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Evaluation of a Wireless Data Transmission Using a Low-Cost Commercial-off-the-Shelf Wi-Fi Router Applied to Dynamic Tests

Mateus Rodrigues Rocha[1,*], Anderson Govertz[1], Rogerio Pirk[2], Edilson Alexandre Camargo[2]

1. Departamento de Ciência e Tecnologia Aeroespacial – Instituto Tecnológico de Aeronáutica – Programa de Pós-Graduação em Ciências e Tecnologias Espaciais – São José dos Campos /SP – Brazil.
2. Departamento de Ciência e Tecnologia Aeroespacial – Instituto de Aeronáutica e Espaço – Divisão de Integração e Ensaios – São José dos Campos /SP – Brazil.

*Correspondence author: mateusmrr@ita.br

ABSTRACT

The use of non-intrusive instrumentation has been growing in different scenarios in the industry. In the aerospace field, non-intrusive or hybrid instrumentation approaches have demonstrated robustness and viability, presenting significant advantages such as mass reduction of space vehicles, flexibility, and reduction of instrumentation lead time. This work presents a brief overview of a hybrid instrumentation system, in which the Wi-Fi standard communication protocol is highlighted. As a case study, the experimental structural modal analysis technique was adopted to show the technical advantages of using this promising data acquisition (DAq) system. To achieve this, test data were acquired using the traditional wired method between sensors, DAq, and the computer, as well as a wireless transmission protocol, via Wi-Fi, between the DAq and the computer. The comparisons of the results of the modal analysis experiments showed good agreement, indicating the Wi-Fi communication protocol is suitable and reliable for the tested scenario.

Keywords: Wireless communication; Modal response; Data transmission; Non-intrusive measurement.

INTRODUCTION

Although traditional wired flight test instrumentation (FTI) has been widely used in aircraft and space vehicles for decades and has proven to be very reliable, this technology is highly invasive, often consisting of kilometers of wires and cables, weighing tons. Wires and cables are also subject to wear, damage, failures, breaks, and cuts, among many other problems. This traditional wired measurement technique may also change the structure's behavior, since wires, cabling, mounts, connectors, fasteners, etc., can add mass and rigidity to the tested structure, modifying the modal parameters. Additionally, another significant disadvantage of this intrusive instrumentation is the high lead time instrumentation that must always be accounted for in aerospace structural test design.

As a replacement for wired instrumentation, wireless instrumentation has been widely studied and recommended. This non-intrusive FTI (NIFTI) uses radio frequency technologies for data acquisition (DAq) and transmission, aiming to eliminate wires, connectors, and mounts, reducing instrumentation time, instrumentation costs, and the weight of space vehicles.

Despite the global trend towards using wireless or hybrid instrumentation technologies for space applications, many of these technologies are not yet widely developed. For both military and space use, reliability requirements are very strict and, therefore,

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research in this area must be conducted. The adoption of wireless solutions should only be implemented if they do not compromise critical operations, allowing adequate and acceptable data transfer rates and accuracy, thereby proving their reliability (CCSDS 2017). Given these facts, the following research question is raised: is it possible to replace conventional data transmission instrumentation with reliable wireless data transmission instrumentation while guaranteeing the same results?

This paper presents a reliability assessment and a comparison of results between an RJ-45 wired connection and a Wi-Fi router. For this research work, a hybrid Wi-Fi data transmission system instrumentation was used for the sensitivity analyses of an experimental modal analysis. Both Wi-Fi 802.11n (2.4 GHz) and 802.11ac (5 GHz) standard communication protocols were chosen instead of the other protocols (Zigbee, Z-Wave, WirelessHART, ISA100.11a, Bluetooth, LXRS, LXRS+, and ANT+) to conduct wireless data transmission experiments. The Wi-Fi protocol was selected due to its high data rate, a good signal range, and its status as a mature and an accessible technology. All these characteristics were essential for conducting the wireless experiments, mainly due to the volume of data transmitted. Additionally, characteristics such as low cost, availability, and easy connection with the DAq equipment available in the Laboratory of Vibration Tests were also considered in this choice. A low-cost commercial-off-the-shelf (COTS) router (estimated at no more than USD 70.00) was used in the experiments. The reliability results of this wireless technology were compared with those acquired using the traditional technique and discussed.

Backgrounds on wireless instrumentation

Non-intrusive instrumentation

Abedi and Wilkerson (2016) describe some scenarios where wireless instrumentation systems can be used, such as space vehicles, satellites, payloads, surface explorations, ground systems, and habitats. A wireless sensor network (WSN) is indicated, where sensors are distributed at specific points within a structure to collect data and monitor physical or environmental conditions, such as acceleration, temperature, pressure, voltage etc. Wireless sensors should preferably be small, with very low power consumption requirements and long-term operational capability, which can be supported by onboard batteries or power scavenged from other available sources.

Frequency bands

Frequency plays a vital role when dealing with wireless communication and significantly impacts the robustness of a wireless network system (Ajmeri 2020). The most common frequency band used worldwide for wireless networks is the industrial, scientific and medical (ISM) band. Higher frequencies mean higher bandwidth, and higher transmission rates can be achieved since data can be transferred in a shorter period. For 5 GHz Wi-Fi (5G), fast data transfer is possible, while 433 MHz offers lower data rates. Lower frequencies are less subject to signal attenuation.

Interference

Interference is a major concern in wireless networks, and this potential is high, because many existing communication protocols and devices operate at the same frequency. During transmission, when there are too many devices scan or broadcast on the same channel, it can lead to failure. These interferences can cause data collision, resulting in packet loss. To avoid frequency congestion and interference, devices must be able to adjust their channels to slightly different frequencies within that band (Abedi and Wilkerson 2016; Dickinson 2014).

Protocol

A protocol is a standard set of rules for how electronic devices communicate wirelessly. Many wireless protocols use carrier-sense multiple access with collision avoidance (CSMA/CA). According to Collins (2016), this mechanism experiences packet loss, latency, and a reduction in transmission determinism. It can also suffer collisions due to simultaneous transmissions from different sensor devices (hidden terminal problem). These factors are unwelcome in wireless FTI because packet delivery is a vital requirement, and mechanisms to ensure data delivery must be considered.

Table 1 summarizes the characteristics of the standard communication protocols, and their main features, such as operating radio frequencies, communication standards, data rates, and power consumption.

Table 1. Transmission characteristics of the standard-based communication protocols.

Communication protocol	Radio frequency	Communication standard	Data rate	Power consumption	LOS range (approximate)
LXRS	2.4 GHz	IEEE 802.15.4	250 kbps	1 mW to 100 mW	2 Km
LXRS+	2.4 GHz	Proprietary	2 Mbps	1 mW to 100 mW	400 m
Zigbee	2.4 GHz	IEEE 802.15.4	250 kbps	50 μA-45 mA	100 m-1 Km
WirelessHART	2.4 GHz	IEEE 802.15.4	250 kbps	4-20 mA	61 m
ISA100.11a	2.4 GHz	IEEE 802.15.4	250 kbps	14.45 mW	500 m
Bluetooth	2.4 GHz	IEEE 802.15.1	1 Mbps-3Mbps	1 mW-100 mW	9 m
Z-Wave	900 MHz	IEEE 802.11, 15, 16	100 kbps	23 mA	100 m
Wi-Fi	2.4 GHz	IEEE 802.11b	11 Mbps	100-300 mA	100 m
	2.4 GHz	IEEE 802.11g	54 Mbps		100 m
	2.4/5 GHz	IEEE 802.11n	150 Mbps		250 m
	5 GHz	IEEE 802.11ac	1,000+ Mbps		< 250 m

Source: ACTIONTEC 2022; Akyol *et al.* 2010; Benevent 2006; Bluetooth SIG 2022; Collins 2015; 2016; Eady 2007; Embedded Centric 2022; Ferro and Portorì 2005; Garnett *et al.* 2006; Hilz and Wirelesshart 2012; Khosrodad 2010; Lansdowne 2024; LORD CORPORATION 2017; NXP Laboratories 2016; TECHI TUBE 2019; Rocha (2024); Vladimirova *et al.* 2007; Wagner 2010; Wagner and Barton 2012; Zigbee Alliance 2017; Z-Wave Alliance 2020; 2022; 2023.

In scenarios where power consumption is not a constraint, and high data rates are required, Wi-Fi is an excellent option. Conversely, if power consumption is a real concern, LXRS, LXRS+, ZigBee, WirelessHART, ISA100.11a, Bluetooth, and Z-Wave could be better options, albeit with lower data rates.

Wi-Fi

Wi-Fi is an open protocol based on the Institute of Electrical and Electronic Engineers (IEEE) 802.11 standard. In Wi-Fi networks, devices can either connect directly to the closest access point in a basic service set (BSS) infrastructure mode or use an independent BSS (IBSS) mode, which allows communication between devices or stations. In this mode, an access point is not required (Chandra and Lide 2007). Wi-Fi has a high-power consumption, a high data transmission rate (from 11 Mbps to 1,000+ Mbps), and a network join time of up to 3 seconds. Wi-Fi networks support between 32 and 255 devices (Ferro and Portorì 2005).

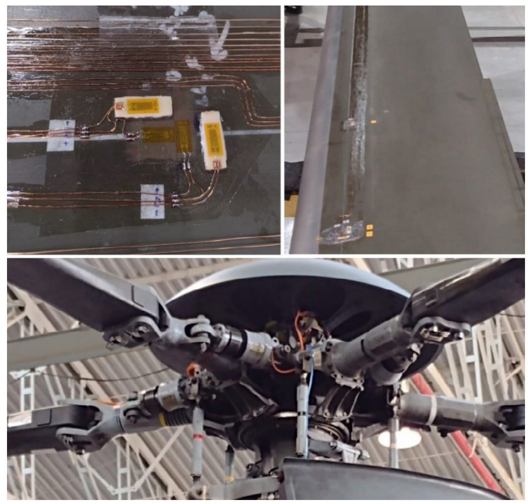
Designed for longer-range connections (up to 250 meters), Wi-Fi supports devices with a high level of power supply. A Wi-Fi device typically consumes between 100-350 mA. Thus, when power consumption is not a significant issue and greater ranges are desired, Wi-Fi is a good solution. Wi-Fi uses the orthogonal frequency-division multiplexing (OFDM) at the physical layer, a variation of the frequency division multiplexing (FDM) (Ferro and Portorì 2005).

The experiments conducted to compare the performance of wired and wireless instrumentation serve as precursors to verifying the reliability of data transmission based on Wi-Fi technology. The minimum requirements chosen to meet the needs of the experiment include a data transmission rate of at least 20 Mbps, a signal range of at least 10 meters, no restrictions on power consumption for the laboratory experiment, and easy cost-effective implementation. Such conditions are analyzed, and a subsequent application in a real helicopter flight using similar technology is conducted. For the real flight, energy consumption is a constraint; however, the energy provided by the batteries was sufficient to complete the tests.

Wireless data transmission for rotating parts

Transmitting data from rotating parts using wired instrumentation is not viable so, in this case, the use of wireless data transmission is applicable. An example is the use of this technology to carry out operational modal analysis (OMA) tests on helicopter blades installed in a centrifuge acceleration test machine. This test is done using wired sensors installed on the blades and data is transmitted wirelessly from the DAq to a computer, in order to understand the structural characteristics of the blades. Subsequently, based on the data from the blades analyzed in the centrifuge, the same technique of wireless data transmission from wired sensors was used in a real helicopter flight. This test campaign was carried out to analyze the structural limits of the main rotor blades of a helicopter during a real flight with in-flight refueling. Wake turbulence from a helicopter flying behind an airplane could cause such disturbances to the helicopter's blades that it would put the rotorcraft and the crew at risk.

Figure 1 shows how sensors are installed on the helicopter blades, with the wires from these sensors going along the surface of the blades to the main rotor, where a DAq module is installed to transmit the data wirelessly into the helicopter.



Source: Rocha (2024).

Figure 1. Wired sensors installed on the main rotor blades of a helicopter with wireless data transmission.

Relevant aspects to be considered

Many other aspects must be mentioned and need to be considered when planning wireless network systems:

Integration with acquisition systems: in a wireless network, remote sensors need to integrate with an acquisition system, as occurs to any wired sensors, to create a homogeneous network (Collins 2016);

Data integrity: is the guarantee that the data sent by the source is fully received by the destination without any change, distortion, loss, or damage (Durresi *et al.* 2005);

Power consumption and sensor autonomy: as wireless sensors are installed without any external wired power source, they need to carry their own batteries. These sensors need to be designed for low power consumption to maintain them working for days, months, or even years without a battery change (Akyildiz *et al.* 2002; Collins 2016; García-Hernández *et al.* 2007; Merz *et al.* 2014);

Electromagnetic interference (EMI) and electromagnetic compatibility (EMC) (CCSDS 2017; Ciccolella and Marliani 2009; Plummer and Magness 2003; Vladimirova *et al.* 2007);

Security, susceptibility (Plummer and Magness 2003), and reliability (Wagner 2010);

Topology, channel interference, signal attenuation, and coexistence with other wireless technologies, security, and difficulty to guarantee performance;

Latency: referring to delaying network communication or, in other words, it is the amount of time it takes for a requested data packet to travel from one point to another (Collins 2015; 2016; Wagner 2010);

Packet loss: during data transmission, the loss of data packets may occur when data packets fail to reach or arrive at their destination. This failure can happen due to factors such as network congestion, hardware, and software problems (Collins 2015; 2016; Wagner 2010);

Time synchronization: the precision of time identification (timestamping) of samples or data packets is a fundamental requirement. Further analyses of the acquired data are only possible if data samples taken from wired or wireless sensors are synchronized so, wireless sensors use high-precision real-time clocks to keep the steadiness of time between resynchronizations (Collins 2016).

These challenges must be solved aiming at a reliable wireless technology (Collins 2015; 2016; Wagner 2010).

Modal analysis

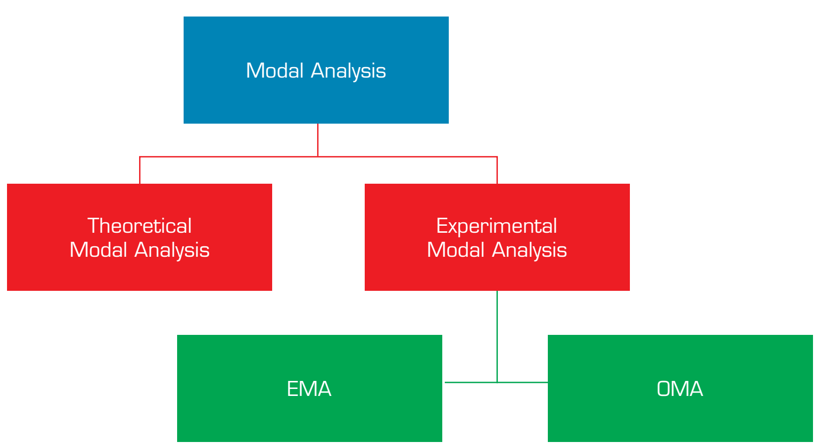
Experimental modal analysis, also known as Ground Vibration Test (GVT), is a test of extensive knowledge in the subject and of great relevance to acquire information related to the modal analysis of the tested models. The GVT is a test carried out in a laboratory, before the analyzed structure enters definitive operation. Often, the GVT presents the characteristic of being a test that must present quick results, since you already have a prototype or even the own final structure as a product to be delivered, such as an aircraft, an aerospace structure, etc. This drives a continuous search for improvement processes for these tests. This discussion addresses a method of wireless data transmission from a GVT, in addition to showing the results obtained with a traditional (wired) test, with regard to DAq.

Modal analysis seeks to obtain the modal parameters, inherent to the analyzed structure, namely, the mode shapes, the natural frequencies, and the structural damping. Conducting a GVT, it is necessary to submit the tested structure to a dynamic load excitation and, as consequence, to measure the structural responses, which are measured through locally installed sensors, traditionally accelerometers. The measured frequency response functions (FRF) accounted by the local the accelerations and the dynamic excitation force, after processing and analyzes using specific codes, will give a combination of natural frequencies, mode shapes and structural damping (Brüel & Kjaer 2003).

Complete modal analysis of structures begins with a numerical model, usually finite element method (FEM), where these mathematical models represent mathematically the studied dynamic system. The FEM, as a numerical solution (Zienkiewicz and Taylor 1977), is widely disseminated and has been used in several fields of engineering, such as concrete, automotive, and aerospace structures, showing good results.

However, this work is devoted to the use of experimental methods to determine modal parameters of structures, using an alternative and low-cost non-intrusive instrumentation. Experimental modal analysis can be divided into two methods: classical experimental modal analysis (EMA) (Ewins 2000) and OMA (Brincker and Andersen 2006). As a general definition, in EMA the modal model is obtained through estimates of the FRF, where a combination of the force excitation and responses at different positions of the structure are used to determine the modal matrices (mass, rigidity, and damping) and the consequent identification of the structure's modal parameters. On the other side, in OMA the modal parameters are identified starting from the inherent operating conditions of the structure, i.e., based only on the structural responses of the model. Since the input forces are not measured, the FRF are also not measured and the identification of the modal parameters is based on singular value decomposition (SVD) by considering the input as white noise (Brincker and Andersen 2006).

Figure 2 depicts, in a general fashion, the state of the art of the complete modal analysis technique.



Source: Costa (2014).

Figure 2. Complete modal analysis.

Classical experimental modal analysis

The EMA is explored in this work. This technique is based on the identification of the inputs and outputs of the dynamic system, which allows validation of the FRF estimated by the coherence functions (Orlowitz and Brandt 2017). Therefore, EMA is a widely used measurement technique.

The characterization of an EMA application is through the physical information of the system obtained from the correlation functions and power spectral density (PSD) functions. In this way, the PSD function, which is related to the identification in the frequency domain, extracts the physical information of the system. While in the time domain the analyses are performed as a system with free response, in the case of the responses obtained in the frequency domain, a small dominant characteristic frequency band is respectively related to each mode. This may offer an advantage over the time domain method since there is a natural modal decomposition, which considers different reference frequency bands for the different modes of the system (Gade *et al.* 2005).

In this work, the identification technique in the frequency domain known as displacement mode shapes (DMS) was used, where the designation "mass-normalization" is applied for the scaling regarding the orthogonality properties of the mass-normalized modal matrix (Ewins 2000; Maia and Silva 1997).

Algebraically, the DMS technique is defined in Eq. 1:

$$H_{jk}(\omega) = \sum_{r=1}^{N} \frac{rA_{jk}}{\omega_r^2 - \omega^2 + i\eta_r\omega_r^2} \tag{1}$$

where $rA_{jk} = \phi_{jr}\phi_{kr}$ is the modal constant. Two important properties of the receptance matrix are highlighted: first, the principle of reciprocity $H_{jk}(\omega) = H_{kj}(\omega)$, known as the symmetry of $H(\omega)$, and second, the modal constants consistency equations that are expressed by the following Eqs. 2 and 3:

$$rA_{jk} = \phi_{jr}\phi_{kr} \tag{2}$$

$$rA_{jj} = \phi_{jr}^2 \; or \; rA_{kk} = \phi_{kr}^2 \tag{3}$$

Experimental research

The following the steps were carried out:

In the first step, documentary and bibliographic surveys were conducted, looking for the most relevant scientific papers in the field of wireless instrumentation. For these surveys, research tools such as Engineering Village and Scopus databases were used.

In the second step, two experiments were performed.

In the first experiment, dynamic signal DAq was done aiming to assess the wireless instrumentation applied to measurements of such dynamic parameters. It is important to highlight that only data transmissions are assessed in this work, as fully non-intrusive instrumentation was not available. However, these studied hybrid non-intrusive instrumentations present low cost, flexibility, and availability, which are important issues to be considered in DAq systems, besides the accuracy.

Afterwards, a modal test of the Acauã unmanned aerial vehicle (UAV) wing structure was performed, where vibration data generated by an electrodynamic shaker were gathered and analyzed. In both experiments, the shaker/structure was instrumented using two different data transmission methods: intrusive (RJ45 wired tests) and a non-intrusive Wi-Fi (2.4G and 5G) instrumentations. For both tests, simple dynamic signals were applied using sinusoidal and random (white noise) excitations, which measured input forces and accelerometer responses. The signal data transmission rates and reliability were also assessed by comparing the results between the two instrumentation methods.

This work presents the comparisons regarding the EMA of the Acauã wing structure, while the survey concerning the first instrumentation tests will be presented in another paper. However, part of the first experiment (random signal test) is presented here due to the fact it proves the reliability of the wireless instrumentation system in comparison to the wired instrumentation.

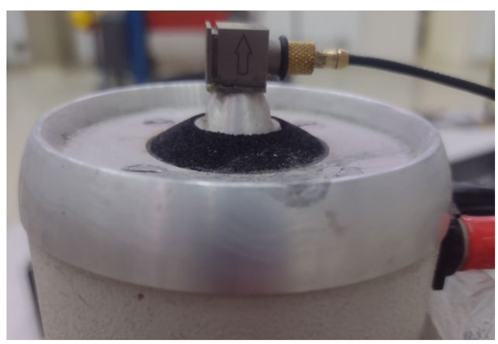
Although data packet loss, data integrity, energy consumption, sensor autonomy, as well as EMI and EMC tests are important for experiments regarding wireless data transmission, these aspects were not the focus of this work and, consequently, were not performed. This is mainly due to the fact that such tests could only be performed on-site, at the time of the use of the final instrumentation in a real flight test operation, where the EMI conditions would be real and, therefore, it would not be possible to repeat and consequently perform such conditions in the laboratory.

Regarding the synchronization aspect, the Connect software from BK Connect (2023) was configured with the Precision Time Protocol (PTP), with all phases and samples synchronous (IEEE 1588 PTP). The B&K Connect software collected the data, processed it, created data packets, and transmitted these packets via Wi-Fi.

Another relevant aspect to be considered is that, although one of the focuses of wireless instrumentation applications is to reduce vehicle mass, such use was not possible in this experiment due to the lack of wireless sensors in the laboratory for a completely wireless instrumentation system. Thus, a hybrid instrumentation approach was used. Another purpose of wireless instrumentation is to be able to make measurements in hard-to-reach/access locations, additionally to the difficulty of taking measurements on rotating parts, where wired measurement is impossible.

First experiment

Figures 3 and 4 show how the structure for the first experiment is displayed. Figure 2 presents the B&K 4507 B tri-axis TEDs accelerometer installed on the top of an LDS V201 electrodynamic shaker, while Fig. 3 shows the notebook connected to a Brüel & Kjaer Data Acquisition Module Type 3160-A-042, using either an RJ45 network cable and a D-Link (MyLink) Intel Dual Band Wireless-AC 8265 Wi-Fi router, with the 2.4G IEEE 802.11n protocol. An amplifier was also connected to Data Acquisition Module and to the shaker and both the sinusoidal and random signals were generated for the experiment.



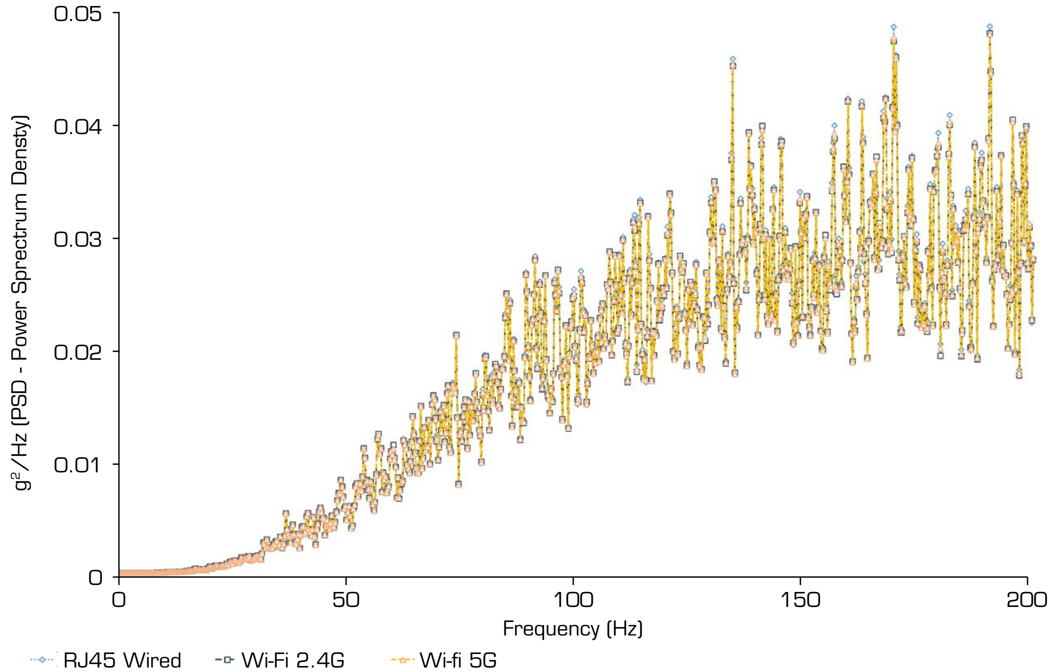
Source: Rocha (2024).

Figure 3. Tri-axis accelerometer installed on the top of a B&K V201 shaker.

Source: Rocha (2024).

Figure 4. First experiment structure displayed. A Brüel & Kjaer DAq Module Type 3160-A-042 connected to a low-cost COTS Wi-Fi router.

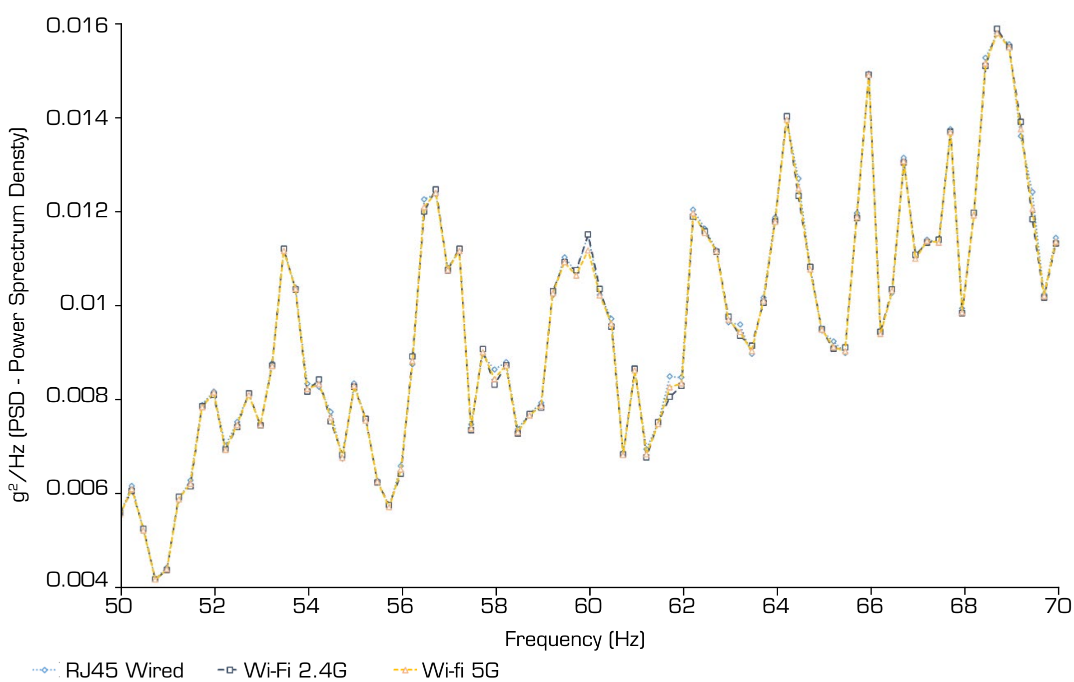
Data was collected and analyzed using the B&K Connect software (BK Connect 2023). Data collection for the analysis used the Autospectrum fast Fourier transform (FFT) lines, which was measured in g^2/Hz (PSD) for the random signal tests. Figure 5 shows a comparison of the random signal, acquired by the RJ45 wired, 2.4G and 5G Wi-Fi DAq systems, with three tests of FFT data randomly selected for comparison.



Source: Elaborated by the authors.

Figure 5. Random signal FFT comparison: RJ45 wired, Wi-Fi 2.4, and 5G.

Figure 6 presents a more detailed section of the graph in Fig. 5, showing a range from 50 to 70 Hz.



Source: Elaborated by the authors.

Figure 6. Random signal FFT comparison: RJ45 wired, Wi-Fi 2.4, and 5G zoomed.

To guarantee DAq reliability when replacing a wired instrumentation with a wireless system, the following two-step assessment procedure was adopted: i) the area under the curves of all the FFT tests was calculated using the definite integral with the rectangle technique (the Riemann sum method); ii) the average area for all the three tests was compared.

Table 2 describes the calculated area under the curves of the random signals as well as the percentage differences for the three analyzed instrumentations.

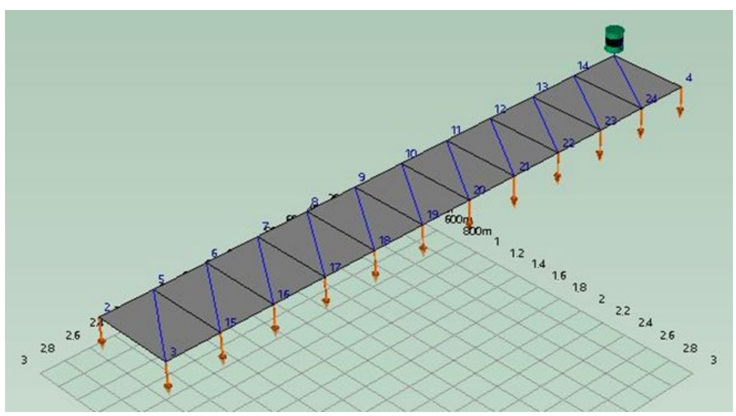
Table 2. Comparison of the graphic average area for the three random signal tests.

Test	Total area	Percentage	Difference from the reference (%)
RJ45 wired	3,577	Reference	-
Wi-Fi 2.4G	3,560	99.53	0.47
Wi-Fi 5G	3,553	99.34	0.66

Source: Elaborated by the authors.

Second experiment

The second experiment setup considered the Acauã UAV wing structure. These classical modal tests consisted of data transmission/acquisition comparisons between wired and wireless instrumentations. Data accuracy, packet loss, latency, and transmission quality were accounted in these instrumentation performance analyses. The method involved the instrumentation of a structure with a mesh of 24 accelerometers to measure the vibration modes of the referred wing structure, as presented in Fig. 7.



Source: B&K Connect (2023), Rocha (2024).

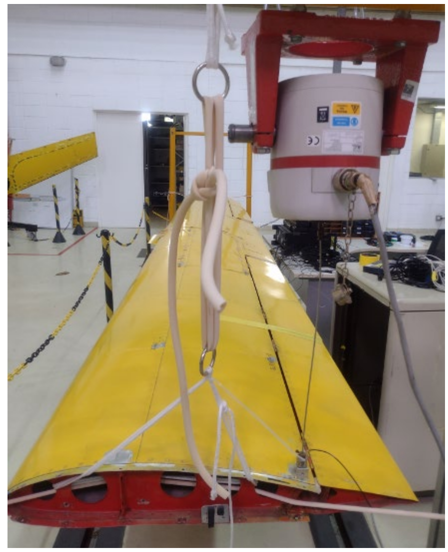
Figure 7. Mesh with the 24 nodes for the accelerometers.

Figure 8 shows a detail of one accelerometer, installed on the lower surface of the structure. Special mountings were glued to the lower surface of the wing, and the accelerometers were properly fixed to these mountings.

Source: Rocha (2024).

Figure 8. Detail of one accelerometer installed on the wing structure.

The Acauã wing structure was suspended by rubber bands to simulate the free-free boundary condition (Fig. 9). Care was taken to ensure that the lowest rigid-body mode of the tested structure was smaller than 10% of the first structural mode (Ewins 2000).



Source: Rocha (2024).

Figure 9. Shaker/stinger/force transducer fixed to the wing structure.

Five Brüel & Kjaer Data Acquisition Modules were used for the experiment: one module was a LAN-XI 50 kHz, Type 3160-A-042 with four input channels, and two output channels and four modules were LAN-XI 50 kHz, Type 3050-B-060 with six input channels each (Fig. 10). Both types were installed in an 11-module LAN-XI Front-end Frame Type 3660-D, which supported 1 Gbps of data transfer (Fig. 11). The Brüel & Kjaer PULSE Front-end Setup Software was configured to use a PTP for time synchronization of the modules.

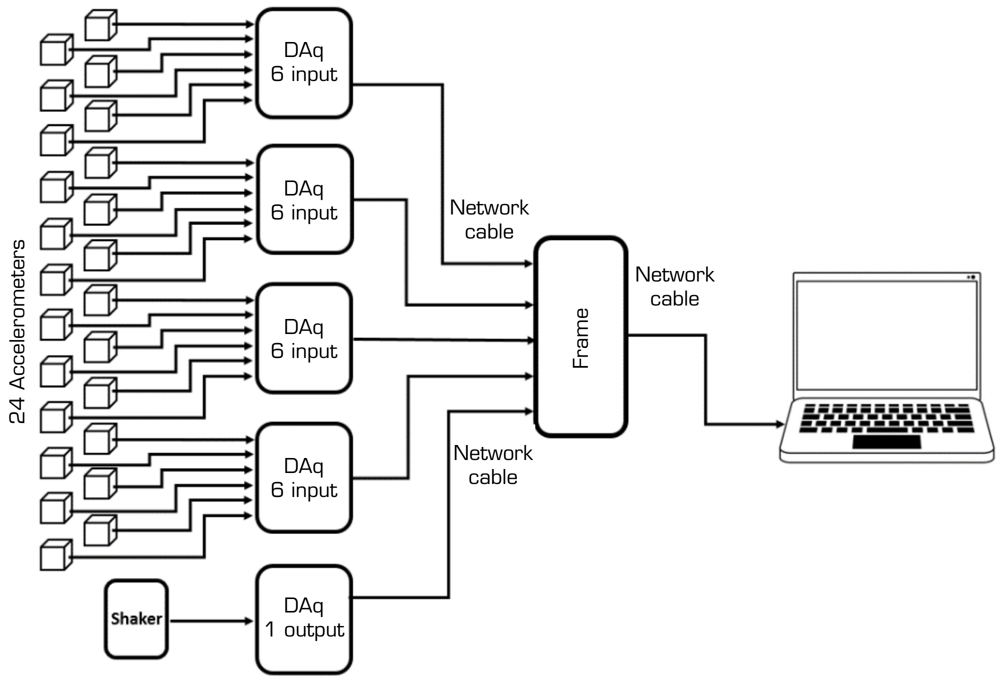
Source: Rocha (2024).

Figure 10. Data acquisition modules.

Source: Rocha (2024).

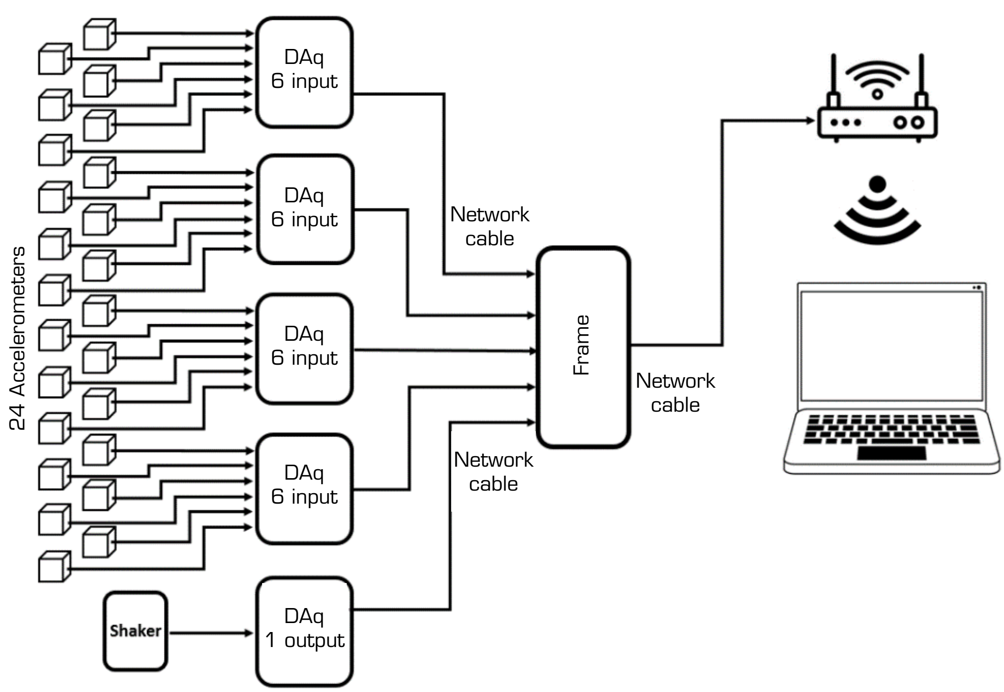
Figure 11. 11-module LAN-XI Front-end Frame Type 3660-D.

Figure 12 shows the diagram of the DAq using an RJ45 network cable. The non-intrusive DAq systems were also setup and the data were transmitted using a commercial Wi-Fi router, as shown in Fig. 13.



Source: Elaborated by the authors.

Figure 12. Diagram of the wired data transmission system.



Source: Elaborated by the authors.

Figure 13. Diagram of the wireless data transmission system.

The wing structure was excited by using an electrodynamic shaker that submitted it to a white noise signal, with frequencies ranging from 10 to 100 Hz, and a frequency resolution of 0.25 Hz. The first vibration mode, the bending mode (z-axis), was identified at 20,197 Hz, while the second bending mode (z-axis) appeared at 54,339 Hz. The first torsion (twist) mode was identified at 28,312 Hz.

RESULTS

In these modal tests, only the 5G Wi-Fi signal was used for data transmission. Even though the Wi-Fi communication mechanism (CSMA/CA) presents some type of latency as a characteristic, the results showed excellent agreement between wireless transmissions and wired transmission. Additionally, no differences between the vibration modes (first and second bending modes and first torsion mode) were observed when RJ45 wired and the 5G Wi-Fi data transmission results are compared.

Table 3 shows the comparison between 5G Wi-Fi and RJ45 wired instrumentations regarding the identified vibration modes. The first bending mode was identified at 20,094 Hz for the 5G Wi-Fi and approximately at 20,100 Hz for the RJ45 wired instrumentation. Similarly, the second bending mode in z-axis was at about 85,192 Hz for the 5G Wi-Fi instrumentation and about 85,174 Hz for the RJ45 wired. Finally, the first torsion (twist) mode was identified at 59,364 for the 5G Wi-Fi and at about 59,393 Hz for the RJ45 wired instrumentation. Table 3 also presents the percentage errors for the three modes, where the 5G Wi-Fi is compared to the RJ45 wired (used as the reference). The identified frequency comparisons showed excellent agreement, with 0.05% being the highest difference, related to the second bending mode.

Table 3. Results of wired (RJ45) and wireless (5G Wi-Fi) modal analysis test comparison: vibration modes.

Mode	5G Wi-Fi	RJ45 wired	% Error
	Damped frequency (Hz)	Damped frequency (Hz)	
1	20.09352	20.09959	-0.03
2	59.36436	59.39338	-0.05
3	85.19180	85.17384	0.02

Source: B&K Connect (2023) Rocha (2024)

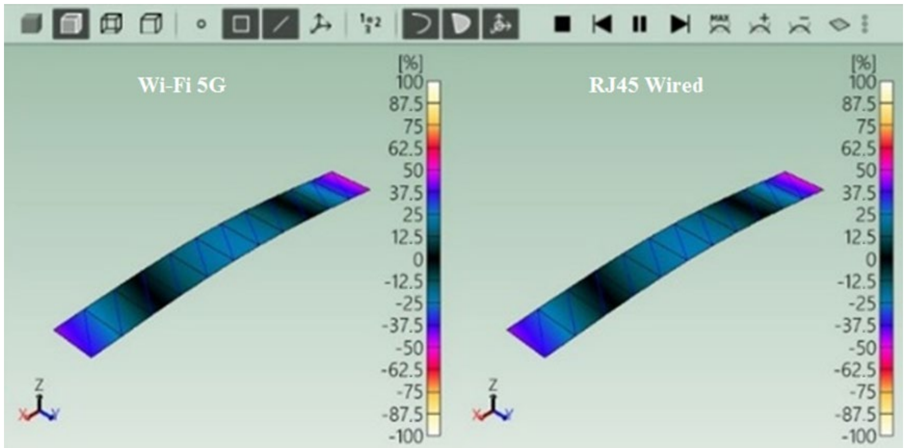
In Table 4, the modal assurance criterion (AutoMAC) matrix is presented. This parameter provides the degree of correlation between two different sets of mode shapes. The AutoMAC is a well-known tool for the quantitative comparison of modal vectors. The three values of 1.00 along the diagonal of the matrix show that the correlation between each mode is 100%.

Table 4. AutoMAC matrix results: wired (RJ45) and wireless (5G Wi-Fi).

5G Wi-Fi	Mode shape 1 (20,100 Hz)	Mode shape 2 (59,393 Hz)	Mode shape 3 (85,174 Hz)
Mode shape 1 (20,094 Hz)	1.000	0.028	0.023
Mode shape 2 (59,364 Hz)	0.029	1.000	0.134
Mode shape 3 (85,192 Hz)	0.022	0.133	1.000

Source: B&K Connect (2023) Rocha (2024)

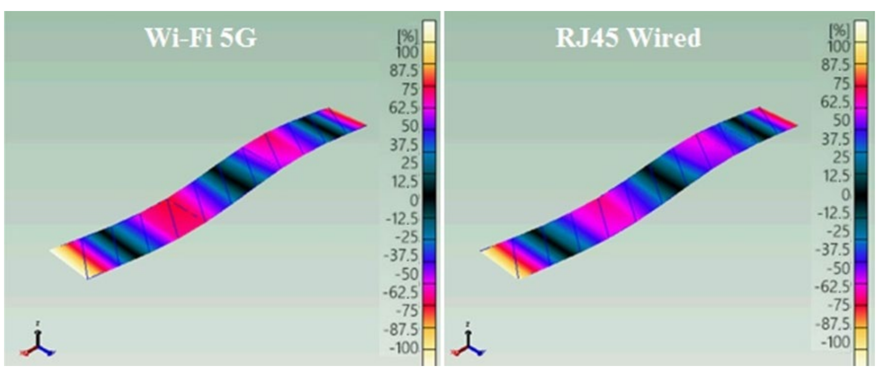
The first bending mode, identified by both instrumentation techniques, is shown in Fig. 14.



Source: B&K Connect (2023)(Rocha (2024)

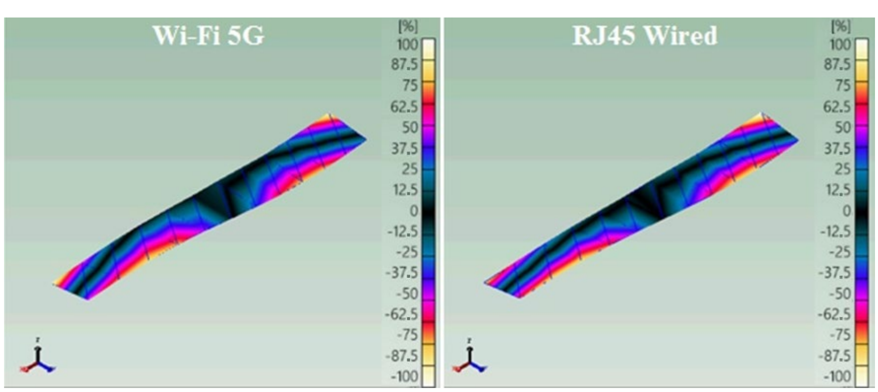
Figure 14. Results of wired (RJ45 CAT5) and wireless (Wi-Fi 5G) modal analysis test comparison. First vibration mode (the image on the left is the wireless, and the image on the right is the wired).

The second bending mode and the first torsion (twist) mode of the wing were also compared and showed no behavior distortion or differences. Figures 15 and 16 show the referred vibration modes, identified by both instrumentation techniques (RJ45 wired and the 5G Wi-Fi data transmission).



Source: B&K Connect (2023) Rocha (2024)

Figure 15. Results of wired (RJ45 CAT5 network cable) and wireless (Wi-Fi 5G) modal analysis test comparison. Second vibration mode (the 3D image on the left is the wired, one and the right 3D image is the wireless).



Source: B&K Connect (2023) Rocha (2024)

Figure 16. Results of wired (RJ45 CAT5 network cable) and wireless (Wi-Fi 5G) modal analysis test comparison. Torsion mode (the 3D image on the left is the wired, and the 3D image on the right is the wireless).

CONCLUSIONS

For the first experiment (random signal assessment), the results show differences between the areas of the curves of 0.47% for the 2.4G Wi-Fi and 0.66% for the 5G Wi-Fi, both in comparison to the RJ45 wired, as shown in Table 1. Both systems showed excellent performance, since they did not present any packet loss or latency. These excellent results proved the Wi-Fi 2.4G and 5G to be reliable as an alternative instrumentation. Therefore, the modal analysis performed in the second experiment (aeronautical UAV wing structure) also proved to be suitable and can be carried out. Regarding the second experiment results, the AutoMAC matrix presented correlation of 100% between each mode, as shown in Table 3. This means that the RJ45 wired and the 5G Wi-Fi first and second bending modes, and first torsion modes, when compared to themselves, are the same.

The Wi-Fi communication protocol proved to be robust, reliable, and advantageous for the operational scenario tested in modal analysis, as well as various other laboratory applications. However, to expand the application scenarios – using wireless technology for long distances, in locations with many physical obstacles, in environments with significant EMI, and/or competing with other radio frequencies – EMC and signal attenuation tests must still be conducted to ensure the reliability of the wireless system. Finally, the full use of non-intrusive technologies will not come without a variety of difficulties and obstacles to be overcome within a critical and challenging environment that is the space one.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS'CONTRIBUTION

Conceptualization: Rocha MR; **Methodology:** Rocha MR and Pirk R; **Software:** Rocha MR; Govertz A; Camargo EA; **Validation:** Rocha MR; Pirk R and Camargo EA; **Formal analysis:** Rocha MR and Pirk R; **Investigation:** Rocha MR and Govertz A; **Writing - Original Draft:** Rocha MR and Pirk R; **Writing - Review & Editing:** Rocha MR; **Final approval:** Rocha MR.

DATA AVAILABILITY STATEMENT

All data sets were generated or analyzed in the current study.

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