Hybridization of wireless technologies for the aerospace instrumentation

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ABSTRACT

Whatever the flight test or space launch vehicle, instrumentation presents strong intrusiveness due to cabling. The industry is resolutely looking for a transition toward wireless architectures for elimination of cabling while not compromising data integrity and network performances.

The ideal wireless solution is a single technology that could encompass all the needs. But there is a wide variety of use cases and associated requirements: data throughput, synchronization accuracy, power consumption, robustness of the link, frequency regulation constraints. Today, no technology is able to cover all these needs. However, multiple technologies show specific characteristics that are optimized for some particular use cases. Hybridization of multiple wireless technologies in a complex system is the right solution to address specific applications with the optimal wireless instrumentation solution and no concession on performance.

INTRODUCTION

The aerospace industry has been looking for ways to eliminate cabling for many years. A reduction in cabling has been enabled by the transition toward Ethernet-based architectures and the continuous evolution of instrumentation equipment toward remote distributed Data Acquisition Units (DAU). These evolutions have enabled the minimizing of cables lengths between sensors (or buses) and DAUs. But even these miniaturized and remote systems still require cabling.
The struggle of cabling is well-known. Installation takes a lot of time and can have irreversible impacts on the structures (holes drilling). Specific areas are hard to reach with a cabled access and late modifications of installations are getting more bulky and costly when instrumentation grows bigger. Cabling also adds considerable weight to the vehicle.

Wireless communication between equipment without compromising performance is highly desirable. However for any aerospace instrumentation program, the technology selection is critical to meet specific requirements for synchronization, data integrity, high rate data transport, low latency, and cyber security. Most of the time, a unique technology is sought, in order to answer many constraints. This paper presents how the specific characteristic of various technologies can be combined through hybridization in viable solutions for the aerospace instrumentation.

TECHNOLOGICAL CHOICES AND ASSOCIATED PERFORMANCES

Multiple technologies have been identified in order to cover the needs for instrumentation. A previous study [1] presents WiFi, UltraWideBand and Bluetooth Low Energy performances and applications. Here is a summary and a step back on a larger sight of this study's conclusion.

High bandwidth (WiFi)

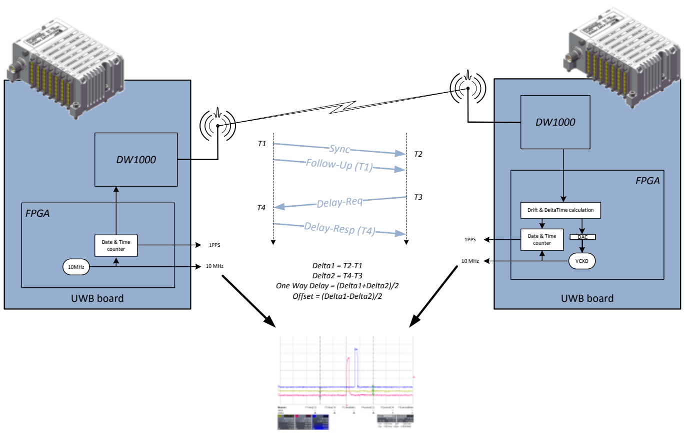
WiFi, based on the 802.11 standard, offers a wide variety of protocols on multiple frequency bands such as 2.4GHz, 5GHz or 60GHz. This technology enables to build complex topologies such as ad hoc or mesh networks and offers high bandwidth data transmission. While 802.11n defined in 2009 promises up to 450Mbps, Wifi5 (802.11ac) defined in 2012 allow the utilization of the 5GHz ISM band and improved this data rate to up to 800Mbps and more recently the introduction of MIMO, OFDMA, 1024QAM, BSS color... in the 802.11ax standard should offer more than 10% improvement of speed in “WiFi 6” with high efficiency multi-user transmission capacity. As only the MAC layer and physical layer are defined by the 802.11 standard, it enables to apply dedicated data transmission protocols. Main usage is to bring Ethernet data through simple IP protocol. Doing so, standard Ethernet-based instrumentation networks are easily replaced by a wireless link. However, this transition can impact Ethernet performances such as the IEEE 1588 Precision Time Protocol (PTP) for clock synchronization. Indeed, no WiFi chip offers today hardware-integrated PTP protocol. PTP can be added at software level, but reducing drastically the synchronization accuracy (from <50ns to >500µs).

The WiFi offers interesting features for complex instrumentation. The extended distribution system of the standard enables to tune every point of the architecture depending on the network needs. 802.11ac is optimized for single access point with high data rate but offers reduced sensitivity. 802.11n will offer more sensitivity but less data rate. Particularly, 802.11s standard offers the Mesh topology with mobile backbone and the 802.11p is dedicated to wireless architectures in vehicular environment. The variety of implementations of the 802.11 standard is to be used depending on each node of the architecture, thus opening to hybridization of WiFi protocols in the same architecture.

The 802.11n implementation was investigated as a good combination of maturity and performances to obtain a large-bandwidth signal with a steady data rate. This standard could enable up to 450Mbps overall data rate, which could cover most common current use cases for aerospace high bandwidth wireless transmission even with the heavy WiFi overheads (rule of thumb being 55% of overall bandwidth).

Enabling accurate synchronization (Ultra-Wide-Band)

Ultra-Wide-Band (UWB) is part of the 802.15.4 standard and was formalized as 802.15.4a. Specifically, the IR-UWB (Impulse-Radio UWB) was investigated and up to 6.7Mbps steady data rate was reached in our tests. This low-power technology is widely used for indoor accurate geolocation. Indeed, BPM/BPSK modulation and time-hopping impulses enable an accurate time-stamping of messages permitting the ranging between two antennas. Based on this principle, an accurate synchronization protocol was implemented in UWB. This technology has shown high robustness to multipath and to noisy environments. It is thus a right candidate for synchronized data transmission in aerospace environment, because its high robustness will ensure a steady synchronization link between devices, even though a loss of data transmission occurs, synchronization could still be achieved which still enables post-analysis.
The UWB is a spread-spectrum technology. It offers 14 channels of 500MHz bandwidth in the 3.1GHz - 10.6GHz spectrum. It is particularly interesting for aerospace applications: the spread spectrum prevents jamming of third-party equipment and susceptibility to highly occupied bands.



1 UWB synchronization protocol

The synchronization architecture is based on a DAC and a VCXO enabling phase and phase clock alignment. This solution was tested and <10ns of synchronization accuracy was reached. Integration of this wireless link in a standard instrumentation architecture safeguards a <100ns accuracy throughout the system (inducing a <1° phase accuracy between two 20kHz signals, equivalent to signals acquisition in the same DAU).

Low-power requirements (Bluetooth Low Energy among others)

Low power is a critical characteristic for long-lasting self-powered devices. A few years ago the low energy consumption was the element of differentiation of technologies like Bluetooth Low Energy (BLE). However, there has been a global awareness of this issue and today Wi-Fi or 5G take measures to limit consumption [2][3]. In a parallel way of these high-speed technologies, BLE, LTE-M, NB-IoT, Wi-Fi HaLow or LPWAN technologies like LoRaWAN or Sigfox are facing a booming use in IoT [4].

Among these technologies, Bluetooth Low Energy appears as a mature solution with adapted performances. It is an implementation of the Bluetooth 4.2 release of the 802.15.4 standard. It is the low-power version of the 4.2. Contrary to UWB and WiFi, this standard is a fully-defined stack with protocol layer already defined. Its protocol is optimized for complex topologies with multi-role nodes. Integration in a dense 2.4GHz environment is permitted by its high-level protocol. The complexity of the radio stack enables a seamless use but also brings jitter and latency. The advertising mode of the BLE enables nodes to stay in a “sleep-mode”, consuming very little energy, and staying available for connection and “wake-up”. The standard allows up to 120kb/s data rate. This technology is suitable for low-power data transmission and sleep/wake-up capacities for remote instrumentation.

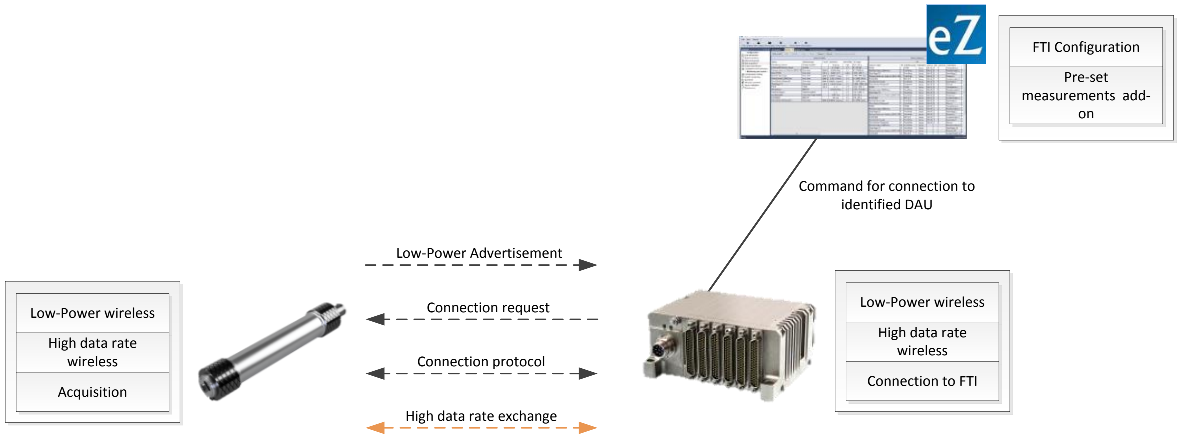
HOW HYBRIDIZATION COVERS THE NEEDS FOR INSTRUMENTATION

Connecting wirelessly with multiple technologies

The struggle with cabling in the particular case of Flight Test Instrumentation (FTI) prevents engineers to quickly modify the measurements architecture. Adding or removing measurement points is usually very complex considering the heavy cable strands that need to be manipulated.

Adding new measurements also usually implies adding more acquisition means. Connecting new measurement points to existing DAU can bring complexity when it comes to modification or addition of connectors. The addition of a new DAU implies not only new cables but also a revision of the instrumentation architecture with hypothetical structural modification of the testing vehicle. An existing DAU can connect to a new system thanks to the multi-device capacity of its wireless connection. Especially, such an addition should be a basic feature of the final solution in the case of a well-designed network architecture.

Several techniques are allowing this. Low-power advertising capacity enables a new device to be permanently available for connection while staying at low energy consumption. Bluetooth-Low-Energy is typically the right technology. With a sleep mode of a whole small DAU consuming <10mW of power, advertising messages are sent every second. The Bluetooth-Low-Energy being a low-power technology, it can prove itself unable to offer sufficient data rate (limited to 120kb/s). Once connected to the FTI, the remote DAU can switch to higher-capacity wireless technology in order to reach higher data rates for a limited amount of time. Chips hosting multiple wireless technologies are available, for example Bluetooth and WiFi.



2 Protocol for wireless low-power and high-bandwidth hybridization

Such protocol enables to quickly add new measurements with equipment that can be battery-powered, staying at low levels of power consumption while permanently available for connection.

For its part, the IEEE 802.11 standard describes two authentication classes: open system and shared key. Open authentication system is a zero-encrypted authentication algorithm defined by the standard allowing all mobile stations attempting to obtain a wireless LAN connection to successfully authenticate while shared key authentication is a process in which the mobile station and the access point are manually assigned a shared key, or password. The first shared key authentication was Wired Equivalent Privacy (WEP). Due to security issues Wi-Fi Protected Access (WPA) was implemented, and Wifi Protected Access 2 (WPA2) appeared as WPA enhancement. WPA3 is still under standardization and will bring further improvement.

System Architecture Evolution (SAE) and 5G Packet Core (5GC) are other interesting solutions to follow with the availability of 5G. Due to the architecture, with the presence of an Evolved Packet Core (EPC) or a 5G Core, the identification is done centrally with the MME (Mobility Management Entity) and especially the HSS (Home Subscriber Server) which manages the functionalities such as mobility management, user authentication and access authorization. This can be the key to the architecture of the future. It can be noted that this solution was selected by the European Union at the beginning of July 2019 as a standard for future automotive applications [5].

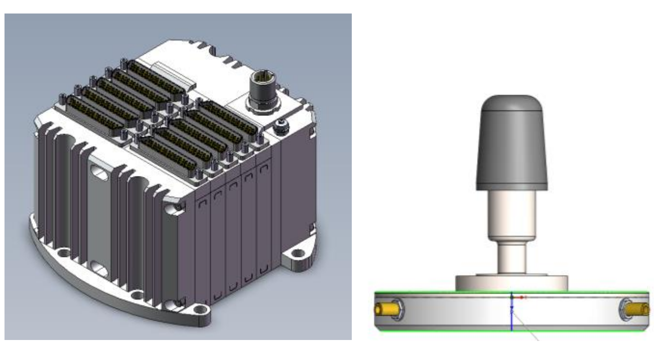
Choice of technologies and management of protocols for connection, authentication, data exchange in complex and multi-modal architecture topologies answer to many factors. Multiple technologies are needed in hybridized solutions. Such choice must be as transparent as possible for the user who mainly looks for reliable, secured and high-performance data transmission whatever the technology.

Hybridizing technologies in applied use case

Data transmission through rotating part is traditionally covered by the use of slip rings. These systems are able to provide both data and power transmission. However, their installation is highly intrusive on the structure, brings a lot of additional weight and offer very limited data rate. The friction also implies frequent and complex maintenance. Typically, installation on helicopter rotors requires the rotor to be dismantled in order to change the slip ring. Zodiac Data Systems was chosen to take part in the CleanSky2 project for the FTI of Airbus Helicopter's RACER. It is an opportunity to deploy this hybrid wireless strategy on the main and lateral rotors. WiFi was chosen for a high-bandwidth data transmission and UWB is added in parallel for very accurate time synchronization of the data.

3 Airbus Helicopter RACER

Rotating parts pose also the problem of the integration of DAUs. Traditional modular DAU with holder mechanics and modules to be plugged in may be problematic. Instead, specific assembly must be made in order to deal with the balance in a very constrained volume. The gravity center of the DAU needs to be very accurately aligned with the rotating axis. A slight imbalance can induce high damages at high speed rotation, jeopardizing the flight. At minimum, it can pollute the measurements made on the structure.
Specific design of the modular XMA DAU was done for helicopter rotor instrumentation hosting 8 generic analog acquisition modules. Its modularity enables the use of other COTS modules for up to 128 channels acquisition in the same mechanical topology.

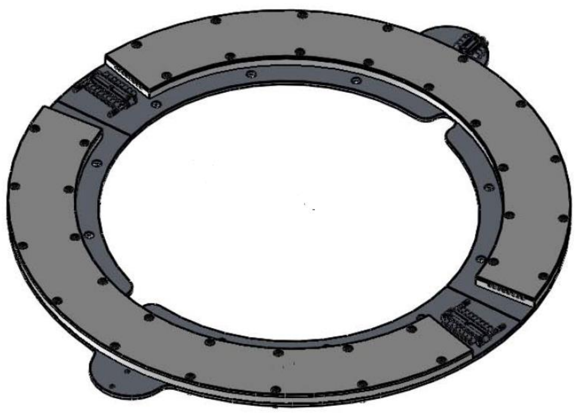


4 XMA Data Acquisition Unit dedicated to rotor and antenna with WiFi-UWB diplexer

The wireless link is done through an antenna passing hybridized WiFi (high energy and narrow-band) and UWB (low energy and spread-spectrum) streams. Multiple UWB channels can be selected to segregate UWB from WiFi frequencies. In order to do so, an RF diplexer has been designed. Integrated near the antenna, the diplexer gathers UWB and WiFi streams or segregates them, reducing the intrusiveness of the whole system.

Wireless Energy source

Multiple roles of the rotating DAU (acquisition, computing, wireless data link) and the small volume available for instrumentation prevent the use of batteries. Optimized inductive coupling system was designed in order to cope with the multiple requirements of low intrusiveness, high reliability and up to 50W steady stream.

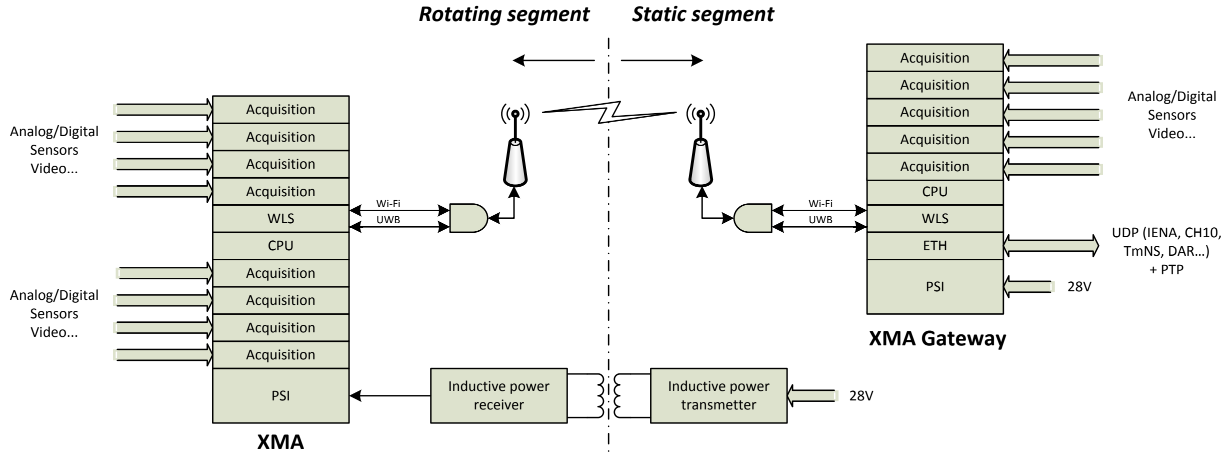


5 Mechanical housing of stator for inductive power transmission

Legacy inductive coupling is well-known from instrumentation engineers as a pain on both intrusiveness and Electro-Magnetic (EM) aspects. Low efficiency of energy transfer and little control of radiation induce high EM pollution because of high radiated energy.

Specific design of the coils allowed reaching 80% efficiency with very low magnetic pollution 1 inch away from the coil. The separation in two coils enables to reduce intrusive installation and maintenance. Choice of material and design for the coil is a challenge because it should minimize magnetic losses and heating while staying robust to helicopter vibrating environment.

Hybridization comes at multiple levels: on a single data link or globally in the architecture. Adaptation to the specific integration and environment is key. Introducing these adapted technologies in COTS products enables to build robust, viable and adapted solutions.



6 Global installation for data and energy transmission on a rotor

REAL ENVIRONMENT TESTS

In order to get real figures on the efficiency of these strategies, real tests are mandatory. Strong expertise in RF simulation and environment estimation is crucial for proper designs but behavior in real environment always brings new findings. Indeed, mechanical structures, EM emissions from active equipment or rotating parts build a highly complex landscape.

Multi-channel and spread-spectrum characteristics of the UWB showed their benefits in aerospace environment. An UWB data link was set on a business jet between the cockpit and an unpressurized and remote area of the aircraft. Measurements by aircraft EM expert showed that a full-power UWB data stream would not jam avionic equipment because its energy level stays under the standard noise floor of the aircraft itself. However, high-power emitters such as radio-altimeter can impact the UWB datalink integrity when antennas are close together. A seamless change of channel mitigated this risk successfully.

Bluetooth Low Energy was tested onboard a light twin-engine aircraft, P68 Vulcanair at ISAE Supaero's facility in Toulouse, France and onboard a long-haul commercial aircraft. Tests have shown a steady 120kbps in Line-Of-Sight with 50m range at 0dBm emitting power. Transmission through two 1mm Aluminum panels at a 6m range was also obtained, even at the vicinity of running engines. However, passing through large and complex mechanical structures showed lower performances: higher emission power was required and with lower data rate. Co-location with high-power emitting equipment near the 2.4GHz frequency band also impacted the data link stability but with a resilient pairing link. Tests have shown expected performances in simple environments, stable pairing, but also low or unstable data rate in complex environments.

WiFi for Rotor datalink was tested onboard a helicopter at Airbus' facilities in Marignane, France. The main limitation for wireless data link from rotor to fuselage is the passing of blades. Tests have shown interesting results as high speed rotor spin still enabled a >30Mbps sustained user payload data rate with optimized radio settings and appropriate data exchange protocol.

CYBERSECURITY

Wireless data link seems to open widely a door for pirate data collection or intrusion in a system. However, cybersecurity for wireless networks is in constant evolution and optimization. Monitoring of technologies at low levels enables to integrate access locks to equipment. Regular renewal of keys for encryption is also a path to higher safety of datalink. As mentioned above, centralized authentication as provided by the 3GPP standards may also prove to be the key to dealing with these cybersecurity problems [6].

Some technologies embed safety in their core. Ultra-Wide-Band enables to add encryption at the physical layer. Also, it can typically hide signal in the time domain thanks to impulse-based signal. Non-regular impulses associated with strong encryption more efficiently prevent eavesdropping by hiding signal under the noise floor [7]. Also, time-hopped codes reinforce the security of the signal. In addition to that, UWB offers accurate ranging between devices. A simple setting can prevent any device located outside a pre-defined safe bubble around the aircraft from connecting to the system. Such strategy is already set for cars unlocking [8].

Security is at the heart of the stakes of such innovations, but a well-constructed hybridization with appropriate security measures must be the way to deal with such rising risks.

REGULATIONS

There are several levels of regulation. The simplest is for standardized technologies operating on ISM bands (2.4GHz for example). This is the case for WiFi or BLE. These technologies, following IEEE 802.11 standards are accepted globally.

More complex is the case of standardized technologies but operating on non-ISM frequency bands. This is notably the case of UWB, whose frequency of use depends on regulations at the country level. Settings of channels used depending on regional specificities is mandatoy in order to comply with local regulation.

Finally, non-standardized or 'not-yet-standardized' solutions are the most limited by the regulation, but could be the solution for wireless when applied to harsh environments as encountered in the FTI. It is important to keep in mind that even if standards are sometimes limiting, they allow the evolution of technologies over the long term (notably the case for IEEE 802.11 or 3GPP).

Proprietary protocols may seem attractive in the short term but do not guarantee sustainability [9].

CONCLUSION

The aerospace industry's desire for less wiring and more flexibility in instrumentation is now becoming a reality. Various standard technologies offer multiple performances and are compatible with the aerospace constraints. While WiFi enables high data rate link, Ultra-WideBand brings highly robust and accurate time synchronization. Ultra-WideBand also opens to highly secured datalink. Bluetooth-Low-Energy offers a low-power datalink for sleep modes of wireless equipment or other low data rate links. Also, tests in real environment and implementation in COTS products has successfully shown applicability of these technologies for aerospace instrumentation. Still, a clear knowledge of the user requirements and the specific constraints must come with extensive expertise of the adjusted wireless technologies. Combining these three standard technologies through hybridization enables to cover most use cases for aerospace instrumentation as long as they are fully mastered and optimized for this domain's specificities when it comes to bandwidth, synchronization, environment complexity, regulation, cybersecurity.

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