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A Novel Loss Tolerant Data Transmission Schemes for Airborne Telemetry System of a Long Range Aerospace Vehicle

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ABSTRACT

The on-board telemetry system of an aerospace vehicle sends the vehicle performance parameters to the ground receiving station at all instances of its trajectory. During the course of its trajectory, the communication channel of a long range vehicle, experiences various phenomena such as plume attenuation, stage separation, manoeuvring of a vehicle and RF blackout, causing loss of valuable telemetry data. The loss of communication link is inevitable due to these harsh conditions even when using the space diversity of ground receiving systems. Conventional telemetry systems do not provide redundant data for long range aerospace vehicles. This research work proposes an innovative delay data transmission, frame switchover and multiple frames data transmission schemes to improve the availability of telemetry data at ground receiving stations. The proposed innovative schemes are modelled using VHDL and extensive simulations have been performed to validate the results. The functionally simulated net list has been synthesised with 130 nm ACTEL flash based FPGA and verified on telemetry hardware.

Keywords: Airborne telemetry; Pulse code modulation; Telemetry format; Plume attenuation; RF blackout; Synchronous dynamic RAM memory

1. INTRODUCTION

The functionality and performance of each subsystem of an integrated aerospace vehicle is evaluated through Telemetry system. Telemetry system[1] collects data from various sensors, sub systems and sources. The sensors convert the physical measurements such as vibration, pressure, strain, temperature etc. into electrical quantities like charge, voltage and current. Since the output signal levels of these sensors are very low, signal conditioning circuits are employed in on-board telemetry to amplify and to band limit the signals. The band limited signals are converted into digital data by the telemetry system. The physical event signals from the external subsystems are monitored in telemetry. In avionics systems, the electronic sub systems communicate via standard interface like MIL-STD 1553[2,3] and data needs to be monitored by telemetry system. Telemetry data format is a method to multiplex the measurements from the various sensors, physical events and MIL-STD 1553 bus data using the Time Division Multiplexing (TDM) method and encode into the format of pulse code modulation (PCM) as recommended by Inter Range Instrumentation Group (IRIG)[4]. The PCM signal is modulated[5] by a carrier and further amplified to transmit into free space through the antenna.

During the launch of an aerospace vehicle, the ground receiving station establishes communication with the on-board telemetry of the launched vehicle throughout its trajectory. The data received by the ground receiving station is primarily used for evaluating the performance of the vehicle. Especially for long range aerospace vehicles multiple ground receiving stations are deployed to acquire telemetry data throughout vehicle trajectory simultaneously with space diversity mechanism. Such ground stations will improve the data availability at ground receiving system rather than improving link margin of individual stations. The location of ground receiving station in space diversity is estimated using predicted trajectory and G/T of respective ground receiving station. These ground stations are connected in network and operated in different modes such as Mono-pulse Mode (amplitude comparison mode), E-Scan Mode[6] and Internal Designated Mode (IDM-Simulated and predicted information) to track the vehicle.

In the operational scenario of long range aero space vehicle, ground stations are deployed as shown in Fig. 1. It has generally three stages like ascent phase or power phase, midcourse phase and terminal phase. In each phase of the vehicle one dedicated ground station is deployed. In certain conditions due to non line of sight (LoS) scenarios or less effective isotropic radiated power (EIRP), multiple stations may also be deployed in the each phase of launch aerospace vehicle as needed. For line of sight availability, altitude of the vehicle trajectory is important as shown in Fig. 1.

In all phases of vehicle, RF link availability throughout the trajectory is a concern due to various conditions like plume attenuation and stage separation in ascent phase and

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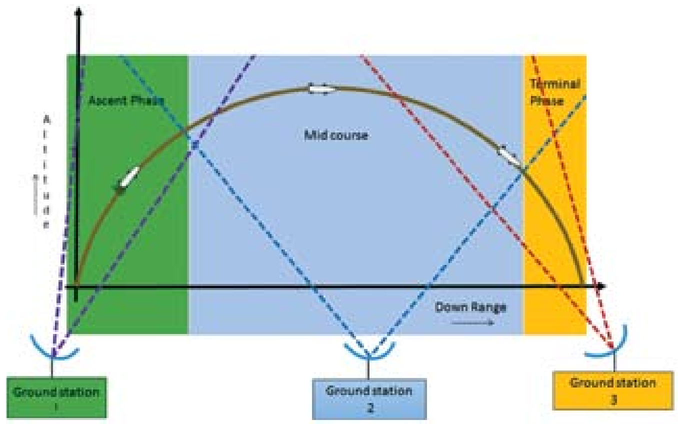

Figure 1. Operational scenario of a typical long range aerospace vehicle.

RF blackout experienced by the vehicle in the terminal phase which are discussed subsequently. The telemetry RF link availability during those conditions can be improved by using different mechanisms[7]. However, this paper further discusses various methods to ensure data availability during RF link loss conditions. Such link loss cases and related literature are provided in the following sub sections.

1.1 Plume Attenuation

During ascent phase, when the first stage of an aerospace vehicle is ignited, heavy ionized plumes from the nozzle of the solid rocket motor exist around the nozzle of the vehicle[8-12]. The ionised exhaust plumes continue till the propellant is completed in all stages. The telemetry RF signal gets attenuated due to reflection, diffraction and scattering while it passes through plume. This is called as plume attenuation which depends on the look angle of vehicle alpha between the vehicle axis and beam of the receiving station[8]. The RF communication is guaranteed only if the ground receiving station beam is far away from the vehicle axis. However, during the ascent phase of the vehicle, the receiving beam will be very nearer to the vehicle axis leading to the interference of RF communication. This might cause the loss of telemetry data at ground receiving station and need to be addressed.

1.2 Canisterised Vehicles

The aerospace long range vehicle has an ejection mechanism comprising a canister and a generator to eject the vehicle from canister so that vehicle flames should not damage ground equipment and also other peripheral systems. The canisterised launch vehicle[13] has the advantages of short launch preparation time and also these sorts of vehicles can be launched from underwater as well. Once the vehicle is canisterised and ready for launch, the system is switched on to verify the health of the vehicle. Since the telemetry RF signal of the on-board telemetry is reflected or attenuated by the metal/composite canister, the ground receiving stations cannot receive telemetry data from ejection to out of canister and the data lost needs to be retrieved.

1.3 Re-entry Phase of a Long Range Vehicles

In general, long range aerospace vehicle attain very high altitudes at high velocities leading to experience different dynamic conditions which change the vehicle characteristics. When the vehicle re-enters the atmosphere during terminal phase, much of the vehicles kinetic energy is converted into heat causing the temperature on the vehicle surface rises to such magnitudes that the surrounding air dissociates and ionizes. Consequently, the flow field surrounding the vehicle becomes highly conductive leading to the attenuation of RF signals. During this period, RF communication is completely blacked out[14,15] which varies in time depending upon various factors like vehicle configuration, velocity, atmospheric density and angle of attack. Several techniques are proposed[16,17] to mitigate the communication blackout and these methods require hardware changes to the existing vehicle configuration, which is not desirable. The blackout time and duration are expected from the simulation studies of a vehicle.

The RF blackout of a re-entry vehicle is typically 15 to 20 sec for a typical long range vehicle[18]. After blackout time, the communication re-establishes for a few seconds before the splash time. To get real time data while vehicle experiences link loss conditions as described in Table 1, the redundant telemetry chain needs to be planned using a high frequency carrier[18]. As transmitting frequency increases, the blackout time reduces[18]. However, such technology is under progress resulting in a trade-off between available technology and link loss time. Hence, a few schemes proposed in this work to overcome link loss problem are presented in the next section.

2. PROPOSED DATA REDUNDANCY SCHEMES

The on-board telemetry data formatted using IRIG standards depends on the bandwidth and the data rate of different parameters of transmission. The data redundancy schemes proposed in this work for multi stage vehicle from launch point to the splash or terminal point of the vehicle are explained in the following subsections.

Table 1. Link loss cases for different conditions

Conditions	Attenuation of RF signal	Duration of link loss	Remarks
Plume attenuation in the ascent phase	30 to 50 dB[9,10]	5 s to 10 s Intermittent loss[10]	Link loss depends on power phase of vehicle.
Canisterised vehicles	(a) Metallic structure > 100 dB (b) Composite Structure > 30 dB	< 1 s	It depends on length of vehicle and ejection mechanism.
RF blackout in the terminal phase	For S-band frequency > 60 dB attenuation[18]	15 s to 20 s	It depends on transmitting carrier frequency and also vehicle dynamics

2.1 Delayed Data Transmission

The proposed delayed data transmission (DDT) scheme requires the data format to have two parts of information, namely, real time telemetry data and redundant frame data which consists of measurements stored in a memory. The key point in this proposed scheme is that the information will be stored in the on-board memory to transmit to the ground station after a specified delay. The critical parameters like navigation, control, physical events, engine etc. are required for performance analysis. This proposed scheme can effectively work during the situations like plume attenuation, stage separation etc., where the vehicle is not visible to the ground station for a few seconds. Once the telemetry link establishes with the ground system, previous telemetry data could be retrieved from the redundant frames. The redundant frame occupies a portion of the primary frame. Both the frames are tagged with a timer field which is the reference to the measurements made by telemetry. The estimated link loss period of the signal is the delayed time in the redundant data frame. In the on-board telemetry system, this delay time is programmed so that the lost data is recovered from the redundant frame. This information is also expressed using the following Eqn (1).

$$F_{inst} = F(r) + F(r-d) \tag{1}$$

where $r>d$ for valid delayed data,

d Delay time or lag time

r Real time or instant

F_{inst} Transmitted frame

2.2 Frame Switchover

The telemetry frame generated by a given measurement plan is loaded into telemetry encoder, which packetises the information based on the format defined in the memory. This frame switchover scheme addresses the data non-availability condition by storing two formats in memory, referred as Area-1 and Area-2. The telemetry packetises data initially as per Area-1. The on-board computer triggers the telemetry to change the predefined non-availability to availability of data, then the telemetry frame switchover from Area-1 format to that of memory Area-2. Assume that the two formats are generated for a vehicle, one format for acquiring, storing and transmitting acquired data and the second format for acquiring, storing and transmitting of acquired and previously store data in a frame. The proposed frame switchover (FS) scheme is also useful for optimisation of data rate for long range vehicles with one format is for initial phase to capture where more parameters needs to be transmitted with high data rate, and the other format only to capture payload data and transmit with low data rates.

2.3 Multiple Frame Data Transmission

This proposed multiple frame data transmission (MFDT) scheme involves the transmission of frame data multiple times by telemetry system at different instants of time to capture link loss at the next instant in the ground receiving station. This scheme is designed to transmit the same packet multiple times after programmable period of time. The time period would be decided by the simulation studies, which gives the time of entry and exit of re-entry phase. During this period, the ground telemetry link loss is predicted due to plasma effect. This proposed MFDT is useful where the telemetry data loss is to be predicted and capture in the next instant.

The MFDT scheme is implemented by reading of stored data at a faster rate than writing of data into memory and also frame is designed such that multiple frames of data is to be embedded in a single frame with high data rate. This method is explained with the following Eqn (2).

$$MFDT_{instdata} = T[(b*n)+k] + T[(p*k)+m)] \tag{2}$$

where,

b time of telemetry link availability after blackout

p b/flight time after blackout

m 0, 1 - - - b

n 0, 1 - - - b; k = 0, 1, 2 - - - (b-1);

In Fig. 2, F1601 is the 1601 frame of telemetry from point A. Let the frame time be 10 milliseconds and after 16secs of flight time (from B) telemetry transmits acquired frame and stores F1, F2, F3, F4 and F5 frames of data. It means that 5 frames of stored information are being transmitted. In the next frame, telemetry system with the proposed MFDT scheme can retrieve the loss of data at any instant of the last 4secs from the received data.

The above proposed schemes demands increased data rate which can be handled with multiple receiving stations using space diversity mechanism. The predicted trajectory information of vehicle, RF blackout instance, location and duration are known to the ground receiving station a priori. The dedicated station for re-entry data over the trajectory of vehicle will look into the pre-defined direction and it acquires RF signal from vehicle after re-entry with directional antennas.

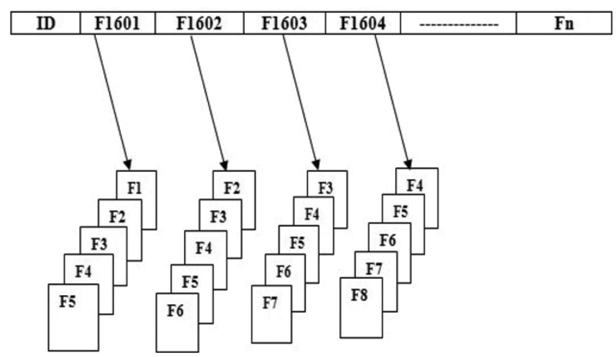

Figure 2. Multiple frames data transmission.

3. PROPOSED ARCHITECTURE

The proposed schemes presented in the Section 2 are employed at different instances of the vehicle trajectory path to ensure the data availability at the ground receiving station. In the case of canisterised vehicle, DDT scheme can be employed to ensure the total vehicle data availability at the ground receiving station. In the case of underwater vehicle, the proposed FS scheme with DDT enables it to retrieve the total vehicle data at the receiving station. During re-entry phase of a vehicle, RF blackout condition is expected. The loss of vehicle data during re-entry phase can be retrieved by employing the proposed MFDT scheme at end phase of vehicle. Hence, it may be concluded that design of on-board telemetry system with the proposed schemes can ensure the data availability at ground receiving station throughout the flight of the vehicle.

In general, pre-defined trajectory and different conditions need to be experienced by a vehicle during the flight is available with the on-board computer long with the corrective measures using control structures or increasing thrust etc. The on-board computer may decide switching between various schemes through event-based logic (like inter stage separation) or timer based (like pre-defined time after or before lift-off) or navigation based (when it reaches the apogee of the trajectory) or any other combination as required. This information can be communicated to the telemetry through the avionics bus for switching the scheme appropriately. Figure 3 shows the proposed architecture for telemetry system developed by employing the proposed schemes presented in Section 2. The functionality of the individual blocks is explained in the following sub sections.

The hardware implementation of the proposed architecture requires a dedicated memory in the telemetry encoder. The telemetry data rate of 4 Mbps is achieved by selecting a buffer to store temporarily 250K words per second. As the data rate increases further, high density memory chip is required. Since the high density 2M X 16 size SRAM occupies more area on PCB, SDRAM with high density and small form factor is selected in this work.

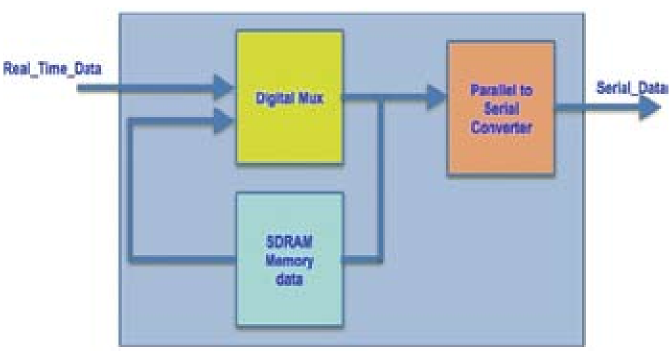

Figure 3. Architecture for redundant data transmission.

3.1 SDRAM Controller Interface with Memory

The memory controller is designed to access the external SDRAM as shown in Fig. 4. The memory contains 25-bit address, and the corresponding address generators are implemented on FPGA. The read and write address generators are controlled by the external read and write control signals. These address generators are initially loaded by the microcontroller.

The end pointer indicates the size of memory limited to the required size. The delay time in DDT scheme and number of multiple times in MFDT scheme can be programmed. The memory pointers are pre-calculated and stored in flash memory.

These pointers are loaded into SDRAM interface of FPGA, either on power, or by micro controller for one format or based on interrupt for second format (FS). The proposed schemes are employed with the integration of SDRAM controller and memory interface with the telemetry hardware. The multiplexed data is stored by the hardware into SDRAM and it reads after pre-defined programmable time.

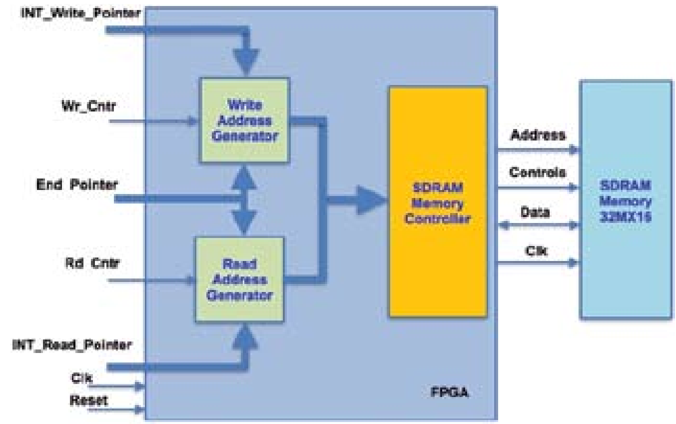

Figure 4. FPGA Memory controller with external SDRAM memory.

4. IMPLEMENTATION OF PROPOSED SCHEMES WITH TELEMETRY HARDWARE

The architectures proposed in the Section.2 are implemented using a micro-controller (C8051F120), IGLOO-FPGA (AGLV5-FG144I) from ACTEL family and SDRAM (MT48LC128M4A2). The SDRAM controller is realised using VHDL and ported on FPGA. The memory controller clock is applied with 50MHz square wave from the crystal oscillator and the same clock is applied to SDRAM. The timing requirements for SDRAM are tuned in the RTL code of memory controller[19]. The memory controller generates commands like Pre-charge, NOP, Refresh and Active commands etc. as per the technical note[19]. The active command[20] means writing data into memory or reading data from memory. The SDRAM is configured as 8M x 16. The configuration of memory is done on PCB with data lines of SDRAM. The micro controller addresses, data, read and write pins are connected to FPGA which enable to write memory pointers of FPGA on initialisation. The memory controller functionality is cleared with external SDRAM with the application code of a microcontroller.

The RTL code of memory controller and associated interfaces are integrated with the telemetry hardware such that the selected parameters are stored into memory. The acquired telemetry data is stored in SDRAM which is merged with normal telemetry data as shown in Fig. 3. The architectures proposed in Section.3 are implemented in telemetry hardware, which is designed such that write, read and end pointers of memory controller are programmable with micro controller. In the application code of micro controller, the FPGA registers are set as per the definitions of frame in the initialisation process. The end pointer value in the case of DDT and MFDT is derived from the number of times the data to be repeated in a frame and storage time as per the requirement. This hardware is tested with various test conditions and results are presented in the next subsection.

4.1 Hardware Test Results

The hardware test setup consists of function generator, on-board telemetry encoder (with implemented schemes) and decommutator system[21] as shown in Fig. 5. The decommutator system is used to decode the serial data into samples based

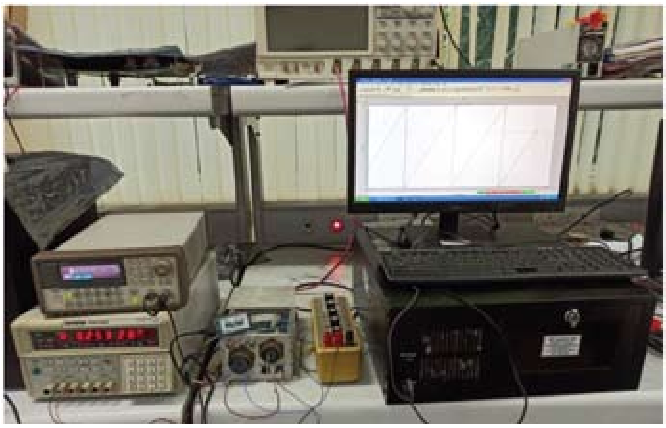

Figure 5. Test setup of Telemetry hardware with implemented schemes.

on the defined format. It displays each parameter information w.r.t to PC time (HH:MM:SS) and provides comparison of parameter values and graphs. This system needs data rate of telemetry system and frame format information for de-commutation. An event simulator is used to start telemetry hardware for acquiring data and send to the decommutator system. This is also used to switchover from one format to another format. The power on condition involves loading the memory pointers of SDRAM into FPGA by the application software (micro controller). The FPGA initialises memory pointers of memory controller and then starts telemetry data acquisition and access SDRAM for temporary storage and for reliable data transmission. The three schemes explained in the Section 2 are simulated and results are presented here.

The DDT scheme results are recorded with the frame transmission rate set for 10 ms and the delay time programmed for 10 s. It indicates that 1000 frames of data to be stored and transmitted after 10 s. A control commutation parameter[4] is selected as an input for analysis. The normal acquisition of control commutation parameter data and delayed data is shown in Fig. 6. The telemetry hardware with DDT scheme transmits real time control data and stored control data in a defined frame[4]. The control parameter amplitude is changed and the same is delayed for 10secs and then transmitted data has been captured.

The delayed control parameter is same as the real time control parameter, but it is delayed by 10 s as shown in Fig. 6. Hence, the data can be retrieved within 10 s of RF signal loss using the delayed data transmission scheme.

As frame switchover takes place, the telemetry hardware reinitialises the memory pointers of SDRAM and switches to the second format. The second format is defined to store multiple times data and re-transmit. The telemetry hardware reads and transmits counter value multiple times. The multiple frames format is selected in the second format and the corresponding data has been captured. As per the MFDT scheme, one sec data consists of 5 s old data. In a single frame, 5 frames of data are embedded. In this case, frame counter is selected and the data is transmitted multiple times. The incremented frame counter value is shown in Fig. 7. Real time frame counter value at an instant is 2989 and the delayed MFDT counter values are 2944, 2945, 2946, 2947 and 2948. Hence, at any instant, real time data plus five frames of stored data is being extracted from the telemetry frame data.

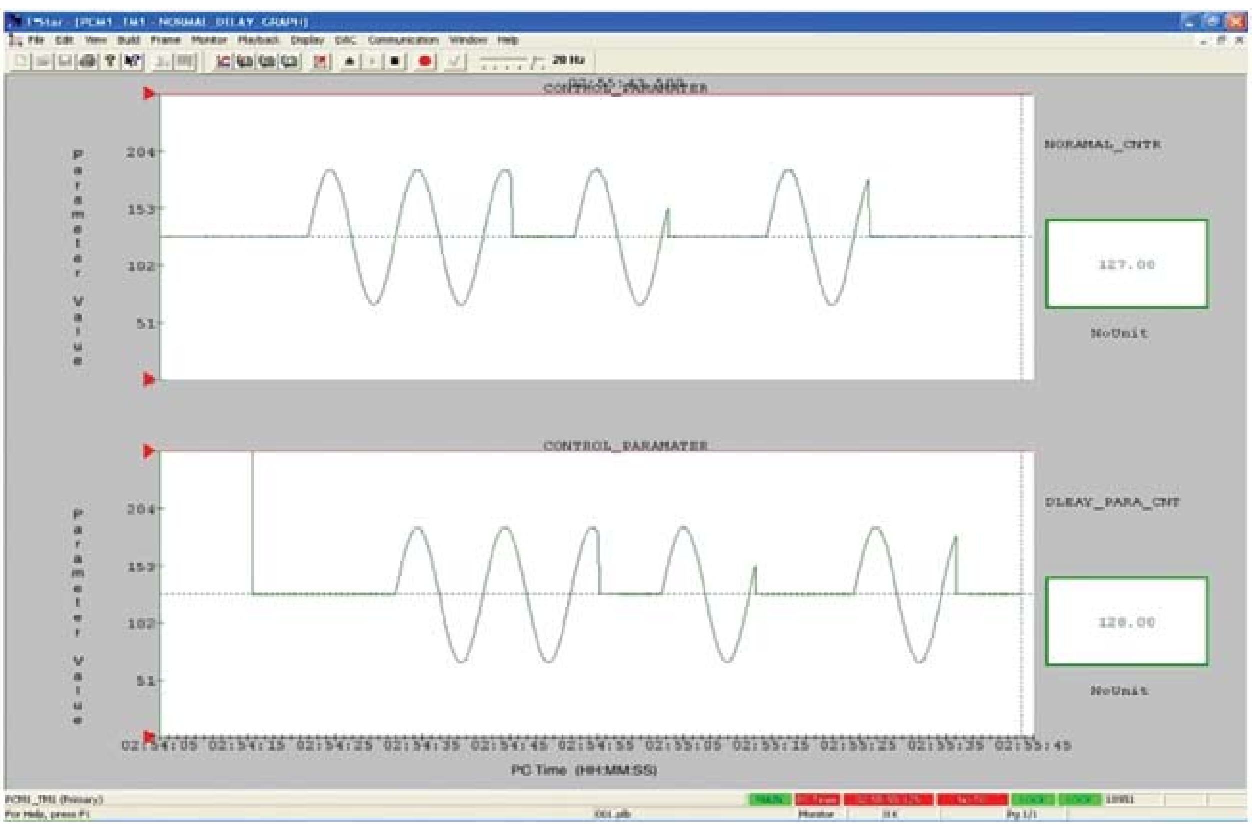

Figure 6. Comparison of a real time parameter (top) and its DDT parameter (bottom).

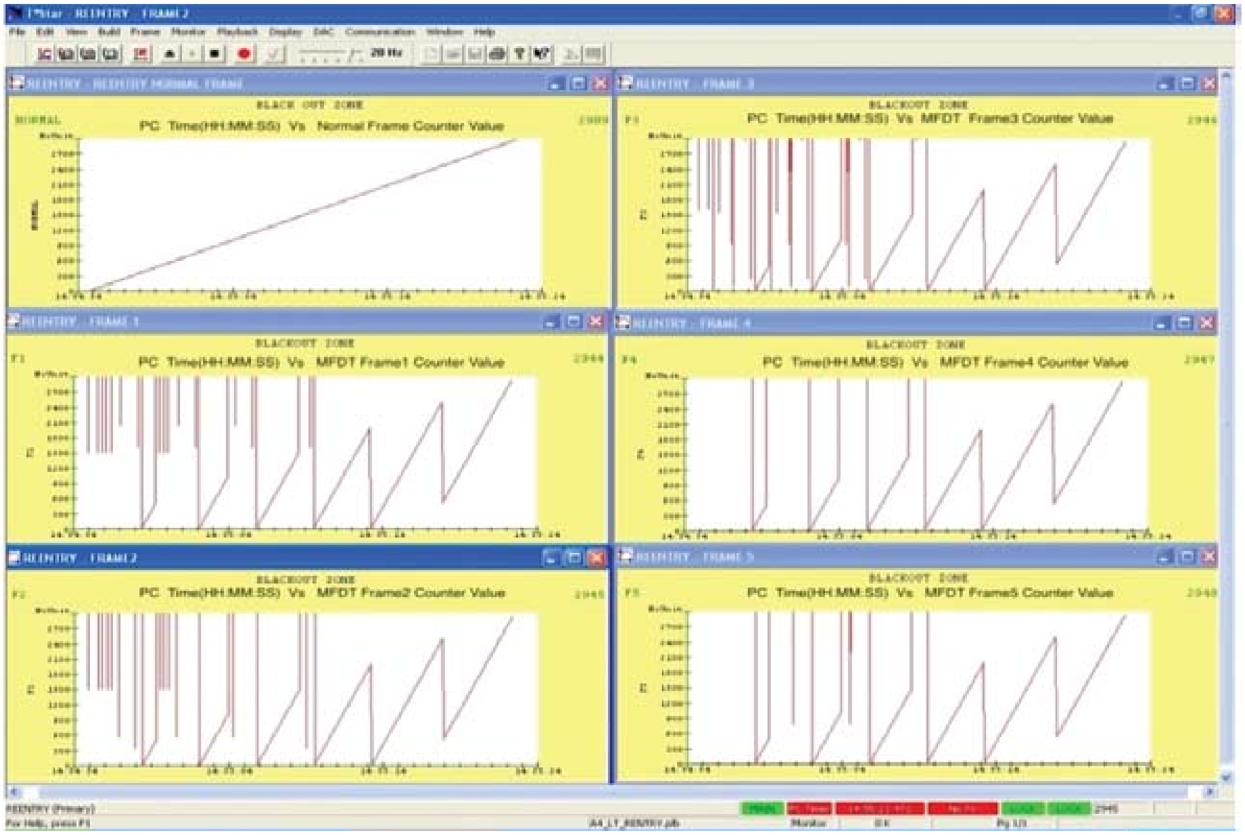

Figure 7. Comparison of a real time frame counter (top left) and its MFDT frame counter (rest) with FS.

Finally, the proposed schemes will provide information continuously in time with defined lag time. It provides sequence of events occurred in the mission even if link loss occurs within delay time. It also ensures the availability of data at ground stations throughout the vehicle trajectory for any preventive measures. The airborne telemetry system is designed to have optimum EIRP with constant BER of 10^-6 over the defined range with maximum data rate. The pre-modulation filter bandwidth is dynamically tuned[5] based on data rate requirement for different schemes as mentioned in the Table 2.

The effect on link margin parameters with proposed redundancy schemes is tabulated in Table 2 using theoretically calculated values[22]. The first row of Table 2 consists of the link budget[22] calculations of the existing link taken as reference with BER of 10^-6. For the FS scheme can be observed, due to increase in data rate the range drops by 50% with other link parameters kept constant. Similarly, to achieve same range as reference more EIRP is required or less C/N (increase in BER) to be tolerated. It can be observed from the Table 2, that in case of DDT scheme, the link margin is reduced drastically due to increase in information data rate. A way out is to increase EIRP when needed by changing transmitting power which otherwise may not be possible throughout the trajectory because of thermal issues especially for a long range vehicle. However, the ground receiving stations specifications like G/T, down range coverage w.r.t receiving station are so designed for acquiring maximum data rate and maximum blackout time with constant EIRP and constant BER of 10^-6. Such multiple stations can be deployed over the trajectory of vehicle to ensure data availability for the increased data rates with the proposed redundancy schemes.

Table 2. Estimation of different link margin parameters with proposed schemes

Scheme	Data rate	Range considered	Required EIRP	Achieved C/N
Reference-PCM/ FM scheme	1 Mbps	5000 Km	46 dBm	12 dB
With FS Scheme	2 Mbps	2500 Km	46 dBm	12 dB
	2 Mbps	5000 Km	46 dBm	9 dB
	2 Mbps	5000 Km	49 dBm	12 dB
With DDT Scheme	11 Mbps	454 Km	46 dBm	12 dB
	11 Mbps	5000 Km	46 dBm	1.59 dB
	11 Mbps	5000 Km	56.41 dBm	12 dB
With MFDT Scheme	6 Mbps	833 Km	46 dBm	12 dB
	6 Mbps	5000 Km	46 dBm	6.23 dB
	6 Mbps	5000 Km	51.77 dBm	12 dB

5. CONCLUSIONS

In this paper, the approach of redundant data transmission with the proposed FS, DDT and MFDT schemes for airborne telemetry was presented. These schemes were implemented on telemetry hardware using microcontroller, FPGA and SDRAM memory. The redundant transmission schemes ensure the availability of maximum data at the ground receiving station throughout the trajectory of the vehicle. Hence, the schemes increase the reliability of data availability at the ground receiving station. It may be noted that the DDT scheme provides redundant data at the cost of doubling the data rate of telemetry. Even with MFDT scheme, data rate of telemetry increases as it depends on the number of times data has to be repeated. It is concluded that only critical parameters need to be selected for redundant data transmission employing DDT or MFDT scheme to optimally use telemetry data rate even with redundancy schemes.

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In the current study, he has contributed in formalising the schemes for airborne telemetry, the test setup, hardware realisation and carrying out the simulation tests and analysing the results.

Dr Lakshmi Bopanna is currently working as an Associate Professor at the National Institute of Technology-Warangal, India. Her areas of interests include digital system design, Microprocessor systems, FPGA Design, VLSI Architecture and IoT. She is also a peer-reviewer for Elsevier journals.
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Dr D.R. Jahagirdar is currently working as a scientist at DRDO, Research Centre Imarat, Hyderabad. He received 'Young Scientist Award' at International Radar Symposium Bangalore in 2005, 'Laboratory Scientist of the year award' in 2007 and 'DRDO Scientist of the year' in 2010.
In the current study, he has contributed in guiding through the selection of methods, hardware test configuration and validation of test results.