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# A Secure, Configurable, Wireless System for Transfer of Sensor Data from Aircraft to Ground

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ABSTRACT

Modern aircraft are complex systems, equipped with hundreds of embedded sensors that record a wide repertoire of data during flight, such as crucial engine and airframe parameters, status of flight control system, air conditioning system, landing gear, life-saving and emergency systems. The data from the sensors is stored in the Flight Data Recorder. Maintenance personnel routinely transfer this sensor data to a ground terminal device to analyze it for aircraft health and performance monitoring purposes. Manual methods of extracting sensor data can be tedious and error-prone when large fleets of aircraft are involved. The motivation for this research was to design and develop an indigenous system for wireless, loss-free transfer of data from an existing 'bought-out' aircraft, in a secure manner. This paper, therefore, presents a novel system to extract sensor data from aircraft to a ground terminal, wirelessly. The wireless system is implemented using unique, configurable Wireless Transmitter Receivers (WTRs) designed for this purpose. The hardware for the wireless transfer of data was designed, interfaced with a modern aircraft's system, and tested with the aircraft on the ground and another flying object. The data from the aircraft's Flight Data Recorder was successfully transmitted and received wirelessly by the ground terminal, over a distance of 50 meters (with aircraft on ground) and 10 Kilometers (with a flying object), in a secure mode with zero packet loss. The WTRs have also qualified the requisite tests for airborne certification.

**Keywords:** Aircraft sensors; Flight data recorder; Wireless transfer system; Software defined radio

## NOMENCLATURE

| | |
|---|---|
| AES | Advanced Encryption Standard |
| ARQ | Automatic Repeat Request |
| ATC | Air Traffic Control |
| AWGN | Additive White Gaussian Noise |
| CE | Conducted Emissions (Testing) |
| CINR | Carrier to Interference Noise Ratio |
| COFDM | Coded Orthogonal Frequency-Division Multiplexing |
| CS | Conducted Susceptibility (Testing) |
| CVR | Cockpit Voice Recorder |
| EMI/EMC | Electromagnetic Interference/ Electromagnetic Compatibility |
| EUT | Equipment Under Test |
| FDR | Flight Data Recorder |
| FPGA | Field Programmable Gate Array |
| HARQ | Hybrid Automatic Repeat Request |
| Hz | Hertz |
| IP | Internet Protocol |
| ISM | Industrial, Scientific and Medical (purposes) |
| Km | Kilometer |
| LOS | Line of Sight |
| MCS | Modulation and Coding Scheme |
| MIL | Military (grade) |
| MIMO | Multiple Input Multiple Output |
| OEM | Original Equipment Manufacturer |
| PKM | Privacy Key Management |
| PTMP | Point to Multi Point |
| PTP | Point to Point |
| QAM | Quadrature Amplitude Modulation |
| QPSK | Quadrature Phase Shift Keying |
| RH | Radio Head |
| RH | Relative Humidity |
| RF | Radio Frequency |
| RPM | Rotations per minute |
| Temp | Temperature |
| SDR | Software Defined Radio |
| SNR | Signal to Noise Ratio |
| SoC | System on Chip |
| SWaP | Size Weight and Power |
| UHF | Ultra High Frequency |
| V/UHF | Very/Ultra High Frequency |
| WiFi | Wireless Fidelity |
| WTR | Wireless Transmitter Receiver |

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## 1. INTRODUCTION

The aircraft's Flight Data Recorder, along with the Cockpit Voice Recorder (CVR) is commonly known as the 'Black Box'.[1] The original black box was designed in 1953, following the investigation of a crash of one of the world's first jetliners. The boxes were painted black in those days to block the stray rays of light that might have ruined the photographic film that stored the data. Today the boxes store data on memory chips and are painted bright orange, to make them easier to find amid crash debris or on the bottom of the ocean.[2] The FDR is an important piece of equipment that records time, altitude, airspeed, direction the plane is heading, etc. Modern FDRs can monitor countless other actions of aircraft, such as the movement of control surfaces, individual flaps on the wings, landing gears, engine parameters, auto- pilot, fly-by-wire systems, and many others. The FDR and CVR are vitally important in the event of a plane crash, as they help crash investigators find out what happened just before the crash. After the introduction of FDRs in commercial aircraft in the 1960s, aircraft manufacturers went ahead with the development of aircraft Health and Usage Monitoring System (HUMS).[3] The HUMS records important data which helps the aircraft maintainers to monitor the 'health' of aircraft systems such as the engine system, oxygen system, hydraulics, fuel system, avionics, etc. The HUMS equipment is also referred to as the FDR since it records data pertaining to all these important systems, in real-time, during the flight of the aircraft. The data is generally stored on hard disks. HUMS and FDR are important parts of military aircraft also.

The HUMS data stored in the hard disk of the FDR is analyzed periodically by the aircraft maintainers to continuously monitor the health of the aircraft systems. On completion of a flight, or at any time, the FDR data is generally extracted in one of these two ways: either the FDR (or its hard disk) is taken out of the aircraft and connected to a Ground Control Computer or the data from the FDR in-situ in the aircraft is collected by the Ground Control Computer via a cable. However, when a large number of aircraft are required to be maintained in a fleet, and there are several flights per day, the task of taking out the FDR (or hard disk) from each aircraft or connecting a cable to the aircraft after every flight becomes a cumbersome task and may not be possible every time (due to short turn-around times, or distance of aircraft from the ground station and other factors). Also, frequent removal of the FDR equipment may lead to disks getting interchanged/ misplaced, wear and tear of the connectors. The above manual methods of FDR data extraction impose considerable workload on the maintainers and are error-prone. Some aircraft use wires, fiber optic cables to download the data. However, when a large number of aircraft at large distances are involved, the wiring gets complex and expensive. Volner and Bores[4] envisaged a 'Glass-box' to mean a Black Box which is 'transparent, wherein, data from the aircraft would flow to ground stations in real-time, to be analyzed on the spot or later on.

It is also pertinent to mention that in the event the Black Box or FDR becomes irrecoverable due to crashes in the ocean or other inaccessible terrain, crucial data which can provide clues to the crash and help prevent future disasters can be lost. Therefore, several researchers have investigated the implementation of schemes to provide wireless transmission of data from aircraft to ground terminal, which would enable the transfer of valuable airplane data to the ground terminal when the airplane is still able to establish a link for the transfer.

### 1.1 Related Work

A. Ashish and S. Chougule[1] utilized XBee-RF Module for wireless transmission of FDR data to the ground. The inventors of the wireless system, T.H. Wright and J.J. Ziarno[5] developed an RF, spread spectrum communication system through which the flight performance data can be downlinked from the aircraft parked at different locations and analyzed. H.L. de Leon and R.E. Quiros,[6] designed a self-contained flight data recorder for small aircraft which captures various onboard flight data in real-time and stores it in non-volatile memory. At the end of a flight, the recorded data is downloaded into a computer using a wireless communications data transceiver also integrated into the recorder. The system developed by Klippert,[7] achieves wireless data transfer using zero-configuration auto network discovery and heuristic triggersto analyze the data in real-time. Wireless transmission has obvious advantages when a large number of aircraft and ground maintenance personnel are involved and flight safety is of paramount importance.

X. Zhang and D. Zhang[8] used airborne wireless sensor networks for monitoring airplane (and its systems') health data within the aircraft. This data from the airplane health monitoring system could also be transmitted wirelessly to ground stations. Ziarno & Gallagher,[9] transmitted data from an aircraft to the ground over an RF communications signal through the skin of the aircraft itself. Wireless communication methods have also been used by Cope and Kaufman[10] to transmit the recorded flight statistics and cockpit voice data from commercial aircraft and transmit the data via a commercial or private satellite network, to a suitable, secure data center on the ground. The data may be sent in Internet Protocol (IP) format or other proven communication formats for voice/data transmission. This downloaded flight data can then be immediately retrieved in the event of an accident, to assist in a mid-flight crisis, or for preventative or predictive maintenance, and/or for flight personnel training.

Tom, Tiwari, Yadiyala, Renuka, & Shivaprasad[11] have presented a scheme for assisting the pilots with runway operations, where the airplane parameters such as altitude, engine RPM, gyro information, etc. are wirelessly communicated to the ground Air Traffic Control (ATC) terminal, by utilizing XBee module and Zigbee software protocol. An interesting scheme to store FDR data in "communicating materials" (which are materials impregnated with hundreds of tiny sensor nodes in the aircraft structure), was presented by Mekki, Derigent, Rondeau, and Thomas.[12] The nodes areintegrated by a wireless sensor network inside the aircraft and store the latest FDR data. In the event of an aircraft crash, the FDR data can be recovered from the aircraft's skin wreckages. Huang, Wang, Zhang, and Fang[13] propose a wireless flight recorder that can transmit the recorded operating data of a plane while in flight, to a ground center, through an aerial network with the aid of satellites. An emergency wireless communication system has been implemented by Gummineni and Polipalli[14] using SDR, as an alternative solution for reliable communication for emergency services. Comitz and Kersch[15] used an SDR to wirelessly receive data from an aircraft's Automatic Dependent Surveillance–Broadcast (ADS–B) system.

A survey of the literature on the subject reveals that, while several papers exist on the wireless data transfer in commercial aircraft, little is known about the work on military aircraft. The aspects such as data security, rugged operating environment, EMI/EMC, etc. assume significance in a defense scenario. In addition, there is little or no literature on implementation of secure, wireless connectivity in 'bought-out' aircraft, that is, aircraft which have been already bought from an original equipment manufacturer (OEM). Such scenarios present the additional challenge of interfacing the wireless hardware with existing connectors on the aircraft and the requisite software / firmware. The researches carried out thus far, also do not mention any details regarding the compliance to the stringent qualification and airborne-certification requirements of the equipment installed on board aircraft.

### 1.2. Motivation for This Research

The following factors were the main motivation for carrying out this research:

Many a time, when an aircraft is lost in an accident, the task of obtaining the data from its Flight Data Recorder becomes a cumbersome task. The loss of aircraft at sea, or in an inaccessible terrain, renders the effort of retrieval of the Blackbox or its FDR, most often, futile. It was therefore felt that, if the data could be transferred wirelessly (whenever the aircraft was within a certain wireless range), there would be some form of 'back-up' data available.

While a number of patents exist on the wireless transfer of data from aircraft to ground, there is very little literature available regarding the design and development of wireless data transfer schemes.

It was felt that an ingenious, effective, versatile solution, could be implemented, with the technologies available today.

### 1.3. Unique Contribution of this Paper

The current method of accessing the FDR data involves manual intervention. The wireless connectivity for FDRs has been explored by authors in[11] and[1] earlier with Zigbee and WiFi-based technologies. In the current paper, a unique wireless system is presented. While any wireless technology may seem suitable for connectivity, the flexibility in terms of operating frequency, custom security overlays, variable channel bandwidth (variable data rates), RF transmit power, etc. are important considerations. The following are the unique contributions and the novelty of our research:

We have developed a novel, versatile system which is user-configurable and scale-able. The proposed system is configurable over a bandwidth starting from 250 KHz to 10 MHz. The scheme can be employed in a simple point-to-point or a multi node setup. The number of users can vary from a 2-node to 64-node scenario.

A new hardware scheme was designed to interface seamlessly with the existing connections, data protocols, and software on the aircraft and ground equipment, supplied by the Original Equipment Manufacturer (OEM) without causing any disruptions.

It possesses the inherent flexibility of operating in licensed and unlicensed frequency bands, and provides enhanced security as detailed subsequently in this paper.

We have also ensured that the Wireless Transmitter Receiver (WTR) units have passed the requisite EMI/EMC and environmental tests to make them fit for installation on airborne platforms.

One of vital constituents of any wireless channel is channel estimation, and that has also been satisfactorily implemented in our scheme.

Our scheme also incorporates adaptive modulation, in order to cater to the vagaries of the radio network and the rugged environment defence aircraft are expected to operate in.

The Size, Weight and Power (SWaP) are the pre-requisites of any airborne equipment. We have ensured that the proposed implementation optimizes and saves power.

The various experiments conducted and results achieved are enumerated in the course of this paper. The remaining sections are organized as follows. Section 2 describes the system model and implementation of the wireless system, Section 3 details a high-level summary of the test results. Section 4 is the discussion for the way ahead and Section 5 is the conclusion.

## 2. SYSTEM MODEL

### 2.1 Implementation Scheme

The broad scheme we utilized to implement wireless connectivity between the aircraft's FDR and the Ground Computer is explained in this section. The schematic of the arrangement is depicted in Fig. 1. We designed suitable WTRs to interface with the existing connectors on aircraft and the Ground Computer (a customized laptop supplied by the OEM of the aircraft). The aircraft was in the hangar and the Ground Computer was positioned at a distance of 50 meters. The Ground Computer already ran software that was reading the FDR data from the aircraft using the traditional, manual methods. We employed two WTRs: one for transmitting the FDR data and the other to receive it. The WTR at the transmitting (aircraft) end worked as a wireless router, accepting Ethernet packets from the FDR device on the aircraft, and transmitted them to the Ground WTR connected to the controller system. The setup is shown in Fig. 2.

The Ground WTR connected to the Ground Computer system processed the received RF signal, demodulated it, and provided the IP packets to the Ground Computer system. When the Ground WTR (connected to the Ground Computer) established a connection with the Aircraft WTR (connected to the aircraft's FDR), IP traffic connection was made and wireless data transfer triggered.

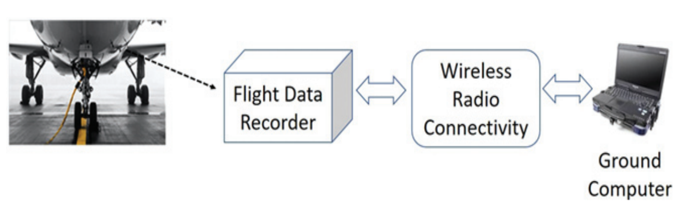


**Figure 1. Aircraft to ground wireless link: Schematic.**

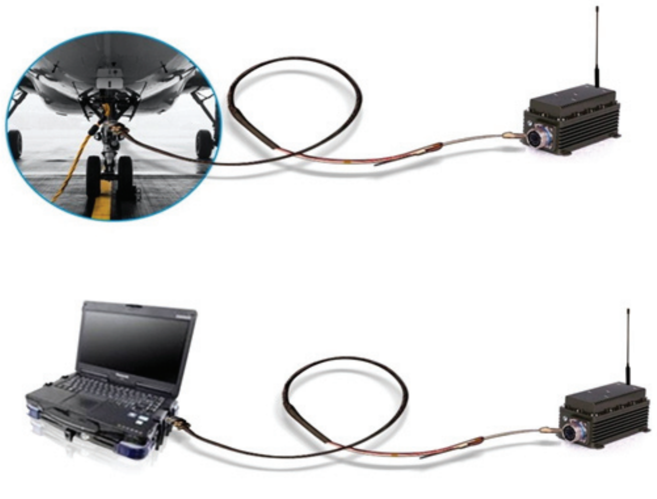

**Figure 2. Overall setup of the aircraft to ground wireless transfer.**

## 2.2 Hardware Implementation

### *2.2.1 Wireless Transmitter Receiver*

The hardware architecture of the WTR designed and developed for this study is shown in Fig. 3. The WTR, similar to an SDR, as mentioned by Wavedytu,[16] Dixon,[17] and Umashankar, Prasad, and Bhattacharya,[18] combines multiple wave-forms and technologies to optimize the radio performance and efficiency for a given wireless scheme. It has user-friendly configuration modes where the researcher can use default configuration or change it, based on the application and network. As shown in the hardware architecture in Fig. 3, the WTR consists of two subsystems: Baseband Unit and Radio Front End. The Baseband subsystem is a wideband low-power radio, supporting all the frequency bands V/UHF, L, S, and C bands. The digital section is supported by Xilinx® 7000 series Field Programmable Gated Array system-on-chip with programmable logic for digital signal processingand protocol functionality. The program logic implements the waveform transmit and receive signal chains including synchronization, modulation/demodulation, and channel coding and decoding techniques. The Radio Head (RH) provides the front-end amplification and filtering for a given frequency band. The radio head also supports transmission and reception through a Time Division Duplex (TDD) scheme. In case a different frequency band of operation or power is required, only the RH needs to be changed. Thus, this architecture enables swift implementation of a different radio specification.

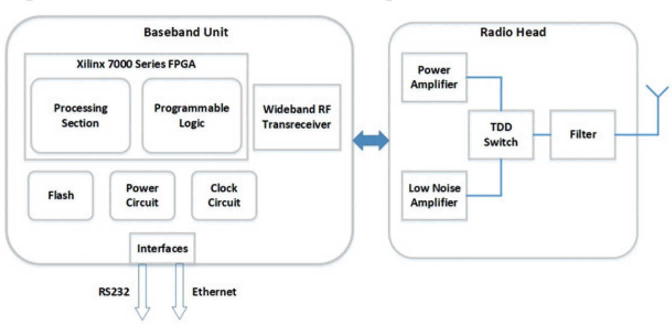


**Figure 3. WTR: Hardware architecture.**

The software architecture of the WTR used is shown in Fig. 4 and depicts the various functional blocks.

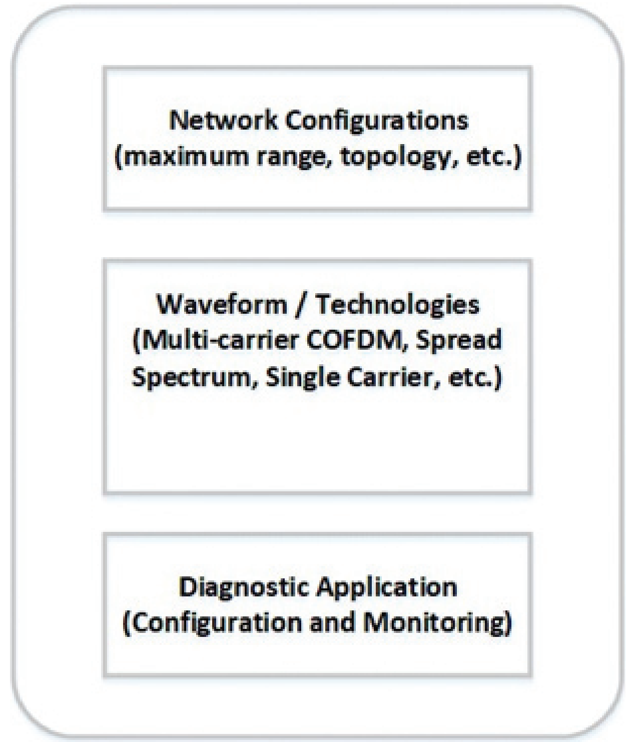


**Figure 4. WTR: Software.**

The Network Configuration block overcomes the disadvantages associated with a fixed configuration and enables the user to configure network related parameters like maximum range, network topology in terms of Point to Point (PTP) or Point to Multi-point (PTMP) or Peer-Peer connectivity (P2P), and the number of users. Using the fixed network configuration adds up more overhead and it results in lower WTR performance. For instance, when ranges such as 1 Km, 10 Km, 30 Km etc, are required, the WTR waveform frame structure uses the optimal propagation delay overhead to support the desired range. The delay optimization improves the through-puts. Similarly, PTP scenario use lower overheads compared to PTMP or P2P network topology. Therefore, our wireless transmitter receiver units can be setup with optimal configuration parameters based on the network configuration.

The Waveforms block is the core signal processing component with all the base- band and protocol functions implemented to process the RF signals. It decides the appropriate technology or waveform for the specified application. For example, for higher data rate, the multi-carrier waveform is used so that the symbol time is larger to accommodate inter-symbol interference. For lower data rates, Single carrier or constant envelope waveformlike Shaped-offset quadrature phase-shift keying or Gaussian Minimum Shift Keying waveform can be used. If a low probability of intercept or anti-jamming features are required, spread spectrum waveform can be employed. The Diagnostic Application supports the user configuration and provides a monitoring interface displaying the Key Performance Indicators like received signal strength, carrier interference noise ratio, and the data rate. The WTRs were configured to operate at 2.4 GHz ISM license-free band for this research study. The radios can however be designed to operate in any specific licensed or license-free bands by changing only RH with minimal turnaround.

*2.2.2 Interface Connectors Design*

The WTR connectors to interface with the existing connectors on the fuselage of the aircraft and the Ground Computer were designed and fabricated. The connector pin configuration of the existing aircraft connection socket to the Ground Computer is shown in Table 1.

**Table 1. Interface connector details**

| Aircraft Connector Pin number | Ground Connector Pin number | Pin Description |
|---|---|---|
| 1 | 6 | Rx+ (Ethernet) |
| 2 | 1 | Rx- (Ethernet) |
| 3 | 9 | Tx+ (Ethernet) |
| 4 | 8 | Tx- (Ethernet) |
| 6 | 4 | -27V (Power) |
| 10 | 16 | +27V (Power) |

Based on this existing configuration, new cable looms were designed to interface the aircraft with the Aircraft WTR and the Ground Computer with the Ground WTR. The new mating connectors designed and manufactured to interfacewith the existing connections are shown in Fig. 5.

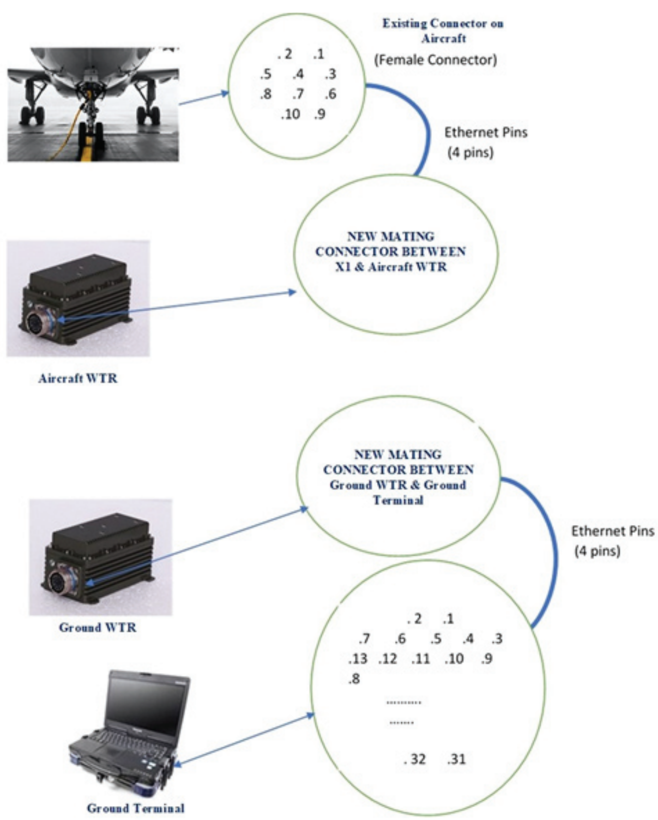


**Figure 5. New mating connectors.**

## 3. EXPERIMENTAL EVALUATION AND RESULTS

The functional performance of our scheme was evaluated with respect to various aspects such as with the aircraft stationary, with a flying object, laboratory emulation in a controlled wired mode and also with EMI/EMC and environmental tests.

### 3.1 Stationary Aircraft to Ground Wireless Transmission

*3.1.1. Test Setup*

The aircraft's FDR (as shown in Fig. 2), was connected to the Aircraft WTR, and the Ground WTR wasconnected to Ground Computer with the help of the hardware interfaces manufactured for the study. The transmitter and receiver were separated by a distance of 50 meters. On powering up the aircraft, WTRs, and Ground Computer, the Aircraft WTR initiated the connection request, the Ground WTR authenticated it and a wireless connection was established. The FDR data transfer was initiated using the existing application in the Ground Computer. The sequence of the data transfer is as follows and is also depicted in Fig. 6.

- The Ground WDR initiates Broadcast channel transmission
- The Aircraft WTR, (by default) in search mode, detects the broadcasted data
- The Aircraft WTR initiates connection request to Ground WTR
- The Ground WTR authenticates the connection request and sends the connection response. This establishes the connection
- The Ground WTR initiates the access request for FDR data
- The Aircraft WTR requests for the necessary bandwidth to transfer the data
- The Ground WTR grants the bandwidth and the Aircraft WTR completes the data transfer.

*3.1.2 Results*

At the operating frequency of 2.4 GHz, we observed transfer speeds of 850 Kbps from aircraft to Ground Computer (and less than 5 Kbps from Ground Computer to aircraft). The wireless transfer of 17 MB data from the aircraft FDR was completed in less than 3 minutes. We viewed the received/downloaded FDR files on the Ground Computer and compared the FDR contents received wirelessly with those obtained through a manual process. We did not notice any error and there was absolute fidelity. There was a 0 % packet loss. The signal-to-noise ratio was 30 dB. The data was of Broadcast type; therefore, after completion of download from one aircraft, FDR data from another aircraft was ready to be accessed.

### 3.2 Flying Object to Ground Wireless Transmission

In order to evaluate the maximum range performance of our proposed scheme, we carried out tests for a 10 Km aerial range with a flying object. The link margin was evaluated at the 10 Km range scenario and the available link margin was mapped to 50 Km range possibility.

*3.2.1. Test Setup*

The outdoor test setup is shown in Fig. 7.

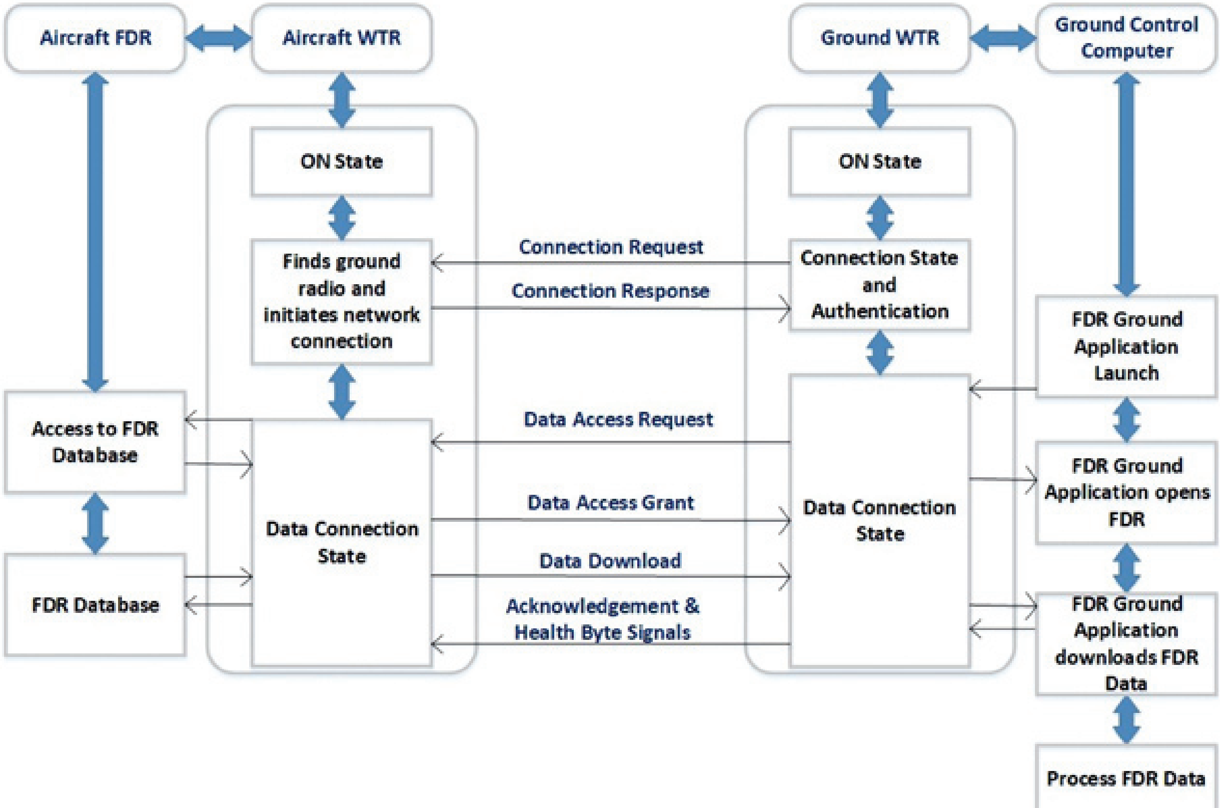


**Figure 6. Data transfer state machine.**

**Figure 7. Wireless outdoor test setup.**

*3.2.2 Results*

Streaming of real-time video and command and control was verified with the integration of the actual flight operation. The video payload used the Ethernet IP packet interface, and the command and control, serial interface. The command-and-control interface supported a full-duplex bidirectional link. Though the video also supported a bidirectional link, in this particular application, video link tests were carried out in a single link direction. The link performance, in terms of the ground control system's received signal strength and Carrier to Interference Noise Ratio (CINR), were monitored continuously. For the 10 Km range, the received signal strength was -75 dBm and, the CINR 20 dB. The results of the outdoor test, at a frequency of 2.4 GHz, and other intermediate ranges, are shown in Table 2.

(Note: QSPK Rate ½ to QAM16 Rate 3/4 Modulation schemes were enabled and for CINR greater than 15 dB, QAM16 Rate ¾ was used.)

### 3.3 Flying Object to Ground Transfer Through Controlled Emulation

The Aircraft and Ground WTRs were connected to laptops to emulate the application data transfers. RF Channel emulator

**Table 2. Outdoor test results**

| Range (Km) | Data Transfer Rates (Mbps) | Packet Loss (%) | Average Received Signal Strength (dBm) | Average CINR (dB) |
|---|---|---|---|---|
| 0.5 | 8.2 | 0 | -50 | 30 |
| 1.0 | 8.2 | 0 | -55 | 30 |
| 5.0 | 8.2 | 0 | -68 | 27 |
| 10.0 | 8.2 | 0 | -75 | 20 |

was used to vary the path loss, delay, doppler and doppler rate. For all the scenarios, the receiver-side data rates and packet loss metrics were measured and used for qualification. It is pertinent to mention that laboratory controlled tests have also been conducted by Ramanath & Babu[19] in a cable-connected mode in AWGN and mobility channels, to validate the algorithms for sensitivity, high Doppler, and multipath conditions.

### *3.3.1 Test Setup*

The channel emulator setup in the laboratoryis shown in Fig. 8. The setup was configured to measure the following parameters:

- The path loss between the Aircraft WTR and Ground WTR (by varying the receiver input signal from -70 dBm to -95 dBm).
- The maximum doppler corresponding to 3 Mach speed and Doppler rate of 500 Hz per second.
- The propagation delay mapped at 100 Km range.

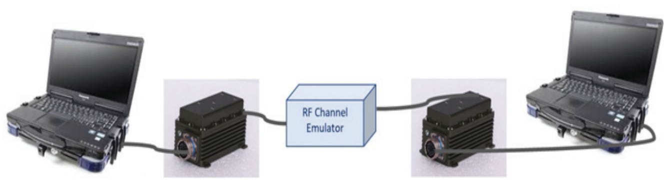


**Figure 8. Lab-based controlled conduction test setup.**

### *3.3.2 Results*

The salient results are listed as follows:

- The transmitted power was kept constant, the path loss sweeps were changed and the receiver input signal varied from -70 dBm to -100 dBm. The data packets were transmitted to receiver and the rate at which no packet loss was observed, is captured in Fig. 9.
- The Figure 9 reveals the flexibility of the WTRs' operation with variable bandwidthand different power levels. Data rates can be scaled with higher bandwidth configurations, at long ranges, and our scheme can operate in lower data rate modes for better connectivity. With this variable adaptation, our method is spectral-efficient.

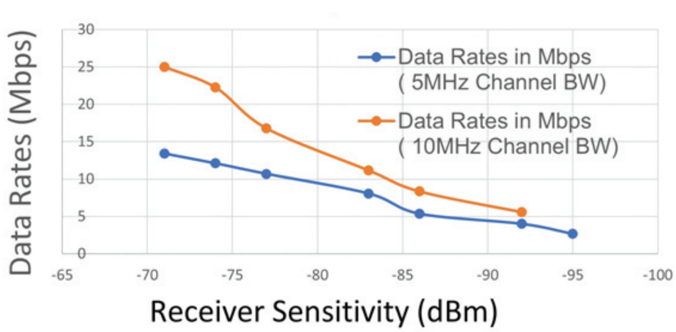


**Figure 9. Receiver sensitivity and data rates.**

- The doppler and doppler rate were configured to the specifications mentioned in the parameter description and at the edge sensitivity of -95 dBm for 5 MHz and -92 dBm for 10 MHz bandwidth configuration, and the data rates versus packet loss was verified. No packet loss was observed.
- A one-way propagation delay of 350 microsecond was configured to emulate the range of 100 Km, and the data rate versus packet loss was verified. No packet loss was observed.

## 3.4 EMI/EMC and Environmental Tests

The Electromagnetic Interference and Compatibility (EMI/EMC) and environmental qualification tests have also been carried out in the laboratories to ensure that the WTRs meet the stringent criteria for installation onboard aerial platforms. MIL-STD-810G Environmental qualification, MIL-STD-461E Electromagnetic compatibility qualification and MIL-STD-704F Electrical power characteristics qualifications have been met for the WTR units. The results of EMI/EMC tests and environmental tests are shown in Table 3 and Table 4 respectively.

The WTR units were exposed to the EMI/EMC and environmental parameters listed in Table 3 and Table 4 and the datarates, receiver sensitivity and packet loss metrics were verified. No degradation was observed with respect to the reference performance mentioned in Fig. 9.

## 4. INNOVATIVE APPROACH AND ADVANTAGES ACCRUED

The wireless system for aircraft-to-ground connectivity in this study has been innovative in the following aspects:

### 4.1. Topology

It facilitates PTMP topology wherein, a single ground computer system can be wirelessly connected with multiple aircraft FDRs. This would be particularly advantageous in a scenario where many aircraft rapidly land and take-off at a single location,and manual intervention for data transfer is not required. The proposed wireless transmitter receivers support this PTMP network topology to connect multiple remote nodes simultaneously. In such a scenario, remote nodes (in different aircraft) would request channel access, and bandwidth would be granted from the ground control station. The ground control station, working as central node, would authorize the remote nodes' request and allocate channel bandwidth on sharing basis. The bandwidth is shared in both time (using multiple time division multiple access time slots) and frequency (with multiple subcarriers using orthogonal frequency division multiple access). The data burst can be at different modulations based on the specific remote node signal quality.

### 4.2 Number of Nodes Supported

The proposed solution can easily support up to 16 nodes without any change in hardware. Our solution can also cater for more than 16 nodes with an enhancement to the baseband processing power.

### 4.3 Link Adaptation

The wireless link can be easily monitored and adapted to dynamically support various data rates through the WTRs. The

**Table 3. EMI/EMC test results**

| Name of the test, standard and specifications | Environmental conditions | Results |
|---|---|---|
| CE 102<br>MIL 461E<br>10 KHz–10 MHz | Temp: 23.2°C<br>RH: 48%<br>Temp: 22.1°C<br>RH: 46% | This requirement is applicable from 10KHz to 10MHz for all power leads, including returns that obtain power from other sources not part of the EUT. The CE Test Setup is as per MIL 461E and the limits comply to figure CE102-1 Basic curve in MIL 461E STD. |
| CS101<br>MIL 461E<br>30 Hz–150 KHz | Temp: 22.1°C<br>RH: 47%<br>Temp: 23.1°C<br>RH: 48% | Conducted Susceptibility test –<br>CS101 Power leads, 30Hz to 150 KHz Test Setup as per MIL 461E and compliance to figure: CS101-1 Curve 1 (above 28V) in MIL 461E STD. |
| CS114<br>MIL 461E<br>10 KHz-2 MHz<br>2 to 100 MHz | Temp: 23.3°C<br>RH: 47%<br>Temp: 23.8°C<br>RH: 47% | CS114, Bulk cable injection, 10KHz to 2MHz. Test Setup as per MIL 461E.<br>Figure CS114-1, Curve 3 in MIL 461E STD |
| CS115<br>MIL 461E<br>Impulse excitation | Temp: 23.1°C<br>RH: 49%<br>Temp: 23.5°C<br>RH: 50% | CS115, Impulse excitation, 30nS with repetition rate of 30Hz as per MIL 461E. The EUT is operational with link function and no loss of radio initialization. |
| CS116<br>MIL 461E<br>Damped sinusoid<br>10 KHz-100 MHz | Temp: 22.5°C<br>RH: 50%<br>Temp: 22.7°C<br>RH: 51% | Conducted Susceptibility CS116, damped sinusoidal transients, Cables and Power leads, 10KHz to 100MHz, maximum current = 10 Ampere. Test setup as per MIL 461E Figure CS116-1, CS116-2 in MIL 461E STD. |

**Table 4. Environmental test results**

| Test details | Observations |
|---|---|
| Random Vibration Test:<br>Frequency 20 to 50 Hz 0.0292, at $G^2/Hz$<br>Frequency 50 to 500 Hz falling to 0.001, at $G^2/Hz$<br>Duration: 5 min per Axis<br>Direction: in all 3 Axis (X, Y, and Z)<br>Condition: Power ON<br><br>High-Temperature Test<br>a. Temperature: +700°C +/- 30°C<br>Duration: 4 Hours<br>Condition: Storage<br>b. Temperature: +550°C +/- 30°C<br>Duration: 4 Hours<br>Condition: Operational | No physical damage observed after these tests |
| Test Details | Observations |
| Damp Heat Test<br>Temperature: +550°C +/- 30°C<br>Humidity: 95% to 98% RH<br>Duration: 4 Hours<br>Condition: Power ON for last 30 minutes on performance check<br><br>Low-Temperature Test<br>a. Temperature: -100°C +/- 30°C<br>Duration: 4 Hours<br>Condition: Operational<br>b. Temperature: -200°C +/- 30°C<br>Duration: 4 Hours<br>Condition: Storage | No physical damage observed after these tests |

remote nodes transmit the received channel quality in terms of signal to noise ratio or channel quality index through the periodic uplink measurement report. These link measurements are used by the control station to allocate the different modulation and coding schemes for each node. For example, if the link condition is poor due to extended ranges or Near Line of Sight situation, the WTR downgrades the modulation and coding scheme (MCS) to maintain the reliable link. Therefore, although different aircraft flights may experience different link conditions, the WTRs would automatically monitor and configure the suitable modulation schemes and maintain the best possible connectivity. The different MCS supported are QPSK, QAM16 and QAM64 with channel coding rates ½, ¾ and 5/6.

### 4.4 Channel Estimation

A dynamic channel estimation algorithm is employed. It uses the demodulated reference symbols received on every slot, to compute the channel estimates with efficient interpolation techniques. Different interpolation techniques were compared for different channel models like Pedestrian-B and Vehicular-A Tapped Delay Line models. Different interpolation techniques were compared for different channel models. Lagrange interpolation scheme which was found better than linear interpolation methods was used. In our application, a LOS scenario was assumed with no severe multipath losses. The channel estimate $y(x)$ for a position $x$ can be given by the equation:

$$y(x) = \frac{(x-x_2)(x-x_3)}{(x_1-x_2)(x_1-x_3)}y(x_1) + \frac{(x-x_2)(x-x_3)}{(x_2-x_1)(x_2-x_3)}y(x_2) + \frac{(x-x_1)(x-x_2)}{(x_2-x_1)(x_2-x_3)}y(x_3) \quad (1)$$

where, $y(x_1)$, $y(x_2)$, $y(x_3)$ are the channel estimates at the nearest reference symbol positions $x_1$, $x_2$ and $x_3$.

The channel estimates for reference symbols were estimated using zero-forcing method with actual known transmitted reference symbols. The WTR uses Cyclic Prefix based Coded Orthogonal Frequency-Division Multiplexing (COFDM) waveform which has high tolerance to multipath delay spread. The frame uses lower granularity time and frequency slots where the channel estimate is done on slot basis to equalize the channel effects for frequency selective time varying fading scenarios.

### 4.5 Dynamic Power

Power Control feature of the WTR supports the dynamic computation of the transmit power. The control channel transmits the reference power in the broadcast to all the remote nodes. Each remote node calculates the path loss of the received signal in every frame, by comparing the received level with the control station's transmit power reference. Based on the allocated modulation and coding scheme, the WTR computes the required transmit power to maintain the minimum signal to noise ratio. This helps to save the power for the radio installed in the aircraft. The resolution of power control is in the range of 1 dB. The power control reference equation is given by:

$$Premote = Pgndctrl + Ploss + SNR_{MCS} \quad (2)$$

where,

Premote = Transmit power for the remote node on the aircraft.

Pgndctrl = Normalized power required to be maintained at the ground control station receiver.

Ploss = Path loss between the transmitter node on the aircraft and the ground control station receiver.

$SNR_{MCS}$ = Signal to noise ratio at the receiver for the modulation and coding scheme employed.

The remote node computes the path loss (Ploss) by measuring the received signal strength with respect to the power transmitted by the ground control station (which is communicated to the remote node over the control channel). In order to maintain the normalized power at the ground control receiver (Pgndctrl), the transmitter node computes its transmit power, as given by Eqn. (2) by compensating for the path loss and the SNR for the modulation and coding scheme being used.

### 4.6 Security

For a wireless mode of communication, Security plays an important role to protect the data. The proposed solution offers multi-layer security by providing:

- User authentication at Network access level. The Privacy Key Management security protocol is used in the security layer to provide authorization, authentication and key exchange. The central station node authenticates a remote node during the initial authorization exchange using digital-certificate-based remote node authentication.
- Message level application data security. The Advanced Encryption Standard (AES) with 128 bit or 256-bit key is used to derive the cipher during the authentication phase. It is periodically refreshed for additional protection.
- Frequency hopping of transmission is built-in to ensure low probability of intercept and as an anti-jamming measure. The hops can be configured by the user between 500 to 1000 hops/sec. Using COFDM waveform, each hop, causes frame overhead of 0.04 %. For example, in 100 Hops/sec, the throughput drops by 4 %, in case of 500 Hops/sec, throughput drops by 20 %, and in case of 1000 Hops/sec, throughput drops by 40 % from the full throughput value mentioned in Receiver Sensitivity and Data Rates (Fig. 9).

### 4.7 Data Fidelity

The reliability of data for momentary variations in environmental conditions, is achieved by validating the packet transfer, through the use of the following techniques:

- Adaptive Modulation and Coding: Adaptable channelcoding rates are employed to increase the communication reliability. Convolutional turbo codes with rates of 1/2, 3/4 and 5/6 are used in the proposed solution. The channel quality is measured dynamically and the coding rates (low or high) are selected based on the frame-by-frame channel measurements.
- Low-latency, protocol level, selective re-transmission

mechanisms are used for the packets received in error. Though at physical layer, channel coding ensures low error conditions, packet loss is still possible in a wire-less condition. These losses can be momentary. Re-transmission helps to avoid these momentary packet losses. Automatic Repeat Request (ARQ) and Hybrid ARQ (HARQ) methods are adopted in the proposed solution. ARQ helps in re-transmission of the full packet in the case of an error condition, whereas HARQ enables the re-transmission of a particular physical layer-level block of a packet to reduce the overheads and improve the latency. These two methods ensure 0% packet loss on the data transaction. The verification is done using by lowering the signal level in the setup described in Figure 8. ARQ and HARQ methods improve the signal reliability by a link margin of 3 to 4 dB. This Re-transmission scheme is shown in Fig.10.

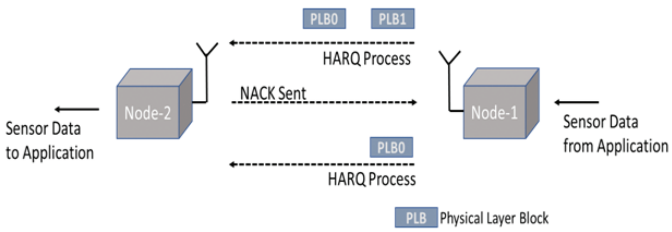


**Figure 10. Physical layer block level re-transmission.**

- The wireless transmitter receivers support frequency-scan feature to give a frequency-versus-power / interference map to facilitate the channel selection. The frequency scan includes two modes: Initial scan and Dynamic scan. The initial scan is done during system initialization. The central station measures the received power for every configured frequency, across the frames, in all the slot periods, and records the measurement report for the low noise channel selection. In dynamic mode, a 'noise measurement zone' is allocated periodically to measure the noise levels across the frames. The allocation of 'noise measurement zone' is configurable. The zone-width in terms of frames depends on the number of channels to be monitored and the specific frames where the performance drops are observed. Typically, less than 5% channel bandwidth is allocated for monitoring. In the band 2.4 GHz to 2.4835 GHz, there is a possibility of interference in the specific channel due to other applications in the vicinity. The proposed solution scans the full band and reports the channel power measured in each channel. The minimum noise floor thresholds can be applied (for example: -100 dBm)for channel selection and usage.

## 4.8 Aircraft-Ready

As mentioned earlier, aeronautical applications demand equipment of low SWaP factor and the WTRs are ideally suited to fulfill this requirement. The proposed solution can be configured for different form-factors and weight options. For lower transmit power (< 1Watt) requirements, the WTR has a dimension less than125 mm x 125 mm and weight < 400 grams. The optimized SWaP was achieved in the following manner.

The Baseband design uses a two chip-based design, with integrated semiconductor devices. The entire digital processing is carried out in Xilinx FPGA SoC device. The low power RF Transceiver is an integrated device with analog-to-digital, digital-to-analog converters, mixer and analog and digital filter sections.

The Radio front end is a Time Division Duplex (TDD) based design to provide optimum form factor. Since utilizing Frequency Division Duplex methods for high ranges and high RF power would have resulted in a 'bulkier', heavier duplexer component, TDD based approach was used to optimize the SWaP for airborne applications.

### *4.8.1 Comparison With Other Solutions.*

The multi-path resistant based multicarrier COFDM waveform is an advanced 4G / 5G equivalent waveform, and our proposed solution can meet the requirements of many tactical networks also. Indigenous development of this advanced technology waveform is unique, and most of the other competitive solutions are using legacy waveforms.

While some of the existing solutions do support wireless transmission mechanisms from Aircraft to ground, the solution described in this paper utilizes a new-generation WTR equipment with the following unique key features.

- Robust transmission and reception mechanisms in terms of 0 % packet loss. In case of not achieving 0% loss, the radio 'Continuous Build in Test' report identifies the specific packet sequence suffering from packet loss, so that backup offline methods can recover the data. Also, in this solution, multipath-resistant, new-generation multi-carrier waveforms have been implemented. The retransmission mechanisms to achieve 0% packet loss are efficient methods in terms of Physical layer block level retransmissions so that bandwidth increase is not noticeable.
- While data security at Application level is implemented in most of the standard and proprietary equipment, in this work, Transmission Security is achieved with Frequency Hopping (at max rate of 1000 Hops/sec), to ensure best possible Anti-Jamming protection against jammers.
- The commercially-off-the-shelf WTR solutions generally support operation in the Industrial Scientific Medical (ISM)'s free-band and these solutions are usually not flexible to adapt to Licensed bands. The solution described in this paper, on the other hand, has been tested in ISM band and can also work in the Licensed band for mission-critical, secure applications. This solution can be customized for a given frequency band with no change in software and minimal change in hardware, due to its modular and flexible architecture.
- The solution supports programmable channel bandwidths and data rates. Therefore, if more sensors and high sampling data rates are required, the same solution can be configured to achieve higher data rates.

## 5. DISCUSSION AND FUTURE WORK

The research can be progressed to the installation of the WTR and antenna on the aircraft, to carry out the testing during taxying on the runway, within the range of the wireless network. The main challenges encountered in the study were the WTR's Form Factor optimization and the limited access to outdoor testing. However, these have been successfully overcome, as evident from the results. While, other existing wireless transceivers may also have been suitable, our research has focused on the unique aspects based on the type of waveform, protocol-based retransmission methods, security in terms of application data security and Frequency Hopping (specifically hopping rate), to make our own unique contribution to the research in this domain.

Moreover, unlike other generic WTRs which may be suitable for land-based applications, our WTR units have cleared the Qualification Testing for airborne application, the approval of the Certification Authority can be easily obtained for installation on aircraft. This study utilized the operating frequency of 2.4 GHz. However, any sub-GHz frequency for a narrow channel of less than 1 MHz can be used to improve the wireless range. Frequencies in L-band and C-band can also be employed. The data rates can be varied and experimented with for obtaining higher ranges.

Further research work may also include enhancing security methods by faster frequency hopping techniques, multi-layered application data level security schemes. Wireless range and data rate performance can be enhanced through MIMO, Antenna Array methods, and Hybrid ARQ. The solution presented here can be scaled upfor supporting more than 16 aircraft (for a large squadron) with one Ground controller station. We believe sustainability and constant performance enhancements are possible with improvements in radio aspects. The radios also can be customized for onboard recording with a specific memory requirement to make sure data backup is available.

## 6. CONCLUSION

A modern aircraft is a complex system of systems whose performance needs to be monitored closely. Therefore, numerous sensors are installed in the aircraft to monitor the performance of its various sub-systems. This paper presents a wireless system for extraction of the data from the aircraft sensors. An aircraft-to-ground wireless link has been successfully designed and developed and interfaced with a bought-out aircraft. The wireless transfer has been successful with the aircraft on ground, and a flying object at a range of 10 Km. The WTRs have passed the stringent EMI/EMC and environment tests and are certification-ready for installation on airborne platforms. The wireless mode of data transfer was compared with the manual/wired mode and complete data match was observed without any loss. Our application-oriented system is simple, cost-effective, and very efficient. Its implementation on the aircraft would be a 'game changer' to achieving flight safety and redundancy. The wireless system proposed would be extremely useful for remotely monitoring the performance of other complex machinery as well.

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He has guided this entire study by providing crucial inputs during the course of the implementation.