performance 1553 is summarized in Table 1.

TABLE 1 - HIGH PERFORMANCE 1553 QUANTITATIVE OBJECTIVES

Capability	Target Range	Units
Data Rate	20 – 500	Mbps
Payload Efficiency	> 90	%
Bit Error Rate	$< 10^{-12}$	Errors per total Bits
Latency	< 100	µsec
Address Range	Up to 256	Terminals per Bus

4. COMMERCIAL TECHNOLOGIES USED FOR CARRYING HIGH SPEED DATA

This section provides a brief overview of various modulation schemes that have been used and transmission standards that have been developed in the telecom industry for expanding the data carrying capability of telephone, cable TV and power lines. Properly applied, these techniques may be able to provide a substantial increase in the data carrying capability of MIL-STD-1553 buses.

4.1 Modulation Schemes

4.1.1 Quadrature Amplitude Modulation (QAM)

QAM is a popular line code that is used in both single carrier and multi-carrier systems. The term “carrier” in this context means “bandwidth channel”.

In QAM, there are two signals, each having the same frequency but differing in phase by 90 degrees (one quarter of a cycle, from which the term “quadrature” arises). One signal is called the I (In-phase) signal, and the other is called the Q (Quadrature) signal. Mathematically, one of the signals can be represented by a sine wave, and the other by a cosine wave. The two modulated signals are combined at the source for transmission. At the destination, the signals are separated, the data is extracted from each, and then the data is recombined into the original information.

The most common forms of QAM in telecom applications are 64-QAM, 128-QAM, 256-QAM and 1024-QAM where the number represents the number of bits per symbol. The higher the number the higher the data rate.

4.1.1.1 Carrier-less Amplitude Phase (CAP)

CAP modulation describes a version of QAM in which data is modulated on a single carrier (i.e., bandwidth channel) that is then transmitted. The carrier itself is suppressed before transmission (it contains no information and can be reconstructed at the receiver), hence the adjective "carrier-less."

4.1.1.2 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a multi-carrier technique and as such it uses many small bandwidth channels to convey the encoded information. It is sometimes called Discrete Multi-Tone (DMT). The carriers are spaced apart at precise frequencies. This spacing provides the "orthogonality" in this technique which prevents the demodulators from seeing frequencies other than their own.

NOTE: A single carrier system uses one large bandwidth channel with a high symbol rate. A multi-carrier system uses many small bandwidth channels, each having a lower symbol rate. The aggregate throughput of each system is the same. The trade-off between the two methods has to do with implementation issues (inter-symbol interference, noise susceptibility, EMI, etc.). The single-carrier system is more sensitive to time domain distortion while the multi-carrier system is more sensitive to frequency domain issues.

4.2 Telecommunication Standards

This section contains a brief description of some of the standards that have been defined for transmitting high speed data over telephone lines and power lines.

4.2.1 Digital Subscriber Line (DSL)

High-speed-data-over-telephone-line standards are known as Digital Subscriber Line (DSL) standards. They are often classed as “xDSL” standards where x is a placeholder for a specific DSL standard (ADSL, HDSL, VDSL, etc.). Early DSL standards were issued by ANSI, ETSI, and the ITU. The current standards are issued by the ITU.

4.2.1.1 Asymmetric Digital Subscriber Line (ADSL)

The baseline ADSL standard is ITU-T Recommendation G992.1. ADSL divides up the available frequencies in a telephone line on the assumption that most Internet users look at, or download, much more information than they send, or upload. Under this assumption, if the connection speed from the Internet to the user is three to four times faster than the connection from the user back to the Internet, then the user will see the most benefit (most of the time).

CAP was the initial modulation scheme employed by ADSL; however, DMT was chosen for the first ITU standard in 1996. All modern installations use DMT. Upstream traffic utilizes frequencies between 25.875 and 138 kHz while downstream uses 138 to 1104 kHz.

The service limit for ADSL service is typically about 2 to 3 miles from the central office. At the extremes of the distance limits the signal quality decreases and the connection speed goes down. ADSL customers far from the central office may see speeds far below the promised maximums, while customers nearer the central office have faster connections. ADSL technology can provide maximum downstream (Internet to customer) speeds of up to 8 Mbps at a distance of about 5,000 feet, and upstream speeds of up to 640 Kbps. In practice, the best speeds widely offered today are 1.5 Mbps downstream, with upstream speeds varying between 64 and 640 Kbps.

A newer version, ADSL2 (ITU-T Recommendation G992.3/4) can deliver 12 Mbps downstream up to 8,000 feet, while ADSL2+ (ITU-T Recommendation G992.5) delivers 24 Mbps at distances up to 5,000 feet.

4.2.1.2 Very High Speed Digital Subscriber Line (VDSL)

The baseline VDSL standard is ITU-T Recommendation G993.1 released in 2004. VDSL uses up to 4 different frequency bands, two for upstream and two for downstream. The frequencies range is 200 kHz to 12 MHz.

The modulation technique is either QAM or DMT which are not compatible, but have similar performance. DMT is more commonly used.

VDSL provides higher bit rates than ADSL although it does not have quite the reach of ADSL. VDSL can be configured for symmetric or asymmetric transmissions. At 1,000 feet, asymmetric bit rates of 52 Mbps downstream and 6 Mbps upstream are achievable. Those bit rates drop to 26 Mbps and 3 Mbps at 3,000 feet.

For symmetric transmission, the one-way maximum bit rate is 26 Mbps at 1,000 feet and 13 Mbps at 3,000 feet.

4.2.1.3 Very High Speed Digital Subscriber Line 2 (VDSL2)

VDSL2 is an enhancement to VDSL and is defined by ITU-T Recommendation G993.2. It was approved in May, 2005. VDSL2 is considered to be a key enabler for what the telecom industry calls the “triple play” (video, voice, and data).

VDSL2 permits the transmission of asymmetric and symmetric data with one-way data rates up to 100 Mbit/s on twisted pair wires using frequencies up to 30 MHz. These rates drop off quickly as length increases, but below 3,000 feet, they are significantly higher than VDSL or ADSL2+.

Over short distances (a few hundred feet) both upstream and downstream data rates are 100 Mbps. At 1,000 feet, upstream and downstream data rates fall to around 90 Mbps. At 2,000 feet, downstream is about 50 Mbps, while upstream is about 35 Mbps. At 3,000 feet the downstream data rate is still 30 Mbps while the upstream data rate is 10 Mbps.

ITU-T G993.2 specifies DMT modulation; however, it is worth noting that Japan and Korea have adopted a QAM-based system and they are much further along in their development.

4.2.2 Powerline Communications (PLC)

There is a recently announced specification for achieving broadband connectivity via electric power lines. The technology is generically known as Powerline Communications (PLC). An industry consortium, the Universal Powerline Association (UPA), was announced in January, 2005. The UPA is responsible for preparing PLC interface specifications which will then be presented to standards bodies such as IEEE or ETSI. The baseline specification was approved in January, 2006. The specification was prepared by a group of European companies known as the Open PLC European Research Alliance, or OPERA. The resultant specification is the OPERA Specification Part 1 - Technology, and the OPERA Specification Part 2 - System.

PLC networks utilize OFDM in the frequency range of 2 to 30 MHz. The maximum data rate is 200 Mbps. The frequency is sub-divided into 1536 sub-bands with 2 to 10 bits per symbol. PLC uses Reed-Solomon FEC, data encryption, scrambling, and 4-D Trellis Coded Modulation.

PLC uses a Master/Slave architecture to control the traffic on the bus. A token-passing scheme is employed to eliminate collisions. QoS provisions are built-in through the use of 8 “service classes” or Priority levels. This enables deterministic behavior on the wire, i.e., guaranteed bandwidth and latency. There is a Convergence Layer defined to translate between Ethernet (IP) packets and the lower level PLC symbols.

Applications typically include distribution of audio/video and broadband services from central service points to houses, apartment complexes, business buildings as well as in-home distribution. Low voltage (to the house) wiring can carry 200 Mbps signals between 200 to 500 m. The leading consumer products supplier is Corinex located in Vancouver, BC. The two leading chipsets suppliers are Intellon located in San Jose, CA and Design of Systems on Silicon (DS2), located in Valencia, Spain. DS2 products offer the 200 Mbps throughput with programmable bandwidth, latency allocation and frequency notching (to avoid undesirable frequency bands) and multicast functionality for both video and audio.

NOTE: There are other industry groups working on PLC besides OPERA. According to the UPA website, the UPA has initiated discussions with the HomePlug Alliance and the CE Powerline Communication Alliance.

5. RESEARCH IN TRANSFERING HIGHER SPEED DATA OVER LEGACY 1553.

5.1 Early Research

From approximately 1998 to 2002, there were 4 different approaches evaluated to see if it was possible to send data at higher rates over existing MIL-STD-1553 wires. These approaches are summarized below. The first two were “conservative” attempts to send data using the same waveform, word formats and protocols as MIL-STD-1553 just clocked at a higher rate. The last two were more “radical” attempts at transmitting data at much higher speeds over unused frequency bands using modulation techniques borrowed from the telecom industry.

An important distinction between the conservative and radical approaches is that while both methods retain backward compatibility with the 1 Mbps bus, the conservative approach relies on time-sharing of the 1 Mbps bus while the radical approach works simultaneously with the 1 Mbps bus.

5.1.1 Over Clocked 1553 #1 – ERA Technology and ASSC Data Interfaces Subcommittee

Beginning in the late 1980s, a European company, ERA Technology, recognized the advantages of carrying higher speed data over existing MIL-STD-1553B style[1] cable plants. ERA Technology, in conjuction with the Avionics Systems Standardization Committee (ASSC), began compiling information and test results from several companies including C-MAC, MCE, Raychem and Amphenol. The goal was to provide a moderate increase in speed (the target was 5 Mbps) with no changes required in the bus and only minimal changes required in the terminal hardware.

NOTE: In their literature the ASSC acknowledged that the SAE Next Generation 1553 Task Group was investigating applying advanced modulation schemes borrowed from the telecom industry to achieve data rates of 100 Mbps or higher, but using these techniques would require more radical changes to the terminal hardware.

The technique investigated by the ASSC can be thought of as “over clocked 1553”, but they recognized that simply increasing the clock rate of the encoder/decoder and modifying the filter and slew rate of the transceiver are not the only factors that influence increased speed. There are issues with all the elements of the existing bus hardware that have to be taken into consideration to provide the transition to higher speed. These elements include couplers, bus cable, stubs, and isolation transformers.

The transformer in the coupler may be the most important element in the bus network regarding their effect on signal waveform. Testing showed that a small insertion loss is exhibited by the transformer up to 2 MHz with varying increases in attenuation as the frequency was increased above this point. It was noted that the various couplers from different manufactures had differing frequency responses which would fall off by 2.5 dB between 1 and 5 MHz, while others had flat responses to much higher frequencies. The testing indicated that a diminished insertion loss of the coupler could still work in some networks up to 5 Mbps but was very dependent on the bus configuration (e.g., bus length, number and length of stubs).

According to the ASSC, most protocol devices in terminals would function adequately at 5 MHz simply by increasing the clock rate; however, transceivers designed to work at 1 MHz are not likely to work at higher speeds. Modifications to both the transmitter and receiver would be necessary. The rise and fall times would need to be optimized for the new signalling rate and the filter capacitor on the receiver would need to be changed.

These studies and tests indicated that 2 MHz should be easily achievable with only minor modifications to the filter in the transceiver and with properly designed transceivers, 5 MHz could be achieved. One company, National Hybrid, has a terminal on the market today that operates at 2 MHz.

For more information, refer to the ASSC reports listed in 2.2.2.

5.1.2 Over Clocked 1553 #2 – Aeroflex UTMC

The second independent evaluation was accomplished by Aeroflex UTMC. For this test, a dual 1 Mbps/20 Mbps AS1773 protocol device (UT6916 ASCENT) was utilized driving a 300 foot bus. Since this protocol device was designed for a fiber implementation, the test bed required custom drivers and receivers to drive the 78 Ω copper medium.

The test results were mixed. In the absence of noise, there was no problem in receiving the 20 MHz periodic pulse at the end of the data bus. There was 20 dB of signal attenuation from the transmit end of the bus to the receive end of the bus. This attenuation was largely due to the data bus cable. Manchester bi-phase encoding was used, but was unsatisfactory for this application due to a low signal-to-noise ratio resulting in an unacceptable Bit Error Rate. Also, at the 20 Mbps data rate the shape of the digital data became unrecognizable due to inter-symbol interference. It was felt that most of the problems with the transceivers could be overcome with adaptive filtering and DSP components.

[1] In the UK, the Ministry of Defense standard Def Stan 00-18 (Part 2) is equivalent to MIL-STD-1553B.

Aeroflex suggested several design enhancements that could be used to improve the data rate and quality of the signal such as shaping the impulse response of the channel with a low pass preconditioning filter. While testing has proven that over clocking is feasible, it has yet to be demonstrated how their design enhancements can be implemented in production hardware.

For more information, refer to the White Paper by D. Slocum listed in 2.2.1.

5.1.3 PAM-4 Modulation – Mobile Dynamics

This was the first to attempt to transfer data over frequency bands well above the band used by Legacy 1553. The system used a baseband bandwidth carrier of 30 MHz that was modulated utilizing PAM-4 (Pulse Amplitude Modulation) encoding and equalization filtering on the receive end. If the equalization filter were not utilized inter-symbol interference and crosstalk due to frequency selective attenuation would have rendered the signal unreadable.

A demonstration was performed on a worst case 1553 network. A PAM-4 encoded transmit signal (a clock signal from a BER tester) was induced at one end of the bus. The signal was received at the other end of the bus and sent back to the BER tester where it was decoded. The highest results achieved during this kind of testing was >120 Mbps with a BER of 10^{-10}.

The project was disbanded due to lack of funding before additional testing could be accomplished. Although there may have been some promise of a working system it was never tested concurrently with a MIL-STD-1553B signal nor was it demonstrated in the presence of EMI.

For more information, refer to the White Paper by F. Trans listed in 2.2.1.

5.1.4 xDSL – SBS Technologies

The last evaluation was a test of xDSL technology performed by SBS Technologies. Two different kinds of DSL modems were tested. The test setup was as follows:

One hundred feet of MIL-C-17 cable was used to connect the modems. The modems were connected to the bus via bus couplers and 7.5 feet of the same cable as the main bus. Two standard desktop PCs were connected to the modems, one as a server, the other as a client. A 1553B bus analyzer/generator was also connected on each end of the bus to monitor traffic and to see if the DSL traffic had any effect on the MIL-STD-1553B traffic.

Raw audio/video data was transmitted from the server and reproduced on the client computer.

The first test was conducted using CAP/QAM modems, modulated at 386.7kBaud. These modems successfully passed data at a rate of 2.1 Mbps, full duplex (2.1 Mbps in each direction simultaneously).

The high speed (DSL) traffic and the 1553B traffic were first tested independently. The DSL traffic went undetected by the 1553B analyzer. The 1553B traffic was intermittently detected by the modem but did not cause the modem to reset.

When the DSL and 1553B traffic were tested simultaneously, the telecom modems reported a significant number of errors whenever the 1553B transactions were scheduled at rates above 10 Hz.

The second test was conducted with ADSL modems using Discrete Multi-Tone (DMT). This system is full-duplex although in an unbalanced fashion. The upstream data rate (from client to server) was 760 Kbps while the downstream data rate was 10.1 Mbps.

As before, the high speed (DSL) traffic and the 1553B traffic were first tested independently. The DSL traffic occasionally would flag a protocol error on the 1553B analyzer possibly due to an attempt to lock onto the signal. This was probably due to some sub-channels being too close to the 1 Mbps base bands. The 1553B traffic was detected by the ADSL modems of a sufficient nature to cause the modem to reset the link. Given this outcome, there was no point in testing the DSL and 1553B traffic simultaneously.

This test setup (with the CAP/QAM modems) was tested in an EMI chamber. It was determined that the shielding effectiveness to shield emissions was acceptable to 25 MHz, and that the output power would have to be increased to make the system less susceptible to incoming (ingress) EMI.

It was apparent that this approach has potential to allow higher speed transmission on legacy 1553B networks. There are several things that could have been done with this setup to investigate if it could be made to work on a multi-drop bus like 1553B but the program was shelved due to lack of funding.

For more information, refer to the White Paper by B. Graber listed in section 2.2.1.

5.2 Ongoing Research

From about 2002 to the present, two companies, Data Device Corporation (DDC) and Edgewater Computer Systems, Inc. (Edgewater), have been doing extensive research into transmitting data at much higher rates over existing MIL-STD-1553 cables.

5.2.1 Edgewater Computer Systems, Inc.

For many years Edgewater has been developing an Extended 1553 technology that will provide data rates up to 200 Mbps with a BER of 10^{-12} over existing MIL-STD-1553B cable plants while not impacting 1 Mbps 1553B traffic.

Edgewater conducted a detailed study and determined that commercial off-the-shelf DSL technologies such as CAP and DMT would not be suitable for the development of Extended 1553. Edgewater designed a system from scratch in order to achieve predictable and deterministic operation, immunity to electromagnetic interference, and electromagnetic compatibility, among other requirements. Edgewater's design is a multi-carrier waveform system that can readily adapt to the unpredictable channel variations of the 1553 data bus media. The waveform physical-layer protocol includes efficient line encoding and Forward Error Correction to achieve high throughput with low Bit Error Rates. Edgewater was instrumental in the preparation of MIL-STD-001553B (USAF) w/CHANGE 5, better known as "1553B Notice 5".

For more information, refer to the Backgrounder White Paper listed in 2.2.2.

5.2.2 Data Device Corporation

Beginning in 2003, DDC has been researching how to adapt DSL-based technologies to MIL-STD-1553B avionics buses. Their new technology, called HyPer-1553™, is based on single-carrier QAM. Based on analysis and measurements taken on a production F-15E, DDC believes data rates of 200 Mbps or higher are achievable with HyPer-1553, but the actual data rate that is realized on a given platform will depend on several factors including the length of the bus, the number of couplers, and the noise present.

In 2004, DDC teamed with Boeing and Honeywell to perform a flight demonstration of HyPer-1553 on an F-15. The demonstration occurred in December, 2005. During the demonstration, image data was transmitted between a rugged computer mounted in the forward equipment bay and a modified Joint Direct Attack Munition (JDAM) mounted on a wing pylon station. The results showed that data was transferred with no errors at 40 Mbps in parallel with 1 Mbps MIL-STD-1553B data. Data was also transferred at 80 and 120 Mbps on a second bus dedicated to the higher speed data.

For more information, refer to the Test Report listed in 2.2.2.

6. TECHNICAL DISCUSSION AND MEASUREMENT DATA

6.1 Elements of Data Carrying Capacity

The upper bound of the data carrying capacity on a given channel is governed by Shannon's equation:

$$C = BW \times \text{Log}_2(1 + \frac{S}{N}) \quad \text{(Eq. 1)}$$

where:

C = Capacity

S = Signal Level (at the receiver)

N = Noise Level (at the receiver)

BW = Channel Bandwidth (between the transmitter and receiver)

The Channel Bandwidth is determined by the MIL-STD-1553 couplers and interconnecting wire between the transmitter and receiver. Each of these elements are analyzed in 6.2. The Signal-to-Noise Ratio (SNR) that reaches the receiver is a function of the transmit signal level and the attenuation and noise in the channel. Signal level and noise are analyzed in 6.3 and 6.4, respectively.

The characterization data used in this section is based on testing and measurements done by Data Device Corporation. For more information, refer to the White Papers by M. Hegarty listed in 2.2.2.

6.2 Bandwidth Analysis of 1553 Bus Elements

A typical 1553B bus structure is shown in Figure 2. Assume the length of the main bus is 200 feet. The transmit data path that forms a channel between two transformer coupled 1553 terminals consists of: a twisted shielded stub cable from the transmitting terminal to the transmitting coupler, a twisted shielded bus cable from the transmitting coupler to the receiving coupler (passing through a number of bus couplers along the way) and a twisted shielded stub cable from the receiving coupler to the receiving terminal. Assume all of the couplers in Figure 2 are identical. The different terminology used for couplers (i.e., "transmitting", "receiving", and "bus" coupler) is used to differentiate the signal path of interest. Each of the elements along this transmission path have an effect on the overall characteristics of the channel and will be addressed in the following sections.

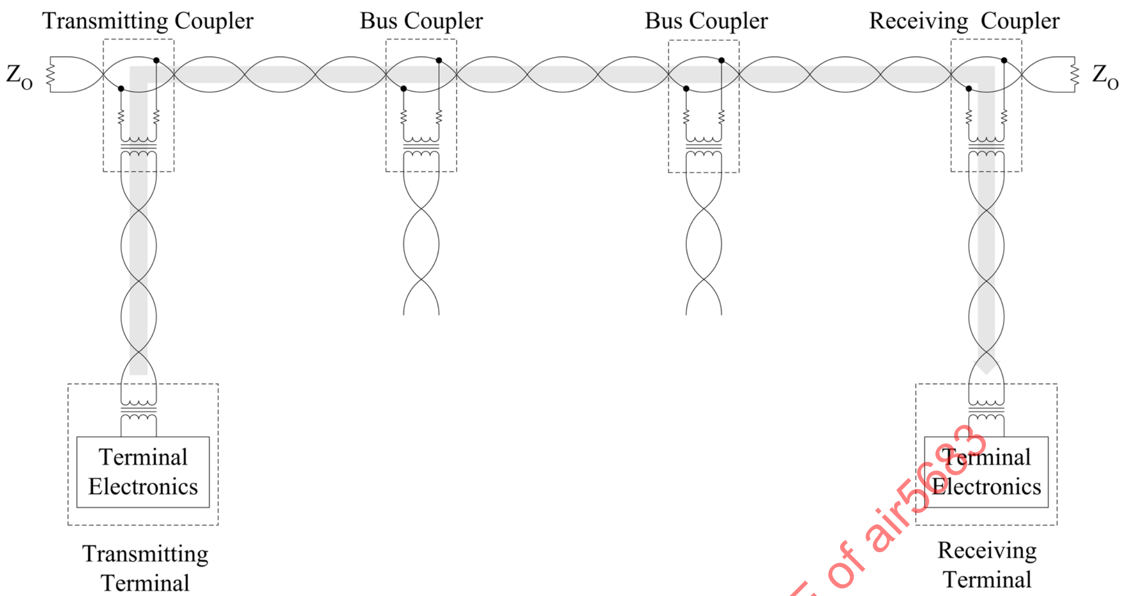

FIGURE 2 - TYPICAL MIL-STD-1553 BUS STRUCTURE

6.2.1 Wire

The frequency response of a 200 foot section of a typical cable used in 1553 buses is shown in Figure 3. It is important to note that this particular cable had a capacitance of approximately 21 pF/ft while MIL-STD-1553 allows for capacitance of up to 30 pF/ft so the attenuation of an installed Legacy 1553 bus may be worse than what is shown in Figure 3.

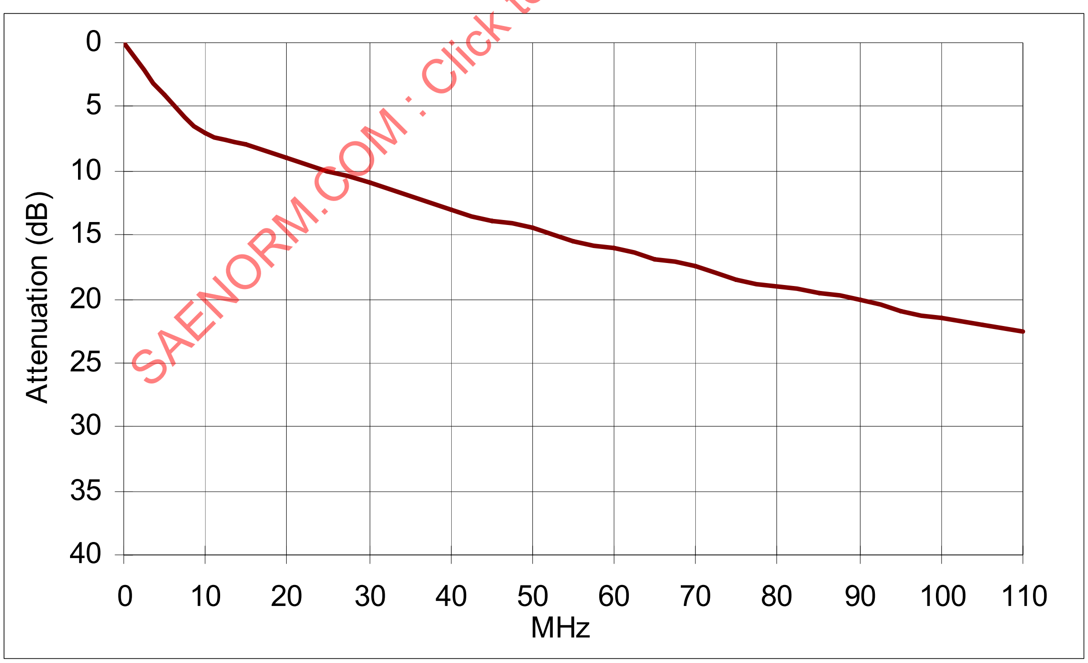

FIGURE 3 - ATTENUATION OF A TYPICAL 200 FT MIL-STD-1553 CABLE

Another parameter of interest is the impedance of the cable and how it will behave at higher frequencies. It has been determined through testing of many different cable plants that there is not a significant variance in performance from cable to cable even at higher frequencies. The couplers create a much more significant impediment and variance than the cable.

6.2.2 Couplers

A typical MIL-STD-1553 bus coupler consists of three ports. Two of the ports are used to connect the coupler to the main 1553 bus segments. The main 1553 bus effectively passes through the coupler between these two ports. The other type of port on a coupler is a stub connection. The stub connection uses a coupling transformer and series isolation resistors in connecting the stub port to the bus. Each of these couplers must be considered when analyzing the performance of the overall network.

6.2.2.1 Transmit Coupler

Figure 4 illustrates the test setup used to characterize the frequency response of a 3-stub transmit coupler. A test signal was applied to a stub port and the resulting signal delivered to the bus is measured at one of the bus ports. Tests were run on both single stub couplers and a three stub coupler. In addition, tests were run with a 2-foot stub cable and with a 20-foot stub cable in order to understand the impact of reflections on the stub. Figure 5 shows the Transmit Coupler insertion loss of a typical single stub coupler with a stub length of 2 and 20 feet.

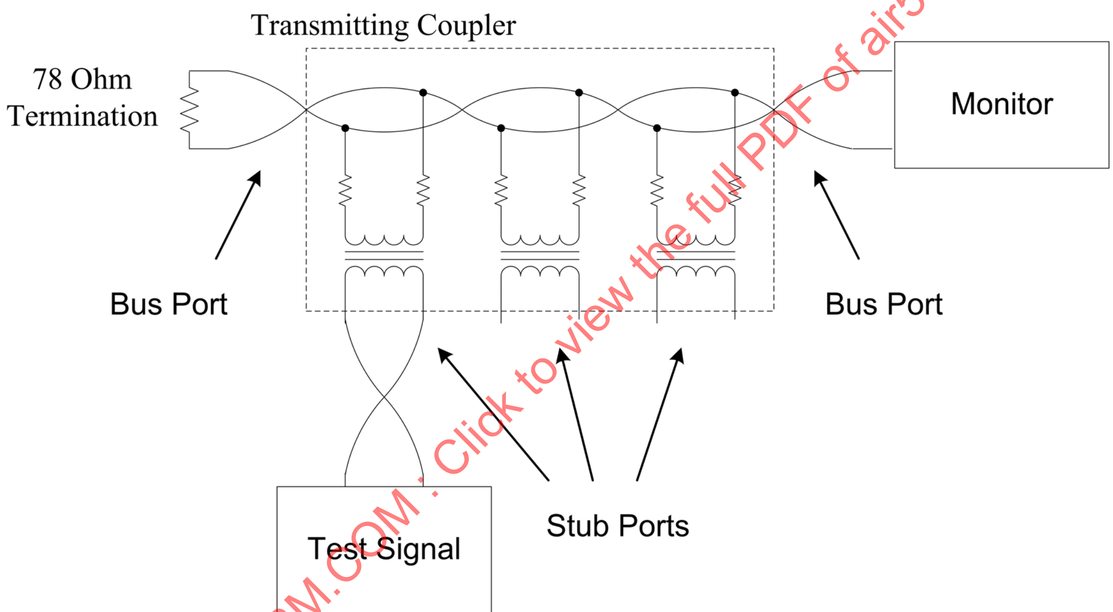

FIGURE 4 - MIL-STD-1553 TRANSMIT COUPLER TEST SETUP

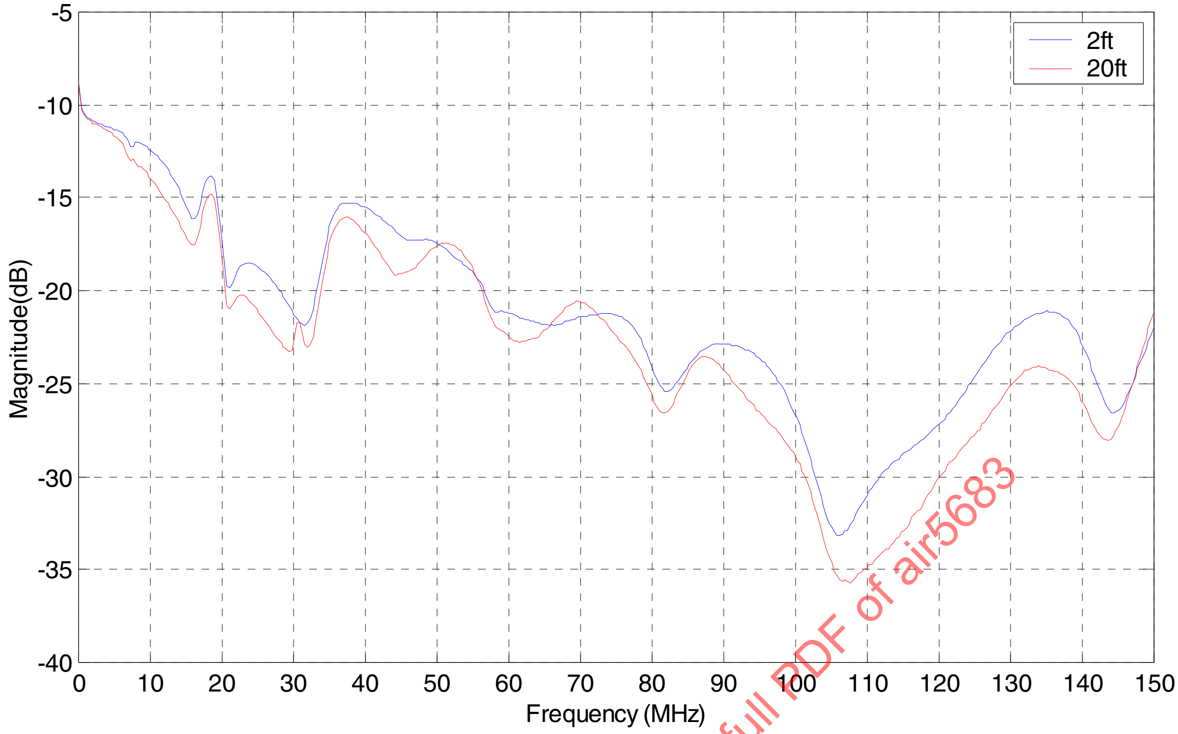

FIGURE 5 - TYPICAL MIL-STD-1553 TRANSMIT COUPLER INSERTION LOSS

The results of this test show that bandwidth below 20 MHz is very usable and that with proper equalization bandwidth out to 90 MHz is also usable.

6.2.2.2 Bus Coupler

A test was run to characterize the loss through a bus coupler. Both single stub and three stub couplers were tested. Figure 6 shows the test setup. The results of the test on a typical three stub coupler are shown in Figure 7.

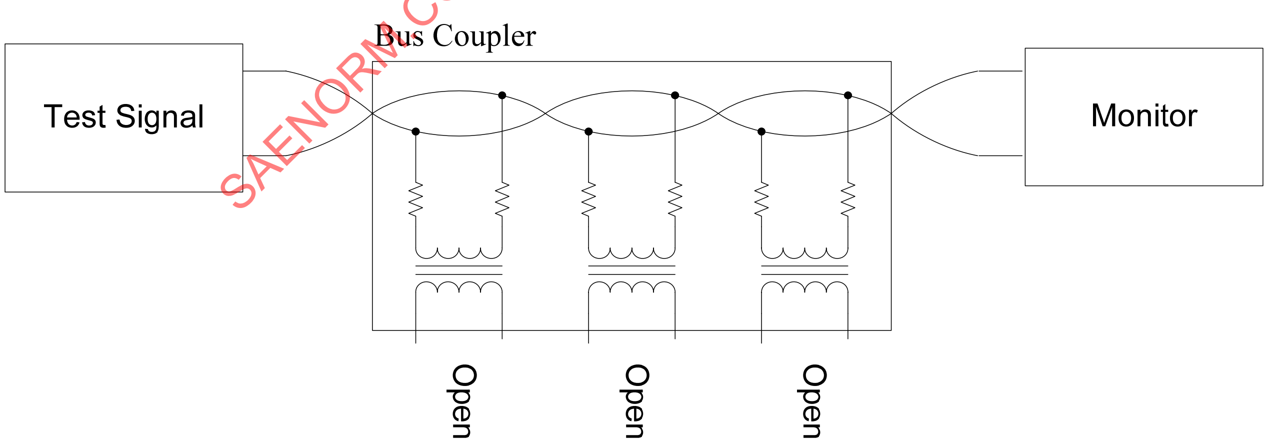

FIGURE 6 - MIL-STD-1553 BUS COUPLER TEST SETUP

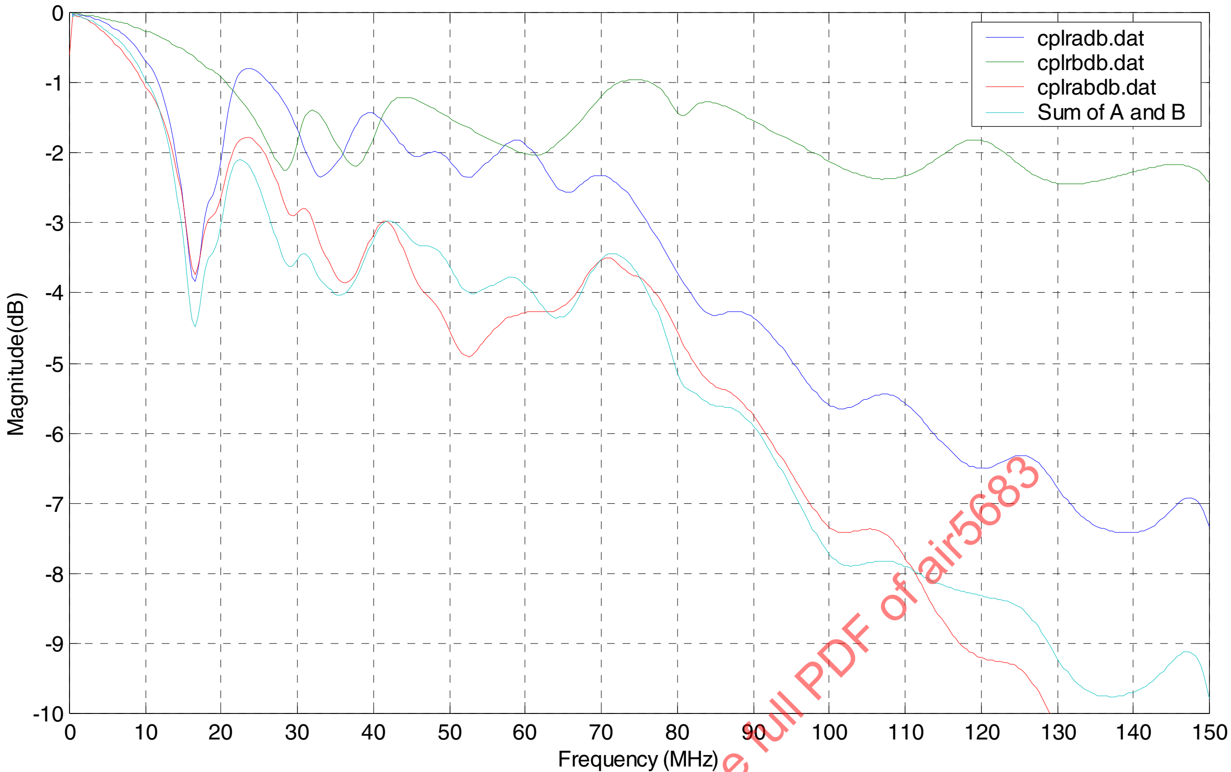

FIGURE 7 - TYPICAL MIL-STD-1553 BUS COUPLER INSERTION LOSS

In Figure 7, ‘Cplradb.dat’ is a three stub coupler, ‘cplrbdb.dat’ is a single stub coupler, ‘cplrabdb.dat’ is the single and three stub coupler in series, and ‘sum of a and b’ is the power sum of the single and the three stub coupler. The results of these measurements demonstrate that the individual coupler response curves can be added and that the loss can be approximated as 2 dB of loss per coupler in the range of 15 to 80 MHz.

6.2.2.3 Receive Coupler

Figure 8 illustrates the test setup used to characterize the frequency response of a receive coupler. A test signal is applied to the bus port and the resulting signal delivered to the stub is measured at one of the stub ports. The coupler shown in Figure 8 is a three stub coupler in which the unused stub ports were left open. Tests were run on both single stub and three stub couplers. In addition, tests were run with a 2 foot and 20 foot stub cables. Figure 9 shows the Receiver Coupler insertion loss of a typical single stub coupler for both 2 and 20 foot stub lengths.

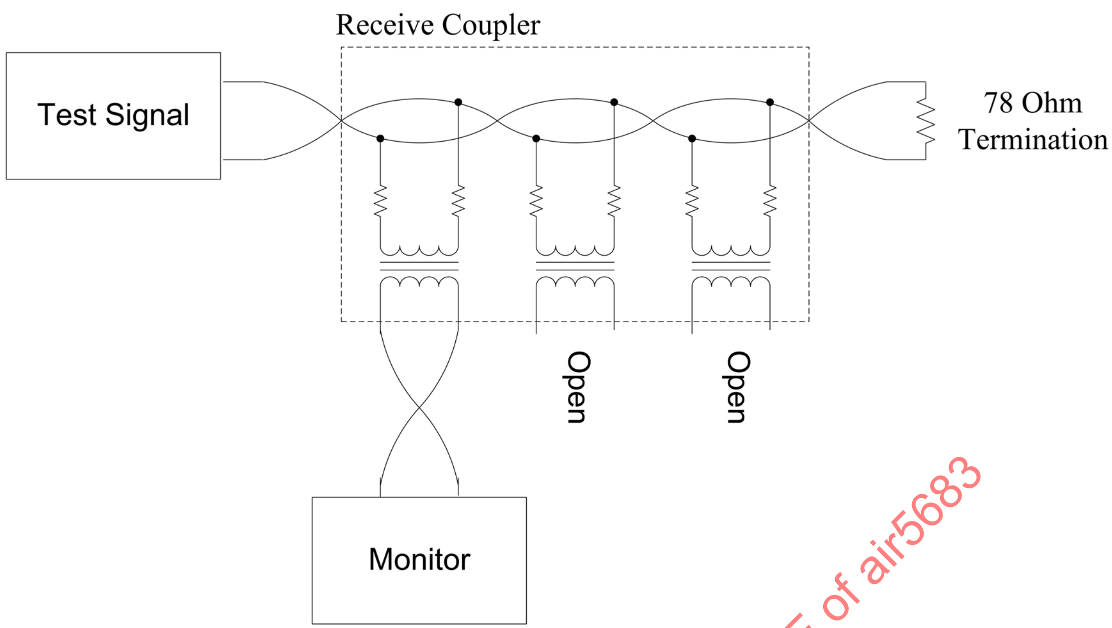

FIGURE 8 - MIL-STD-1553 RECEIVE COUPLER TEST SETUP

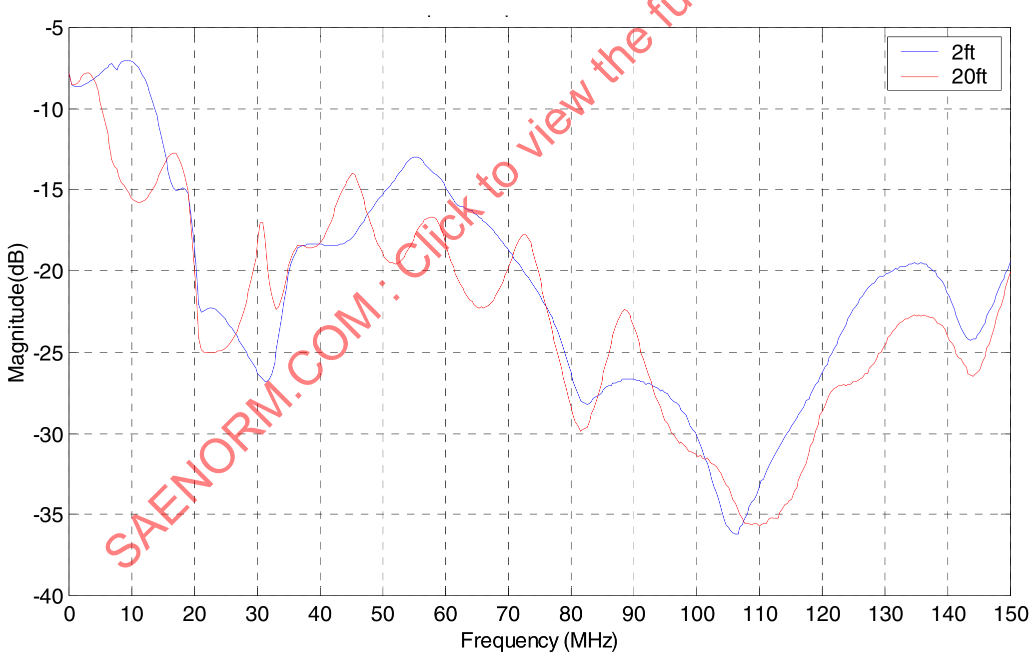

FIGURE 9 - TYPICAL MIL-STD-1553 RECEIVE COUPLER INSERTION LOSS

Reflections on the stub are significant because of the high impedance of the receiving terminal. The impact of these reflections is particularly significant in the range below 20 MHz which is the most attractive portion of the spectrum.

6.2.3 Simple 1553 Network Response

Combining the results from Transmit Coupler, Receive Coupler and 200 feet of wire gives the response for a simple 200 foot bus as shown in Figure 10. (There was no Bus Coupler in this particular test setup.)

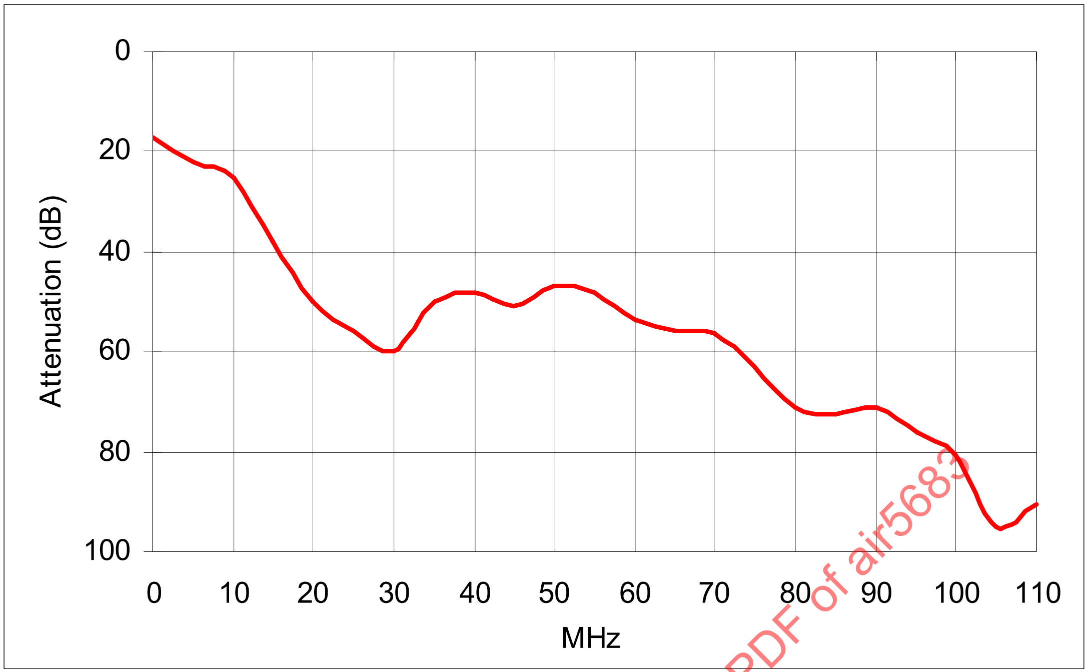

FIGURE 10 - SIMPLE 200 FT BUS NETWORK RESPONSE

Every MIL-STD-1553 bus installation will have a different frequency response characteristic. From testing of various network configurations and different hardware it has been demonstrated that one of the largest contributors to the variability of higher frequency performance in any given bus configuration is the high frequency characteristics of the MIL-STD-1553 couplers and the number of couplers between two communication nodes. To a lesser degree, the total length of the wire between two nodes has been shown to have an effect on the available bandwidth.

The highly non-linear frequency response of the channel dictates the need for some form of equalization on the channel. The size of the usable bandwidth will depend on the complexity of the equalizer. There appears to be at least 40 MHz of usable bandwidth available for a High Performance 1553 signal.

6.2.4 Additional Channel Bandwidth Impediments:

6.2.4.1 Aging Bus Infrastructure

It is anticipated that the wiring infrastructure may demonstrate additional bandwidth limitations as connectors age. The affect of aging wiring on available bandwidth has not been studied in detail.

6.2.4.2 EMI Filter Pins

Some subsystems include EMI-filter pins (or “transorbs”) in the LRU/WRA connectors that could produce an additional impediment to High Performance 1553 signals. No analysis of these pins has been done.

6.3 High Performance 1553 Signal Levels

It is desired to set the transmit signal level for an Extended 1553 waveform as high as possible to improve the signal-to-noise ratio and in turn allow higher bit rates and lower bit error rates. There are at least two important considerations to setting the maximum transmit signal level on the bus. First, it is important that the signal does not interfere with legacy 1 Mbps MIL-STD-1553 traffic and secondly, the radiated emissions from the MIL-STD-1553 wire must meet the appropriate sections of MIL-STD-461.

It has been shown that the egress EMI (Radiated EMI) concern is significantly more limiting to the maximum possible transmit amplitude of the HP-1553 signal than its affect on Legacy 1 Mbps MIL-STD-1553.

6.3.1 Radiated EMI Performance

6.3.1.1 Test Network

A sample 1553 network was constructed by Data Device Corp. and tested to the RE-102 radiated emissions electric field limits (10 kHz to 18 GHz) defined in MIL-STD-461. The test network consisted of a 300 foot bus with 18 bus couplers, sometimes referred to as a “deLong bus” (see Figure 11). The couplers were mounted to a copper ground plane sheet that was mounted on a sheet of plywood. The 1553 test network was placed on the ground plane of the EMI chamber and was covered with grounded foil. Sections of the network cable were individually lifted off the ground plane and placed on a rack with the appropriate spacing and elevation from the ground plane in order to expose that section to the antenna that detects the radiated electric field.

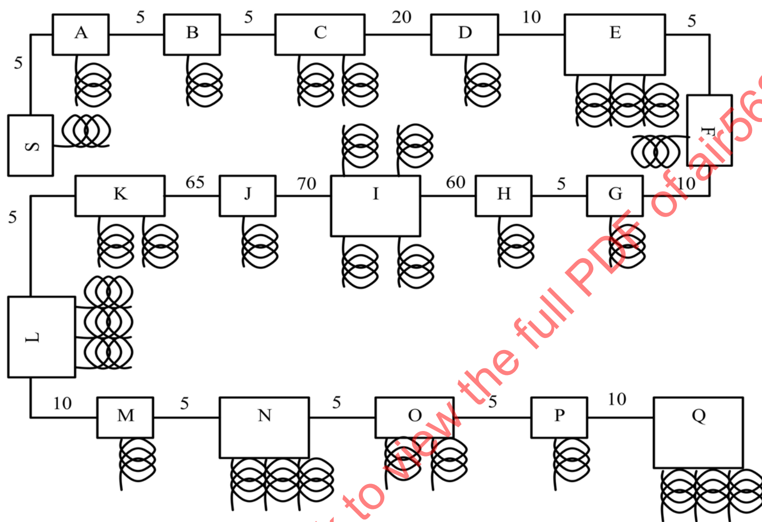

FIGURE 11 - EMI TEST NETWORK

EMI results will be significantly dependent on the spectral content of the transmitted signal. An arbitrary waveform generator was used to create signals that are representative of single carrier or multi-carrier modulation schemes that may be used to carry higher speed data on MIL-STD-1553 buses. The intent was to determine what the limits are on the power spectral density (PSD) in order to meet the MIL-STD-461 radiated emissions level. These PSD limits would then apply to any line code because they define the radiated field strength as a function of signal power density. The spectrum and amplitude of the test signal used is illustrated in Figure 12.

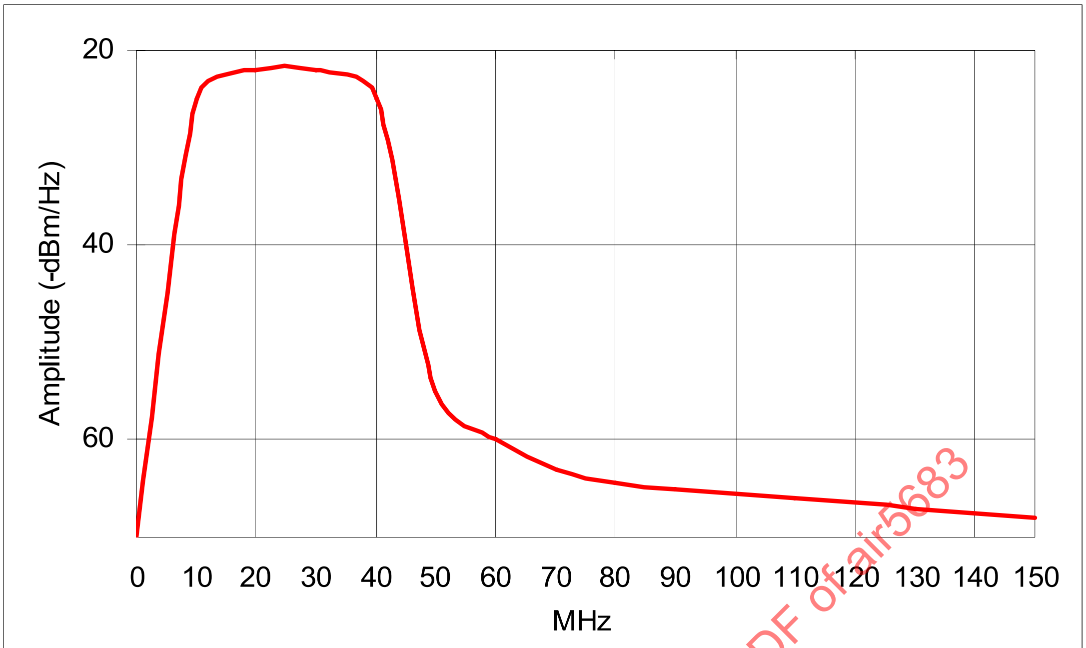

FIGURE 12 - SIGNAL SPECTRUM OF A TYPICAL MULTI-LEVEL MODULATION SCHEME

6.3.1.2 Test Results

The allowable emissions levels for test RE-102 in MIL-STD-461 are shown in Figure 13 below for reference.

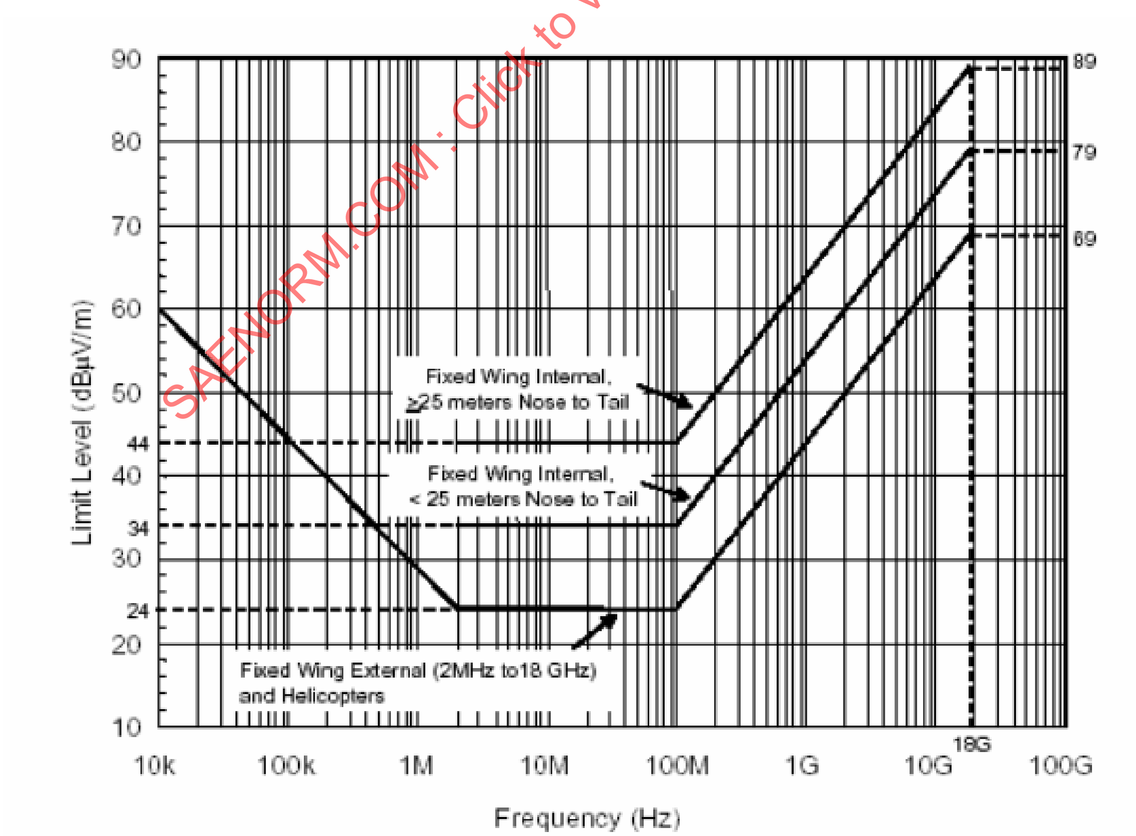

FIGURE 13 - MIL-STD-461 RE-102 EMISSION LIMITS