



Domain: Electronics Engineering, Telecommunications and
Information Technology

PhD Thesis

- A B S T R A C T -

Contributions to the implementation of Wireless Sensor Networks in the Space Industry

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Introduction

Over the past few years WSN (*Wireless Sensor Networks*) have been the object of intense research and development in various domains of the technological society, of which a distinct group is formed by industrial applications. These are characterized by strict requirements of reliability, security and resilience, resulting in design and implementation constraints which are much more restrictive than for regular commercial applications. Consequently, industrial applications require a deterministic behaviour of the WSN in order to avoid uncertainties in the transfer of data. In extreme environments, because of significant logistical costs, battery life needs to be in the order of years. Some applications need packet re-transmission capabilities and automatic re-configuration which are characteristic to *mesh* type of networks. All of these requirements, which are typical for the industrial domain, can also be found in the Space Applications sub-domain, where the use of WSN yields multiple benefits, such as the reduction of wired harnesses, further leading to reduction of weight, reduction of assembly and testing time, easy system reconfiguration and increased reliability of communications. WSN also addresses situations where the routing of cables is too expensive or technically not feasible, e.g., when wires need to be routed through mobile joints operating outside of the satellite.

In Europe, the responsible organization for the implementation of space programs which supervises the research activities is ESA (*the European Space Agency*). ESA and its similar counterparts NASA (*National Aeronautics and Space Administration*), JAXA (*Japan Aerospace Exploration Agency*), China - CNSA (*China National Space Administration*) and Russia - Roscosmos, have shown interest over the past 10 years for WSN applied into the space domain. Inter-agency cooperation is managed by CCSDS (*The Consultative Committee for Space Data Systems*, www.ccsds.org) and results in recommendation documents which are then used as a common reference by member agencies for the design and execution of future space missions. In the case of Europe, ESA funds WSN research programs both for ground applications such as AIT (*Assembly, Integration and Testing*), and for intra-spacecraft communications, meaning communications inside the satellites or other spacecraft. According to the TRL (*Technology Readiness Level*) scale which is used by ESA for classifying technologies between TRL1 and TRL9, currently European WSN are assessed between TRL3 and TRL5 depending on the maturity level and in accordance with the actual constraints of the respective missions. This evaluation stems from direct experience and from the literature survey of ESA projects to date and it is demonstrated by this thesis. There is a plan in 2022-2023 to raise the TRL of European WSN to TRL6 and to execute a first IOD (*In Orbit Demonstration*) test flight which will include some of the results shown in this thesis.

In this context, the thesis summarizes the state of the art related to WSN utilization in space and describes a coherent methodology applicable to space research projects, with practical examples of the necessary steps.

Ultra Wide Band - UWB Communications

UWB (*Ultra Wide Band*) is a radio communication technique which uses very narrow impulses for encoding the information. Current commercial UWB transceivers use an impulse duration of 1ns to 2ns. As a result, the spectral power is distributed over a much wider frequency spectrum as compared to NB (*Narrow Band*) transmissions, as is shown in Figure 1. More precisely, the occupied bandwidth is 500MHz for 2ns impulses and approximately 1GHz for 1ns impulses.

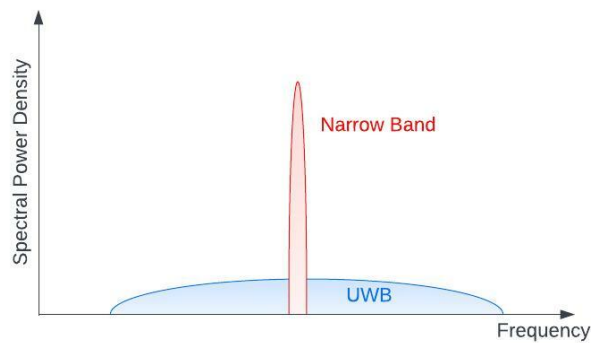


Figura 1 - Densitatea de putere spectrală - comparație UWB cu NB

This characteristic makes UWB technology immune to the multi-path fading effect, making it suitable for communications inside a highly reflective environment such as inside a satellite, which was demonstrated into a preliminary study by ESA.

Open communication standards utilized by space WSN

In the industrial domain, WSN have been subject to sustained research which has stimulated the technology evolution in order to meet the specific requirements for high reliability, determinism, predictability, sophisticated security, self-configuration and immunity to noise and interferences. Figure 2 shows the main characteristics of an industrial WSN.

Determinism	Reliability	Security	Low Power
TDMA CSMA-CA	Self configuration Self routing Resilience to interference Channel black-listing	AES encryption Authentication/Autorization Message integrity Message unicity	3-5 years battery life Energy harvesting

Figure 2 - Main characteristics of an industrial WSN

One very important aspect is the inclusion of ISA100 wireless communication protocol on the CCSDS list of technologies which are recommended for intra-satellite applications. This inclusion is one of the author's contributions and it came to realization as a result of the presentation of the activities described in this thesis to the CCSDS *On-board Wireless Working Group*.

WSN in real space missions

To date, the application of WSN in real space missions is limited to the validation on the ISS (*International Space Station*) during the course of two projects: the WiSe-Net experiment implemented by Airbus Defense & Space in 2015 and the Wireless Compose experiment implemented by the German Space Agency DLR (*Deutsches Zentrum für Luft und Raumfahrt*) in 2018. Experimenting on the ISS is a natural first step due to the relatively mild, controlled environmental conditions and low radiation levels compared with the actual space environment. Within WiSe-Net, the tests were conducted using a NB (*Narrow Band*) type WSN which was used to acquire and transmit data of physical measurements (temperature, humidity, luminosity and acceleration). During the Wireless Compose experiment the tests were conducted onto a UWB type WSN which was used for the positioning of the German astronaut Alexander Gerst within the European module Columbus. Both experiments were successful, and they validated the correct functioning of the respective WSN, without interfering with the onboard equipment.

The other WSN test was an IOD (*In Orbit Demonstration*) executed in LEO (*Low Earth Orbit*) as an experiment included in the CHIMERA mission operated by ESA and launched in 2021. Within CHIMERA, two UWB communication devices designed within the research projects coordinated by the author were programmed to establish a radio link and to compute communications statistics further relayed by the satellite subsystems to the mission control center. The communications statistics include radio specific parameters such as RSSI (*Received Signal Strength Indicator*) and PER (*Packet Error Rate*), as well as specific parameters related to the extreme environmental conditions of temperature, vacuum and radiations.

The effort made to integrate with the CHIMERA satellite platform constitutes a major personal contribution of the author and is an important step towards the demonstration of UWB technology in space. The expertise gathered during the project will serve as a basis for the next IOD opportunity.

Motivation

Within the space industry, data transmission onboard satellites is typically implemented using wired systems and *bus* type deterministic protocols such as MIL-STD-1553 or SpaceWire. Wireless communications, which include radio communications used in WSN, are something new and they require a different approach for the design execution, testing and operation of the satellites. Nevertheless, the advantages that WSN bring are significant and they justify the efforts required by their adoption. Amongst these advantages are the following:

- a) *Reduction of the satellite dry mass through the reduction of cables.* Cables make up to 10% of the satellite mass and therefore any reduction has significant impact on the launch costs. A reduction with 50% of cable mass can translate into a 1.000.000 USD launch cost reduction.
- b) *Reduction of AIT activities complexity.* By reducing the number of cables, the assembly and integration time is also reduced, which has a direct impact onto the production costs of the satellite.
- c) *Reduction of the physical constraints imposed by the routing of cables.* Cables occupy a certain volume and they require the observation of specific bending radius with each change of direction. The use of WSN allows data connections between elements which would be otherwise difficult to connect via wire either because of position, or because of the need to route the wire through a mechanical articulation or other mobile elements.
- d) *Elimination of costs due to design changes.* Throughout the design and manufacturing of a satellite, there can be design changes which impact the harnessing, which can also happen in late phases of AIT. The costs associated with the harness redesign are increasing exponentially with how late they appear in the process, and using wireless completely eliminates these costs.
- e) *Reduction of the risks for mechanical defects.* By eliminating wires, the associated connectors are eliminated too and therefore a possible source of mechanical defects is also eliminated.
- f) *Reduction of the labor volume necessary for the wired harness.* All interconnections between satellite sub-systems require the writing of ICD (Interface Control Documentation), which is greatly simplified in the case of wireless communications.
- g) *Reduction of human errors during AIT activities.* By reducing the number of the wired connections between subsystems the risk of errors by human personnel is diminished both in the assembly process and in the testing process, thus increasing the reliability of AIT operations.
- h) *Increase of the flexibility of inter-connections topology.* The elimination of wires leads to the possibility of reconfiguration of subsystems interconnections not only before launch, but even during mission operation for functional optimizations or to address some defects.

Besides the above advantages, WSN bring with them a series of specific challenges which need to be considered. Such aspects which require special attention are:

- a) *Electromagnetic compatibility.* The electromagnetic energy used by the WSN for communications may affect the correct functionality of onboard equipment and satellite systems.
- b) *Maturity level.* Although in ground applications WSN have reached a high maturity level (TRL9), in space applications the current level is TRL5 with ongoing activities

towards TRL6. One such project is WiSAT-3, which is a project coordinate by the author as personal contribution.

- c) *Technical novelty.* The design and operation of WSN requires specific knowledge which need to be acquired. The engineers responsible for these activities must bring their knowledge base up to speed in order to ensure the correct and efficient utilization of WSN in space.
- d) *Communications reliability.* The novelty of WSN utilization in intra-satellite communications also means a lack of historical background of operational performance. This must be compensated through series of tests in laboratory environments and through the inclusion of WSN in IOD missions.
- e) *Power supply.* WSN nodes are powered by electrical energy obtained from batteries or through a connection to the satellite power bus. An interesting development direction is constituted by using energy harvesting techniques.
- f) *Data transfer rates.* Because the radio spectrum is a limited resource, data transfer rates will be limited by physical constraints such as frequency, modulation or medium access techniques.

Objectives

The main objective of the thesis is to demonstrate the feasibility of using WSN onboard satellites throughout the entire mission operation by following the methodology defined by ESA. To this goal, the thesis presents a study of using WSN for communications inside an operational satellite and for replacing parts of the communication wired harness.

Two complementary applications are analyzed, one for point-to-point communications for tunneling data between two processing units and one for point-to-multipoint communications used for implementing a star topology between a processing unit and several optical sensors.

The operational satellite considered is Eu:CROPIS, which is a mission operated by the German Space Agency DLR. This satellite, shown in Figure 3, was launched in December 2018 and was in operation until December 2019. All the system Requirements and a part of the verification tests presented in this thesis were defined and executed in the DLR laboratories using data and mock-ups corresponding to the real mission. The communication subsystem inside the spacecraft is composed of two separate sub-networks: "*Spacecraft Network*" and "*Payload Network*", each of them having their own network controller and using different wired communication protocols. The *Spacecraft Network* segment is implemented using the SpaceWire technology in a point-to-point topology, while the *Payload Network* segment is implemented using point-to-multipoint links over RS422.

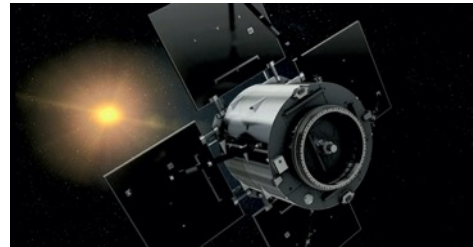


Figure 3 - Eu:CROPIS satellite

The specific objectives of the study consist of the replacement of both wired network segments, *Spacecraft Network* și *Payload Network*, with UWB sub-networks, adapted to the specific requirements of each of them, with the ultimate goal of implementing a coherent WSN communication across both segments.

For the purposes of the study, the WSN network was implemented via a custom ISA100 porting onto a physical layer (PHY) 802.15.4 - UWB in the UWB frequency channels 1 to 6, between 3.5GHz and 6.5GHz, as shown in Table 1. The advantage of this custom implementation is provided by the adaptation to the application requirements, in particular the replacement of the standard PHY layer which is 2.4 GHz with a PHY layer in the UWB technology. The increased data rate of UWB (6.8 Mb/s versus 250 kb/s as defined by IEEE802.15.4 in 2.4 GHz) allows for the reduction of the time slots from 10ms to 5ms and results in the increase of the data capacity of the communication channel. This porting of the ISA100 onto a PHY layer implemented with UWB, coupled with the reduction of the time slots down to 5ms constitutes an international premier and is part of the author contribution as coordinator of the series of projects WiSAT-1, UWB4ISS, WICO4SAT și WiSAT-2, in which this implementation was realized. The only similar study in the world was executed by Honeywell in 2014 during an ESA funded project which has achieved functional demonstration at a maturity level of TRL3.

The specific objective for the point-to-point application is the implementation of a UWB communication tunnel between the CDHU (*Command Data Handling Unit*) and PDHU (*Payload Data Handling Unit*), thus replacing a wired link which otherwise would be implemented using the SpaceWire protocol.

To achieve this goal, besides the radio communication link itself, another task was the translation from the SpaceWire protocol to the UART interface by instantiating a SpaceWire IP Core from Star Dundee onto a FPGA Xilinx ZCU102 platform.

The specific objective for the point-to-multipoint application consists of the design and implementation of a WSN between the PDHU and 3 optical sensors which are traditionally connected through RS422 wired interfaces.

The optical sensors are built around a photo camera which is used in space applications (Spinel SC20MPC) and they implement a proprietary communication protocol defined by the manufacturer. According to project requirements, this protocol had to be implemented onto WSN nodes so that the PDHU would not notice any difference between wired communications (RS422) and wireless communications (UWB).

After the summarization of the functional test results for both applications, the thesis presents the stages through which the hardware equipment was qualified at the maturity level TRL5, which has required a systematic verification campaign through thermal vacuum testing, mechanical vibration and shock testing and electromagnetic compatibility testing.

Methodology

The studies shown here were executed during research projects funded by ESA and coordinated by the author. The working methodology is therefore aligned with the general way of ESA to conduct research projects and consists of the succession of a series of predefined stages which together make a project. The advancement from one stage to another is possible only after a formal meeting between the project team and the ESA representatives and is conditioned by the successful evaluation of the previous stage. Figure 4 summarizes these stages along with the associated deliverables and the project review meetings which determine the advancement from one stage to another. Each stage is described through one or several WP (*Work Packages*) which detail the scope, duration, budget, sub-activities, dependencies and expected outcomes.

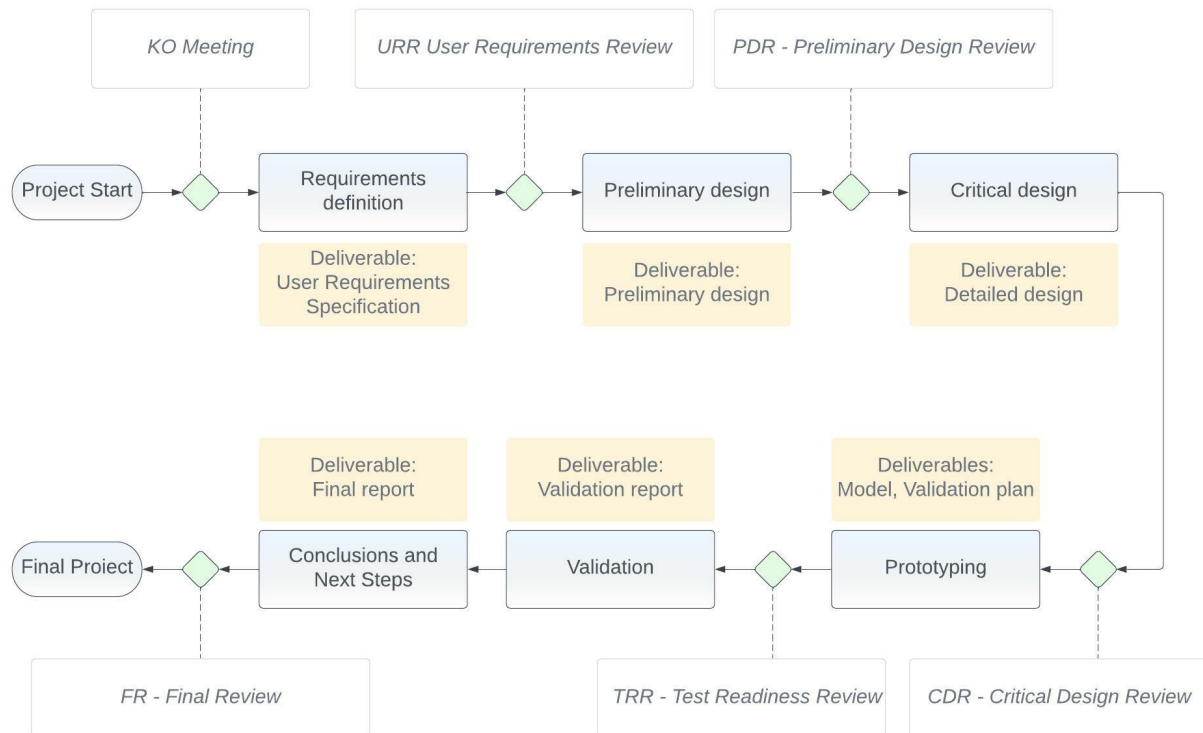


Figure 4 - The stages of an ESA research project

For each particular project, the working stages were the following:

1. Requirements definition; the result of this stage is a document containing the user requirements and system requirements.
2. Preliminary design; the result of this stage is the preliminary design documentation.
3. Detailed model design; the result of this stage is the detailed design documentation.
4. Model prototyping; the result of this stage is the Verification and Validation Plan along with the model in one or more units.
5. Model validation; the result of this stage is the document which summarizes the data obtained from the verification and validation campaign.
6. Conclusions and recommendations; the result of this stage is the project Final Report.

The UWB VN360 radio modem

The main component used for achieving the objectives of the thesis is the VN360 UWB modem which was designed during the WiSAT-1 and WiSAT-2 projects, coordinated by the author during the study.

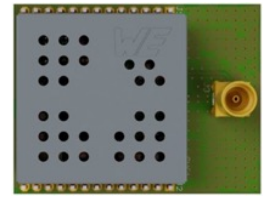


Figure 5 - VN360 UWB modem by CDS

The VN360 modem, shown in Figure 5, includes as main components the radio transceiver DW1000 manufactured by Decawave and an ARM Cortex M4 STM32L486 processor manufactured by ST Microelectronics. The DW1000 transceiver implements the PHY physical layer according to the 802.15.4-2011 standard and offers access to the data and control registers through a SPI interface. The ARM processor implements the protocol layers MAC, Network, Transport and Application according to the ISA100 standard and with the OSI general communication stack model.

There are two distinct variations of this modem, one with integrated SMD antenna and another with an external antenna connected via a MMCX connector. The integrated antenna variation is more compact and robust, however the external antenna variation is more flexible and allow for performance optimizations by proper selection of the antenna. The external antenna variation also allows the insertion of a rejection filter on the RF path which can prove necessary in some applications where certain frequency bands corresponding to harmonics of the carrier frequency have supplementary restrictions because of some specific requirements of the mission (see also the electromagnetic compatibility section.)

The intra-spacecraft sensor network used in Eu:CROPIS is divided into two segments called "*Spacecraft Network*" and respectively "*Payload Network*" as shown in Figure 6. This type of architecture is traditionally used in satellite systems and is therefore representative for other space applications, given the respective specific aspects.

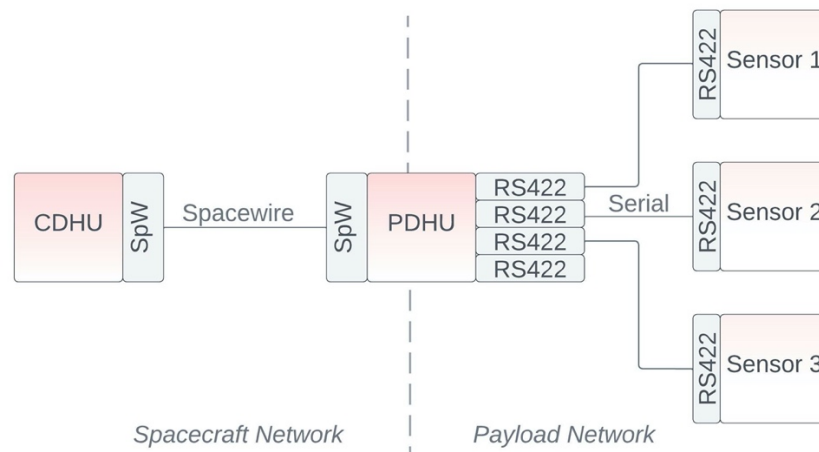


Figure 6 - Wired network design

The Payload Network segment is organized around a data controller PDHU (*Payload Data Handling Unit*) to which are connected three optical sensors built around a photo camera Spinel SC20MPC. The connections between the sensors and the PDHU are implemented with UART serial interfaces adapted to RS422 and configured for 115.2 kbit/s data rate. The higher-level communication protocol is proprietary Spinel and was implemented according to the manufacturer specifications. The communication protocol with the

sensor is point-to-point and therefore does not allow the direct integration of the sensor in complex networks, either wired or wireless.

This limitation of the sensor points to a possible future innovative application of WSN, allowing integration through the addition of addressing and routing capability to devices and sensors which were designed strictly for point-to-point applications.

Further, the PDHU controller is connected via a point-to-point link implemented using the SpaceWire standard at the speed of 40Mbit/s with the main satellite controller, called CDHU (*Command and Data Handling Unit*), thus forming the *Spacecraft Network* segment. The protocol used for communication between the two OBC (*On Board Computers*) is PTP (*Packet Transfer Protocol*) which is specified by CCSDS (*Consultative Committee for Space Data Systems*).

In order to replace the wired connections with wireless, two distinct applications were implemented, one for each network segment, so that in the end the resulting network is formed of two distinct WSN in spatial coexistence, as shown in Figure 7.

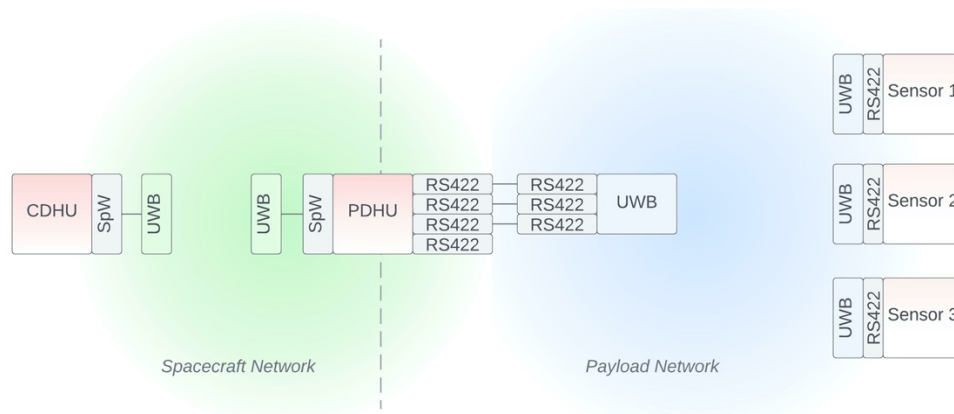


Figure 7 - Wireless network design

Because of this segmentation of the network, there are two distinct WSN operating in the same constrained space. In order to avoid interference, the two WSN were configured for functioning on two distinct channels, although, if necessary, the networks can coexist on the same channel by using channel codes which are chosen from a list of 16 distinct possible options. During the study tests, channel 5 was utilized for the *Spacecraft Network* and channel 2 was utilized for the *Payload Network*.

Test campaign results

The testing campaign for raising the maturity level from TRL4 to TRL5, corresponding to correct functioning in relevant environmental conditions consisted of 4 distinct sections: a) data capacity tests; b) distance tests; c) relevant environmental tests, including thermal vacuum and vibration and d) electromagnetic compatibility tests. The tests were organized according to the sequence shown in Figure 8.

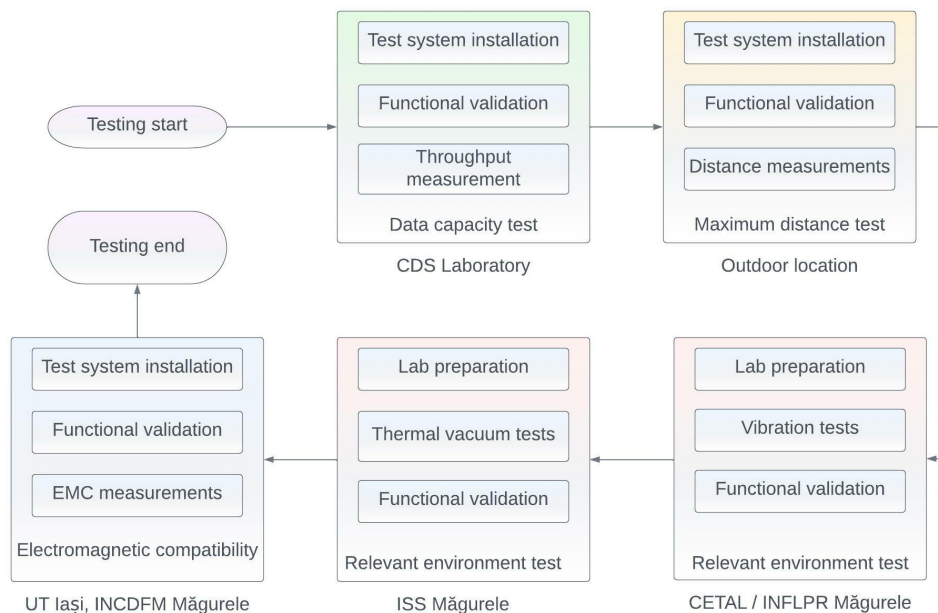


Figure 8 - Tests sequence for TRL5

Following the execution of various tests described in the projects coordinated by the author, ESA has validated the qualification of the CDS VN360 UWB modem to the maturity level TRL5, corresponding to the level of correct functionality in relevant environmental conditions.

The technical results of the tests are summarized below:

- The length of a UWB packet preamble has a direct impact onto the communication performance. For longer lengths (256b), the RSSI and PER values are better.
- There is no noticeable difference in results between the UWB channels tested (1 la 7).
- There is no major difference in results between channels 1, 2, 3 and 5 which are using the 499.2 MHz channel width and channels 4 and 7 which are using the 1331.2 MHz channel width.
- The network performance is not affected by the position of the UWB nodes inside the spacecraft and is also not affected by their spatial orientation.
- The materials used for building the separation panels have a measurable influence on the communication performance. The utilization of Aluminium honeycomb between Carbon fiber composite plates yields to better results than the utilization of the same Aluminium honeycomb rigidized between solid Aluminium plates.
- The UWB nodes antennas should have a similar spatial orientation for optimal results.
- The placement of the nodes at too short distances (cm) can lead to saturation and performance drop, the solution in this case being a reduction in transmission power.

- The shape of the cutouts between the separation panels which is done for allowing the routing of cables between compartments is influencing the UWB network communication statistics. Round or oval cutouts are providing better results than square or rectangular shapes, using right angles.
- For intra-satellite communication applications, where distances are small, it is best to use maximum data rate settings (6.8 Mb/s) to increase the useful data throughput (*payload*) and to reduce latencies.
- The electromagnetic field levels generated by an UWB network are within the general requirements for EMC as specified by space applications.
- Although the distance requirements for intra-spacecraft communications are small (in the range of 3-5m), the tests have shown correct functioning of an UWB link at maximum data rate of 6.8 MB/s up to 130m, which demonstrates that UWB technology is suitable also for applications onboard stratospheric platforms HAPS.
- For longer distances, one needs to consider the effect of PSR drop in narrow regions dependent on: a) the UWB channel and b) the height against the base platform at which the UWB nodes are installed. For increased performance certainty a functional test on a representative mock-up is recommended.
- An important aspect is the power supply of the UWB nodes, which can be the satellite power bus or it can be an independent power source, in which case energy harvesting techniques can be applied. In any event, one must consider that although the average current consumption of an UWB node is typically under 1mA, peak values during transmission can reach 170mA for the short duration of a few ms.
- Useful data (*payload*) throughput obtained on an UWB link is similar or better than the one obtained on a wired MIL-STD-1553, which is the wired protocol taken as a reference for this study. When using a symmetrical distribution of traffic between the two UWB nodes, the total was 1.2 Mb/s useful data throughput, which is over the MIL-STD-1553 specification of 1 Mb/s in total, meaning inclusive of useful data and adjacent information.
- The resilience of the UWB network against intentional interference is remarkable, and in practice it is not possible to totally interrupt the communication of a point-to-point UWB link even with a continuous 26 dBm jamming source placed within 10cm from the nodes.
- The network topologies studied are point-to-point and star. While other topologies such as multi-hop and mesh are possible and specified by the ISA100 standard, they do not seem to be necessary in intra-spacecraft applications due to the short distances, in the order of meters, that exist between the UWB nodes.

Conclusions

The thesis identifies the specific aspects related to the development of an UWB sensor network applied to the space domain, with the methodology and evaluation criteria being the ones universally applied by the space industry, which makes them suitable for being used as an example for the development of technologies for use in other difficult environments.

The conditions for functioning of the wireless sensor networks in space impose specific requirements derived from the characteristics of extreme environment, meaning vacuum combined with a high temperature span, as well as specific requirements related to the launch, meaning vibrations and shocks, all of which have been addressed in detail in the thesis. In addition, there are aspects related to the functioning in conditions of high radiation, which have not been addressed in the thesis as they are part of a future phase of the technology development, leading to the increase of the maturity level to TRL6. The meeting of extreme environmental requirements comes as an added complexity on top of the actual communication implementation, which is in itself a difficult task by the very nature of the ambitious objective of replacing traditional wired MIL-STD-1553 or SpaceWire with wireless UWB.

In order to assess the degree of meeting the ensemble of requirements, space agencies use the TRL maturity scale which allow for an objective evaluation in comparison with the level of maturity of other technologies, but also in relationship with a specific mission, by defining intermediary levels from TRL1 to TRL9. It is worth noting that each mission defines its own set of specific requirements, so the reference values which determine the success of a technical validation may differ on a case by case basis, which means that a product can qualify at one TRL level for a specific mission but could qualify at a different level for another mission. It is therefore recommended that the definition of a TRL level and consequently the definition of the validation tests necessary be done in relationship with a certain mission or class of missions.

In general, to attain TRL4 the product or technology should be perfectly functional in laboratory conditions, should have the theoretical background completely demonstrated and should show a degree of integration and miniaturization which makes them representative for the end result.

Further, in order to move to TRL5 one should verify the correct functioning in accordance to specifications in representative environmental conditions, i.e. in thermal vacuum, using limits for temperature and pressure which are dependent on the mission requirements. Still for TRL5, correct functionality is validated under conditions of mechanical stress by executing dedicated vibration and shock tests with the goal to demonstrate the mechanical survival of the product during and after the launch in space. The design and manufacturing of the UWB nodes which are meant to function in space need to consider the specificity of working in vacuum. All components and materials used need to be vacuum certified and need to have known outgassing characteristics, otherwise they need to be submitted to preliminary qualification tests before utilization, in order to avoid the contamination of nearby equipment. The packaging of UWB nodes which need to function in vacuum is done in special conditions in a clean room, trying to minimize the risk for contamination of other subsystems when unpacking in the satellite integration area.

An important aspect which is constantly monitored throughout the TRL evolution is electromagnetic compatibility. The relevant ECSS standards indicate the principles to be applied and the methods for measurement, without imposing anything else but generic limits for the electromagnetic field depending on frequency. Each mission or class of missions will define its own spectral mask which needs to be observed, which is something to consider when detailing the user requirements and before the actual design of the UWB sensor networks.

Besides these general values, it is possible that some additional restrictions are defined in certain out-of-band frequency bands, in which case the harmonics of the UWB carrier will need to be attenuated either through a specific design of the UWB modem, or by inserting rejection filters between the modem and the external antenna.

The thesis describes in a coherent manner the stages to be followed for the qualification of a space product to TRL5, by synthesizing the practical experience of the UWB sensor networks technology in a series of research projects coordinated by the author, using three real spacecraft as references, i.e. Venus Express, Sentinel 3 and Eu:CROPIS.

The results of the experiments and measurements demonstrate the feasibility of using wireless communications, particularly UWB, for data transfer inside a satellite for the two applications under study, which are sensor networks and data buses. This constitutes an important step towards the adoption of UWB networks in the space industry, where the potential benefits are already identified and quantified and where the reluctance to apply the technology is due only because of the current maturity level.

The next important step will be the qualification at TRL6 and the inclusion of the UWB nodes into an IOD (*In Orbit Demonstration*) program. This effort is currently underway in the frame of an ongoing project funded by ESA called WiSAT-3, coordinated by the author, and which aims for the raising of the maturity level to TRL6 by the end of 2022. The WiSAT-3 project is continuing the present study and addresses among other things the challenges posed by the exposure of UWB nodes to radiations. In this respect the project will analyze the consequences of single SEE (*Single Event Effect*) and cumulative TID (*Total Ionizing Dose*) exposures to radiation doses equivalent to the Eu:CROPIS radiation levels, according to the specifications provided by DLR which was the mission operator..

In other, separate activities, there are efforts to implement energy harvesting technology from light or electromagnetic sources to reduce the dependency of the satellite power bus. This technology is currently at TRL3 (laboratory demonstrated concept) and its evolution will have a major contribution to the adoption of UWB networks for intra-satellite communications by simplifying its utilization.

The implementation of WSN onboard spacecrafts has been approached in an innovative way by porting an industrial protocol, ISA100.11a, over the UWB PHY layer, which resulted in a deterministic communication solution, with time slots allocation in a TDMA mechanism, a solution which meets the requirements imposed by data transfers onboard satellites. The communication protocol selected (ISA100.11a) originates from the Oil&Gas industry where it was developed specifically for meeting very strict requirements for performance and reliability while operating in a difficult environment.

The TRL5 level is significant for a wireless sensor network and is comparable with the experiments run in 2016 by Airbus and in 2018 by DLR on the International Space Station ISS, so in a relatively controlled environment and in easier conditions.

The combination between UWB and ISA100.11a is unique in the world, the only other similar implementation by Honeywell being according to public data at TRL3, so much lower than the TRL5 level demonstrated in this thesis.

Up until now, two VN360 UWB nodes manufactured by ESA following authors specifications have been included in the Flight Model of the LEO experimental mission CHIMERA, which was launched on 17.08.2021.

With the launch of CHIMERA, the two nodes have become the first known wireless sensor network launched onboard an operational satellite.

The low number of experiments performed outside terrestrial laboratories indicate the novelty of WSN utilization in the space industry, as well the methodological rigor which this industry is strictly applying every time it implements a new technology.

Beyond the specifics of WSN and of UWB characteristics, this thesis constitutes a more general guide for researchers aiming to develop and to introduce new technologies in the space domain, from idea to the industrial product, following the standardized steps defined by ESA for advancing on the TRL scale.