An Impact Analysis: Transmission of Multiple Data Rates in Hybrid Avionics Bus

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***Abstract*—In the era of modern technologies, technology advent is so fast that applications are becoming obsolete in the blink of an eye. For technologies which have undergone production, change/replacement will incur huge costs. As a result, Defence and Avionics industries are resisting to adopt technology changes. Therefore, modernisation with minimal hardware invasion to ensure enhanced performance, assured sustenance and backward compatibility should be targeted by design engineers. Technology for Avionics bus networks have moved from simple RS422 networks, MIL-STD-1553B to 10Mbps Full duplex AFDX networks. Each of these networks have defined topology, protocol and design criterion and none of them co-exist with each other. The instant paper introduces addition of Orthogonal Frequency Division Multiplexing (OFDM) based Multi Carrier Wave (OFDM-MCW) supporting 100 Mbps data rate on an existing, active MIL-STD-1553B 1Mbps data channel. This Hybrid avionics bus (MIL-STD-1553B with OFDM-MCW) supports a deterministic, command/response half duplex protocol with ease of maintenance, adaptability, redundancy, determinism, ruggedness, priorities and scheduling modes, enhancing cyber-resilience as well. The impact analysis of such backward compatible data bus network implementation in a Hybrid avionics bus, supporting multiple data transmission with one bus network redundant to another on same physical elements of data bus is discussed in detail.**

I. Introduction

ThisMIL-STD-1553B bus network protocol defines the electrical and protocol characteristics for exchange of data and information between various sub systems. This protocol includes message formats, status words, command words and control formats that ensures transmission/reception of Manchester Bi-phase Pulse Code Modulated (PCM) data and all features necessary for implementing a command response protocol data bus. This bus network will transmit a pulse train (0,1 for data 1 and 1,0 for data 0) at the rate of 1Mbps with multiplexed samples in time from various nodes in an airborne weapon system.

For applications requiring high data rate viz high speed actuation systems, navigation data processing applications etc., 1Mbps will not be efficient and sufficient. Such system upgradation with advance networks like AFDX involves in huge costs owing to replacement of terminal hardware, CAT6A cable routing and integration of hardware switches (for more than one node). Also these advanced bus networks do not support conventional MIL-STD-1553B network necessitating removal of complete coaxial bus cables, bus couplers and associated bus stubs. Engineers may not accept to redesign all nodes for addition of one or two parameters of higher data rates, considering implementation cost, design effort and its stabilisation period. As a result, analysis of airborne weapon system will be compromised with and analysts have to make do with what is available.Therefore, a solution that permits transmission of MIL-STD-1553B data simultaneously with a signal of higher 10X baud rate (OFDM-MCW) using same bus infrastructure emerges as a vital solution. The instant paper provides an overview of Orthogonal Frequency Division Multiplexing based Multi Carrier Waveform (OFDM-MCW) with a transmission band of 25-65MHz, its co-resident implementation, redundancy features, and potential impact on modernizing airborne weapon systems.

II. Description

An OFDM-MCW based bus network generates an OFDM waveform operated in the frequency band of 25-65MHz [1] that can support up to 100Mbps data rate on MIL-STD-1553B. As a communication protocol, OFDM-MCW can be used to enable high bandwidth communications on MIL-STD-1553B networks. The existing communication across various subsystems with MIL-STD-1553B bus which operates at up to 1 Mbps speed can still be retained. OFDM-MCW transmission is entirely independent [2] of MIL-STD-1553B signals and does not necessitate any change in MIL-STD-1553B infrastructure of dual redundant and tightly coupled data bus. This therefore concludes that OFDM-MCW communication can operate at 100Mbps with existing MIL-STD-1553B bus using similar topology of Bus controller and remote terminals. OFDM-MCW introduces a dedicated 100 Mbps data channel on the MIL-STD-1553B data bus without disrupting its existing signalling capability to ensure co-residency.A remote terminal of OFDM-MCW can be programmed to access MIL-STD-1553B bus network for applications that have higher bandwidth requirements than MIL-STD-1553B. Both operations can exist simultaneously over existing MIL-STD-1553B cabling. According to Shannon's Law, throughput of transmission media like bus network is restricted by power and bandwidth. To achieve 100Mbps physical layer rates with OFDM-MCW and without interfering with MIL-STD-1553B, the power is spread over 40MHz. This data transmission reduces the signal levels at any particular frequency in the band of 25MHz to 65 MHz[9] . Figure 1 below shows the frequency bands and relative power levels of MIL-STD-1553B and OFDM-MCW. The two services share the same wires but are sufficiently separated in frequency so that they are completely independent. To MIL-STD-1553B receivers, OFDM-MCW appears simply as noise. Since the OFDM-MCW power levels are small and the frequency well controlled, the 'noise' level added to the MIL-STD-1553B bus is completely outside the noise specification of MIL-STD-1553B. MIL-STD-1553B operates at maximum data rate of 1Mbps, each data bit is transmitted as a Manchester bi-phase code (data bit 1- 0,1 and data bit 0- 1,0). In OFDM-MCW signal band of 25-65MHz, to achieve an average of 100Mbps, 512 tones with 4 bits per tone is opted. This means that there is no ‘frequency hopping’ or split frequency bands for uplinks/downlinks. There is only one transmitter at a time, and it occupies the full band.

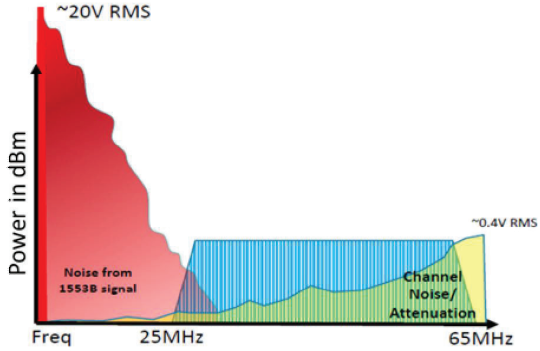

FIGURE 1: POWER SPECTRAL DENSITIES

SERIAL DATA BUSES	STANDARD	TOPOLOGY
1553B	Half-duplex	BC/ Multiple RT/ BM
OFDM-MCW	Half-duplex	BC*/ Multiple RT*/ BM*

TABLE1A: COMPARISON WITH MIL-STD-1553B

SERIAL DATA BUSES	DETERMINISM	DATA RATE/ LENGTH	RESILIENCE
1553B	Deterministic command-response	Up to 1mbps/ based on attenuation	Command-status and data words for robust error checking mechanism
OFDM-MCW	Deterministic command-response	Up to 100Mbps/ based on attenuation	Encryption and authentication for robust error checking mechanism

TABLE1B: COMPARISON WITH MIL-STD-1553B

This paper examines impact of implementation of OFDM-MCW on 1553 bus network. This data fusion approach is as a non-invasive and cost effective solution for an affordable avionics to meet data throughput of data centric applications along while providing seamless transition from low speed 1553B to high speed OFDM-MCW on existing avionics hardware. The conventional MIL-STD 1553B data bus, while robust, faces limitations with respect to data throughput and cyber-resilience. The primary objective of OFDM-MCW is to offer a deterministic, low Bit Error Rate (BER) Command/Response protocol with support for priorities and scheduling modes. A comparison with MIL-STD-1553B standards is elucidated in Table 1 to bring out the advantages and uniqueness of OFDM-MCW in airborne weapon system applications. As MIL-STD-1553B bus architecture gives optimum performance for 1Mbps data transmission, at higher frequencies, signal reflections due to cable length, stub positions and interface location of coupler/stubs etc., play a major role. The key focus of this study is to explore the practicality and benefits of provisioning OFDM-MCW over MIL-STD-1553B for higher data flexibility and ease of system upgrade. This Analysis aims to provide insights into the benefits and practical implementation of OFDM-MCW, for modernizing airborne weapon systems.

III. BUS ARCHITECHTURE OF OFDM-MCW

Before The architecture of high speed OFDM-MCW is designed to enable transmission of high frequency signals and secure data communication in airborne weapon systems based on MIL-STD-1553B. The architecture ensures compatibility with the established MIL-STD-1553B protocol, making it a practical solution for modernizing airborne weapon systems. Key components OFDM-MCW include the following:

A. Multi node network:

OFDM-MCW implemented supports time division multiplexed MCW data with Multiple OFDM-MCW terminals using Bus Controller (BC*), Remote Terminals (RT), Monitor terminal (RT). The bus controller shall allow BC*-RT*, RT*-RT* and all bus monitor (BM*) schedules ensures optimum utilisation of bus and ensures there is only one terminal transmitting at a time. Also there is no fixed tone mapping between any two nodes. Allocation of tone and frequency conversion depends on the frequency of data transmitted. To cater for such requirements, a BC* allows transmission of different message lengths and with different frequencies.

B. Data Channel [6][7]:

Core feature of this bus network is the implementation of dedicated 100 Mbps OFDM-MCW data channel. This channel is designed to support high-speed data transfer

C. Data Bus Components:

The Physical layer signalling controlled by respective protocols essentially activates/deactivates the transmission on a particular bus network. The high speed bus requires bus cables, couplers and stubs. This ensures minimal disruption to the existing data bus infrastructure during its integration

D. Tones [8][9]:

The OFDM technique is used for converting the time domain signal to a frequency multiplexed signal of bandwidth 40MHz. For a 512 tones transmission, the transmission range varies from f_L(Starting frequency) to f_H(Ending Frequency)with signal tones spaced at 78.125KHz(=40MHz/512).

E. Tones-Maps:

512 tones considered in instant OFDM technique will be transmitted as bits/toneviz 1, 2, 4, 8, 12, 16 bits. Generally, bits/tone assignment is finalised based on threshold of operation. If observed SNR is above estimated threshold for 1 bit/tone transmission, 1 bit per tone can be assigned for that tone transmission. For all 512 tones either same number of bits /variable bit assignment can be taken up depending upon noise due to local environment for each transmission (viz Node1-Node2). Also the direction of transmission shall be notified for transmit or receive terminal. The data of number of bits, modulation level (information loaded on channel), direction of transmission essentially constitute a tone map. A training test frame helps the designer to estimate the noise environment for each transmission and obtain optimal tone map. Based on this data, common tone maps can be maintained betweenvarious terminals.

F. Dual Bus:

OFDM-MCW uses the dual bus Bus A, Bus B so that if one bus is impaired, data flow continues on the other bus. The terminals shall be defined with valid tone maps on both the buses in such a way that transfers on both the bus are enabled to ensure dual bus operation. As the overall bandwidth is distributed between both the buses, instead of transmitting on both the buses, the redundant bus shall be called in the event of failure of main bus. This will ensure efficient switching of scheduled data and optimum use of bus bandwidth

G. Terminal:

Based on the addressing limitations, the maximum number of terminals that can be connected on OFDM-MCW is 61. The practical number of terminals is arrived at by other factors like bus length, bus loading and scheduling time. A 328foot length is positively supported in OFDM-MCW network and additional length is based on bus reflections and noise introduced in higher frequencies

H. Backward Compatibility and Cyber-Security Enhancements:

One of the essential aspects of this architecture is its ability to operate concurrently with MIL-STD-1553B without any impact on its conventional operation. This backward compatibility ensures that existing LRUs integrated with a conventional interface can coexist with new LRUs provisioned with OFDM-MCW. The bus network offers inherent cyber-resilience features, including encryption, authentication, and fingerprinting of network interface devices. These security enhancements enable secure and reliable data communication on the 1553B data bus, protecting sensitive information from unauthorized access and interference. It can be concluded that the architecture of OFDM-MCW thereby provides a comprehensive and efficient solution for enhancing data communication in airborne weapon systems. By seamlessly integrating with the existing MIL-STD-1553B data bus infrastructure, reusing data cable/stubs/couplers and offering additional robust and secure 100Mbps data channel, a Hybrid avionics bus is formed that enables higher data rate capabilities in on-board avionics bus while minimizing disruption, providing economical cost and faster time to market.

IV. IMPACT ANALYSIS - HYBRID AVIONICS BUS

OFDM-MCW specifies a bus network that operates concurrently on same physical wiring and with no interaction with conventional MIL-STD-1553B. Impact of such technology concept and its physical effect on system operation by adding a dedicated 100Mbps data channel to an established data transmission of 1Mbps is elaborated in subsequent paras.

A. Co-Existence [3] :

Manchester Bi-phase encoding forms a MIL-STD-1553B data signal which operates at 1Mbps data rate with each data bit transmitted as 0,1(bit 1) and 1,0(bit 0). In OFDM-MCW, orthogonal frequency division multiplexed waveform is transmitted to achieve an average of 100Mbps with 512 tones. It is observed that the frequencies of transmission of MIL-STD-1553B and OFDM-MCW are far apart and the newly added OFDM-MCW has much lower signal level requirements as indicated in Figure 1. To visualize how multiple communications systems can share a common medium separated only by frequency, a wireless systems example can be considered. The airwaves are filled with RF transmissions from all sorts of sources. Receivers tune to their desired band and filter out all undesired sources. MIL-STD-1553B is a 1MHz high-level digital signal while OFDM-MCW consists of 512 low-level carriers spread from 25MHz to 65MHz. To MIL-STD-1553B receivers, OFDM-MCW appears simply as noise. Since these power levels are small and the frequency well controlled, the ‘noise’ level added to the MIL-STD-1553B bus by OFDM-MCW is completely outside the noise specification of MIL-STD-1553B.

B. Backward Compatibility [5] :

The terminals and terminal addresses (RT* and RT) of both OFDM-MCW and MIL-STD-1553B are completely independent. The communication on OFDM-MCW is backward compatible and permits flow of MIL-STD-1553B [4] already established in the network. The bus controllers (BC* and BC) are also independent. If the bus hardware is intact, MIL-STD-1553B continues to operate even if OFDM-MCW fails. Similarly, for a physical bus intact, OFDM-MCW operates even if MIL-STD-1553B fails. Therefore, in a LRU (Line Replaceable Unit) with transceivers supporting both networks, one network essentially works as a redundant network to the other on seamlessly intact physical bus.

C. Implementation of new OFDM-MCW Channel on MIL-STD-1553B:

The following points should be considered for verifying impact

a) Both bus networks operate concurrently on same bus channel without any interaction.

b) The terminal addresses of both the networks are independent

c) Bus controllers are separately identified and programmed for both the networks.

d) OFDM-MCW operates even when MIL-STD-155B fails.

e) MIL-STD-1553B bus operates even when OFDM-MCW fails

f) SAE AS4111 test plan specifies validation test plan for MIL-STD-1553B. OFDM-MCW shall follow same acceptance criterion during its frequency of operation.

D. *Quantification of Effects:* To understand the physical effect of adding a 100M data channel with OFDM-MCW on standard 1Mbps channel the test set up is connected as shown in Figure 3:

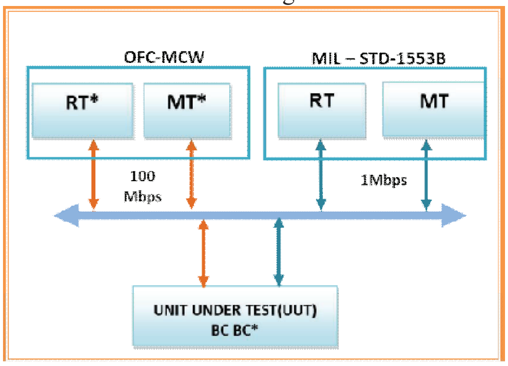

FIGURE 3: OFDM-MCW OVER MIL_STD-1553B

1. *Electrical Bus Isolation:*

This parameter measures the leakage between redundant busses on a MIL-STD-1553B network when both networks are operational. To quantify the bus isolation, peak-to-peak output voltages in active busses and inactive busses of UUT ((Unit under test) are measured using digital oscilloscope for entire region of transmission and ratio in dB of Vpeak-peak (Bus-Active) /Vpeak-peak (Bus-Inactive) are verified. Measurements are taken by activating each bus channel (Bus-A and Bus-B) of a particular network alternatively for 5 times. Leakage for each complaint terminal shall meet pass criterion. It can be observed that the OFDM-MCW terminals have 45dB isolation from 75kHz to 1MHz frequency band (MIL-STD-1553B) and 30dB for all frequencies from 1MHz to 70MHz.This essentially infers that OFDM-MCW limits the isolation between terminals to 45dB for MIL-STD-1553B range of operation. Therefore, an OFDM-MCW can be modelled as an additional MIL-STD-1553B terminal

2. *Input Impedance*

To obtain bus loading effects of a terminal, input impedance of bus network has to be defined. The input impedance can be measured with both UUT ON/OFF condition in isolated network using a 1Vrms voltage swept over frequencies from 75 KHz to 1 MHz. Test cases are carried out with both OFDM-MCW and MIL-STD-1553B connected to same stub and independent stubs. It was observed that in single terminal configuration with different stubs, input impendence measured for both networks is greater than 1KΩ for transformer coupled and 2KΩ for direct coupled configuration. Similarly, in single terminal configuration with single stub, input impendence measured for both networks is half the previous case of two independent stubs. With respect to input impedance, OFDM-MCW can be modelled as having same MIL-STD-1553B terminal characteristics.

3. *Output Noise:*

This parameter is used to verify noise coupled to load. The output Vrms on inactive bus channels are measured in ON/OFF condition for UUTas shown in Figure4. A Digital Oscilloscope or a Vrms meter that can measure upto 70MHz signal is used in test setup and UUT is switched on and off for 10 times and data is recorded after unit is stabilised in both the cases. The measurements indicate that for frequency of upto 5MHz, OFDM-MCW measures same level as that of MIL-STD-1553B(14mV for transformer coupled and 5mV for direct coupled). For frequencies 5M-10M Hz, the noise measured is less than 10mV and close to zero in transformer and direct coupled respectively, This shows that OFD-MCW terminal is better than MIL-STD-1553B terminal with respect to noise characteristics.

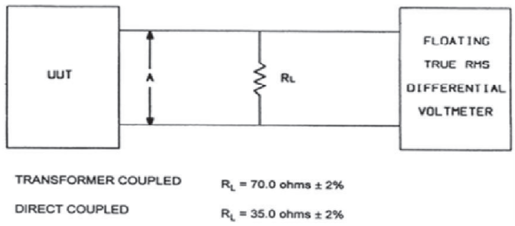

FIGURE 4: TEST SET UP FOR OUTPUT NOISE

- Output noise $PdBm = 10 \log (V^2 / Z) + 30dB$,V=Line Voltage,Z=Impedance at terminal

Type	**1553B (dBm)**	**OFDM-MCW (dBm)**
Transformer Coupled	-25.4	-26.0
Direct Coupled	-31.4	-34.0

TABLE 2: TEST SET UP FOR OUTPUT NOISE

4. *Power ON/OFF noise:*

This parameter measures the effect of power cycling or transient voltages on bus terminals. The spurious noise pulses produced on bus lines during power on/off sequences of UUT are verified. UUT shall be switched ON and all output terminal voltages are measured during transient. Similarly, UUT shall be switched off and all output terminals are measured for transient behaviour. For effective statistics the measurement is done 10 times and transient behaviour is measured on both networks. The maximum allowable output noise is ±250mV for transformer coupled and ±90mV for direct coupled in both networks. As OFDM-MCW matches the test output of MIL-STD-1553B, it can be characterised to be an additional MIL-STD-1553B terminal for Power On/OFF noise parameter.

5. *Summary of Test Data (Transformer coupled(TC)/ Direct Coupled(DC)):*

PARAMETER	**1553B CHANNEL AS PER SAE AS4111**	**EXPERIMENTAL TEST DATA WITH ADDITION OF OFC-MCW CHANNEL**
Output noise	14 mVrms (TC) 5 mVrms (DC)	14.4 mVrms (TC) 5.4 mVrms (DC)
Electrical Bus Isolation	45 dB	45.5 dB
Power on/off noise	<±250mVpk (TC) <±90 mV pk (DC)	<±250 mVpk (TC) <±90 mV pk (DC)
Input impedance	1 kΩ(TC) 2 kΩ(DC)	1 kΩ (TC) 2 kΩ (DC)

TABLE 3: IMPACT ANALYSIS

V. CONCLUSIONS

The system effects for addition of OFDM-MCW is verified through measurement of electrical bus isolation, input impedance, output noise and power ON/OFF noise. For all MIL-STD-1553B parameters identified as per standard test and validation matrix of SAE AS 4111, it can be concluded from test data that the performance of OFDM-MCW is same or even better in certain cases. From this test data, it can be inferred that the addition of a OFDM-MCW terminal on existing MIL-STD-1553B network has same effect as that of additional MIL-STD-1553B terminal. Hence the potential benefits of co-existence, redundancy and backward compatibility with OFDM-MCW can be utilised by designers to realise a rugged high speed Hybrid avionics bus.

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